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Tree Crown Affects Biomass Allocation and Its Response to Site Conditions and the Density of *Platycladus orientalis* Linnaeus Plantation

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Abstract: Tree crown plays a crucial role in the process of photosynthesis and the formation of biomass. The site conditions and stand density have a significant impact on tree and crown growth, as well as biomass formation. Understanding crown growth and its influence on the allometric growth of the biomass of various organs under diverse site conditions and densities is critical to comprehending forest adaptation to climate change and management. This study examined the growth of trees, crown, and biomass in 36 plots of young *Platycladus orientalis* plantations across three site conditions (S1: thin soil on the sunny slope; S2: thick soil on the sunny slope; S3: thin soil on the shady slope) and four densities (D1: $\leq$1500 plants/hm^2; D2: 1501–2000 plants/hm^2; D3: 2001–3000 plants/hm^2; and D4: $\geq$3001 plants/hm^2). The findings of this study showed that S3 demonstrated the best tree growth, with considerably higher DBH and V than S1 and S2. In addition, as the number of trees grew, the average diameter at breast height (DBH), height (H), and volume (V) all decreased greatly. Poor site (S1) suppressed the canopy, decreasing crown width (CW), crown length (CL), crown ratio (CR), crown surface area (CCSA), and crown volume (CCV), while increasing crown efficiency (CEFF). This same trend was seen in D4, where CR, CCSA, and CCV were all much smaller than the other densities, but CEFF was the highest. Subjective and objective indicators were less responsive to changes in crown growth than crown composite indicators like CCSA, CCV, CEFF, and CR. Site condition and density had a major impact on biomass accumulation, with S1 and D4 having a much lower biomass than S2, S3, D1, D2, and D3. More biomass was allocated to the stem in S3 and D1, and more biomass was allocated to branches and leaves in S2, S3, D1, D2, and D3, resulting in a nearly isotropic growth of branches and leaves. The effect of crown indicators on the biomass of each organ varied according to site condition and density. In varied site conditions, crown and DBH ratio (RCD) contributed the most to stem biomass, whereas CL contributed the most to branch and root biomass. CL had the largest effect on biomass accumulation at various densities. This study demonstrates how site condition and density affect tree and crown development and biomass accumulation, providing theoretical guidance for plantation management under climate change.

Keywords: allometric partitioning theory; *Platycladus orientalis*; site conditions; stand density; crown morphology; biomass allocation

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1. Introduction

As trees grow, they absorb carbon dioxide from the atmosphere and use it to construct biomass, which consists of organic matter [1]. The biomass allocation pattern refers to the proportion of biomass distributed among different tree organs such as stems, leaves, branches, and roots [2]. Juvenile trees generally allocate more biomass to aboveground organs like leaves and stems, whereas mature trees allocate more biomass to belowground organs like roots [2]. In addition, biomass is related to the wood density of the species, with higher wood densities having greater biomasses [3–5]. External factors and resources involving water, nutrients, and light influence biomass distribution among organs, and the proportion of biomass distributed among different organs reflects the plant growth trade-off strategy [2,6]. Tree adaptation to resource acquisition capacity is characterized by variations in the proportion of biomass allocation among tree organs, which can accurately reflect the effects of environmental changes on trees [7,8]. Two hypotheses explain how biomass is distributed among tree organs: the optimal allocation theory and the allometric partitioning theory [9,10]. The optimal allocation theory states that the environment influences the biomass allocated to each organ. In contrast, the allometric partitioning theory claims that biomass allocation depends only on tree size [11,12]. The biomass allocation pattern of a specific tree species can be analyzed under various environmental conditions by utilizing either empirical measurements or models. Combining these observations with the allometric growth coefficient makes it possible to identify the extent to which the environment influences biomass allocation and to reveal the underlying biomass allocation strategy [2,13].

Tree crown plays a fundamental role in essential physiological activities, including photosynthesis and transpiration, and is thus essential in the regulation of light, precipitation, and nutrient cycling within forest ecosystems. The characteristics and health of the crown are important indicators of tree vigor, biomass accumulation, and distribution within different organs [14–18]. Reviewing the literature shows that crown research can be categorized into four types: (1) crown structure and visualization simulation [19–23]; (2) the crown and forest productivity relationship [18,24–29]; (3) forest health evaluation [19,30]; and (4) crown and forest physiological and ecological process [31,32]. Several studies have shown that adding crown indicators into the biomass models can improve model accuracy [28,29,33,34] and increase the biological explanatory ability of the models [35]. However, there has been little research on the impact of the crown on biomass accumulation and distribution to different tree organs.

Crown indicators can be divided into three categories according to the method of investigation and calculation. The first category is objective indicators, which are those that can be measured directly using measurement tools, such as crown width (CW) and crown length (CL); the second category is subjective indicators, which are those obtained by the investigator through observation and estimation, such as crown dieback (CDBK), crown density(CD), crown light exposure (CLE), and foliage transparency (FT); the third category is composite indicators, which are calculated from multiple objective and subjective crown indicators, such as crown ration (CR), crown surface area (CCSA), and crown volume (CCV) [15,30,36–38]. Many studies have shown that crown indicators are closely related to forest productivity [19,39–41]. However, some studies have also shown that the correlation between the crown and forest productivity is uncertain, such as in young forests, the crown is a significant factor in productivity formation [42], while the effort of the crown decreases in the mature forest [40].

Crown growth is significantly influenced by the site conditions and stand density [43–45]. The contribution of the crown to tree growth varies with site conditions [46–48]. Stand density is also crucial for crown growth, which affects tree growth, biomass accumulation distribution, and productivity formation [44,49]. The degree of correlation between crown and biomass accumulation varies with densities [50]. Several studies have been conducted to explore the effects of site condition and density on tree growth, such *Populus* [51], *Cunninghamia lanceolata* Lambert [52], *Platycladus orientalis* Morton Arboretum acc. [44], and *Pinus tabuliformis* Carr. [53]. Despite the importance of the crown in determining the biomass allocation pattern and its response to site conditions and stand density, there is a lack of research on this topic.

Naturally occurring in northwestern China, Korea, and the Far East regions of Russia, *P. orientalis* has also become a naturalized species in Europe, North America, eastern Africa, and various Asian countries such as Japan, India, and Iran [54]. The *P. orientalis* is an evergreen tree with a pyramidal crown, branches that grow diagonally upward, and scale-like leaves [55]. One of the distinctive features of *P. orientalis* is its ability to adapt to harsh environmental conditions, and therefore it is widely planted for wind and soil conservation purposes [56,57]. Additionally, its slow-growing but long-lived nature makes it a great option for landscaping [58], and its wood is often used for construction and furniture production [55].

P. orientalis is the main plantation in Beijing. The ninth forest resource inventory in 2019 showed that the area of *P. orientalis* plantations was approximately 124,000 hectares, of which 88.5% were young forests. They are mainly planted in low mountain areas (≤800 m altitude), with the area of sunny slopes and shady slopes accounting for 54.3% and 38.5%, respectively. Investigating the influence of site condition and density on the crown growth and biomass accumulation of *P. orientalis* plantation in Beijing can better understand its productivity formation and carbon sequestration, thus providing a scientific foundation for forest management. We have set up 36 plots of four different densities in three main site conditions to examine the growth patterns, biomass accumulation, and crown effects of young *P. orientalis* plantations (≤40 years old) in Beijing. Our research seeks to answer the following questions: What are the growth patterns of *P. orientalis* plantations in different site conditions and densities? How does biomass accumulation differ between site conditions and densities? How does the crown affect the biomass allometric growth pattern, and how does this vary with site conditions and densities? We hypothesize that (1) better site conditions and lower densities are more optimal for tree and crown growth; (2) different site conditions and densities influence biomass allocation proportions and the allometric growth relationship in various tree organs; (3) the tree crown impacts the allometric growth patterns of different organs' biomass and varies with site conditions and densities.

2. Materials and Methods

2.1. Experimental Site

Beijing (39°28′–41°05′ N, 115°25′–117°30′ E) is located at the northern end of the North China Plain, with plains and mountains accounting for 38% and 62% of the city's total area, respectively, and an average altitude of 43.5 m. It has a warm, temperate, semi-humid, continental monsoon climate with four distinct seasons; annual sunshine hours are 2000–2800 h; the frost-free period is 180–200 d; annual precipitation is about 600 mm, with summer precipitation accounting for 74% of the year. The annual precipitation is about 600 mm, with summer precipitation accounting for 74% of the year; the zonal vegetation is warm temperate deciduous broad-leaved forest, and the main tree species include *P. orientalis*, *P. tabuliformis*, *Larix gmelinii*, *Robinia pseudoacacacia*, and *Styphnolobium japonicum*. The age range of the *P. orientalis* plantation was 29–32 (Table 1).

Table 1. Stand information table.

Site	Density (Trees·hm^{-2})	Mean Age (a)	Mean Elevation (m)	Mean Slope (°)	Slope Aspect	Site Index
S1	D1 (1083 ± 44)	30	185	23	ES	9
	D2 (1875 ± 14)	30	185	23	ES	9
	D3 (2458 ± 30)	30	185	23	ES	9
	D4 (3300 ± 28)	30	185	23	ES	9
S2	D1 (1200 ± 62)	29	128	18	ES	9
	D2 (1833 ± 22)	29	128	18	ES	9
	D3 (2525 ± 28)	29	128	18	ES	9
	D4 (3308 ± 22)	29	128	18	ES	9
S3	D1 (1266 ± 44)	32	210	21	E	10
	D2 (1850 ± 14)	32	210	21	E	10
	D3 (2541 ± 33)	32	210	21	E	10
	D4 (3291 ± 44)	32	210	21	E	10

2.2. Experimental Design and Investigation

A split-block design was employed, which considered two factors, site condition and density. Site condition was the main factor with three levels [59]: thin soil on the sunny slope (S1, poor site quality), thick soil on the sunny slope (S2, medium site quality), and thin soil on the shady slope (S3, high site quality). The soil condition in each site condition, such as soil water content, soil water availability, soil texture, soil nutrient, and site index, were introduced in former studies [60–62]. The results showed that the soil water content, soil water availability, soil texture, soil nutrient, and site index were greater on shady slopes than on sunny slopes.

Density was the secondary factor with four levels: $\leq$1500 plants/hm^2 (D1), 1501–2000 plants/hm^2 (D2), 2001–3000 plants/hm^2 (D3), and $\geq$3001 plants/hm^2 (D4). All sample plots were chosen from undisturbed stands, free from pests, and diseases, and the same management practices were applied to all plots. We investigated 36 sample plots of 20 m $\times$ 20 m for all trees with a diameter at breast height (DBH) greater than 5 cm within each plot. Further details of the sample plots can be found in Table 1.

Individual tree investigation indicators include DBH and tree height (H). The DBH was measured with a caliper accurate to 0.1 cm, and the H was measured with a measuring pole accurate to 0.1 m. Based on the results of individual tree investigation, the mean DBH, H, volume (V), ratio of height to DBH (RHD), relative dominant height (RDH), and relative dominant diameter (RDD) of the stand were calculated.

2.3. Crown Indicators Investigation and Calculation

(1) Objective indicators

Crown Width (CW, m): the vertical projection width of the crown, divided into east–west and north–south crown widths; measure with a measuring tape, and take the mean value, accurate to 0.1 m.

Crown Length (CL, m): the vertical length from the bottom to the top of the crown, accurate to 0.1 m.

(2) Subjective indicators

Crown Light Exposure (CLE): direct light received by the crown surface. The crown surface was divided into four sides and the top for a total of five light exposure surfaces. These five surfaces were observed and classified into six levels, from 0 to 5, as shown in Table 2 [15].

Table 2. Crown light Exposure rating table.

Class	Condition of Division
0	There is no light at all in the crown
1	There is light at the top or on 1 side of the crown
2	There is light at the top of the crown or on 1 side (2 sides in total)
3	There is light at the top of the crown or 2 sides (3 sides in total)
4	There is light at the top of the crown or on 3 sides (4 sides in total)
5	There is light at the top of the crown or on 4 sides (5 sides in total)

Crown dieback (CDBK, %): determined by the percentage of crown dieback area over the entire live crown area, divided by 5% as a unit (Table 3), which can reflect the intensity of competition. When CDBK < 5%, the tree grew normally, 6%–20% in light competition, 21%–50% in moderate competition, and >51% in severe competition [15].

Crown Density (CD, %): refers to the percentage of crown branches, leaves, and other tissues that block light from passing through the crown. After determining the canopy profile (the profile of the *P. orientalis* crown is close to a cone), observations were made at a unit division of 5%, consistent with the CDBK, see Table 3 [15].

Table 3. Standard table for Crown Dieback, Crown Density, and Foliage Transparency.

Code	Percentage (%)	Code	Percentage (%)	Code	Percentage (%)
00	0	35	31–35	70	66–70
05	1–5	40	36–40	75	71–75
10	6–10	45	41–45	80	76–80
15	11–15	50	46–50	85	81–85
20	16–20	55	51–55	90	86–90
25	21–25	60	56–60	95	91–95
30	26–30	65	61–65	100	96–100

Foliage Transparency (FT, %): the percentage of sky visible through the living crown divided by every 5% as a unit; the division method is consistent with the CDBK, see Table 3 [15].

(3) Composite indicators

Crown Surface Area (CCSA, m^2), calculated using

$$CCSA = 4\pi \cdot CL/(3 \cdot R^2)\ [(R^2 + R^4/(4 \cdot CL^2))^{1.5} - (R^4/(4 \cdot CL^2))^{1.5}] \cdot CD, \quad (1)$$

Crown Volume (CCV, m^3), calculated using

$$CCV = 0.5 \cdot \pi \cdot R^2 \cdot CL \cdot CD, \quad (2)$$

where: R is the radius of the CW, 0.1 m.

Crown Production Efficiency (CEFF): the ratio of CCSA to CCV, calculated as

$$CEFF = CCSA/CCV, \quad (3)$$

Crown Ration (CR, %): CL to H ratio.
Crown Fullness Ratio (CFR): CW to CL ratio.
Crown and DBH Ration (RCD): CW to DBH ratio.

2.4. Biomass Model

Using published literature to calculate the biomass of each tree organ [63]:

$$WS = 0.1253\ (DBH^2 \cdot H) \cdot 0.7330,\ R^2 = 0.9900, \quad (4)$$

$$WB = 0.1374 + 0.0129 \cdot DBH^2 \cdot H,\ R^2 = 0.8480, \quad (5)$$

$$WF = 0.0535 + 0.0100 \cdot DBH^2 \cdot H,\ R^2 = 0.9410, \quad (6)$$

$$WR = 0.1604 + 0.0110 \cdot DBH^2 \cdot H,\ R^2 = 0.9750, \quad (7)$$

$$WT = WS + WB + WF + WR, \quad (8)$$

where WS, WB, WF, WR, and WT were the total biomass of stem, branches, leaves, roots, and aboveground, respectively, accurate to 0.1 kg.

2.5. Data Analysis

The experimental data were analyzed using Excel (Excel 2019, Microsoft Corp., Redmond, WA, USA), and outliers were removed using the three-standard-deviation method. Tree measurements within each sample plot were averaged to represent the stand level. A two-way covariance analysis was performed in R software to evaluate the primary and interactive effects of site condition and density on each indicator (R4.1.3, R Development Core Team, 2021). Additionally, differences in indicators under the same site condition or density were examined through a one-way analysis of variance (one-way ANOVA).

The relationship between tree organ biomass, as well as the relationship between crown indicators and tree organ biomass indicators, were fitted using the equation:

$$y = b \cdot x^2, \quad (9)$$

where x and y represent two indicator factors.

Before analysis, the crown indicator values, and biomass values were logarithmically transformed (base 10). The equation was then transformed into log form:

$$\lg y = \lg b + a \cdot \lg x, \quad (10)$$

a represents the slope of the relationship between indicators, i.e., the allometric or relative growth index.

A value of $a = 1$ implies a linear relationship between two indicators, whereas $a \neq 1$ implies an allometric relationship. The absolute value of a reflects the strength of the allometric growth relationship between x and y, while b is the allometric constant, which is the Y-axis intercept [64].

The Standardized Major Axis Method (SMA) was employed to determine if any significant discrepancies existed between the slope and intercept values in the equation to compare the response relationship of various indicators to site condition and density. If any differences were found in either the slope or intercept values, or both, it was considered that the allometric growth relationship was different. The SMA analysis used the "SMATR" package in R software (R4.1.3, R Development Core Team, 2021). Using Origin software (Origin 2021, OriginLab, Northampton, MA, USA), we generated histograms. Ridge regression analysis was implemented using the Ridge regression method in SPSS software (SPSS 26, IBM Corp., Version 26, Armonk, NY, USA) to evaluate the influence of different crown indicators on organs' biomass accumulation while controlling for collinearity between independent variables. The contribution of crown indicators to biomass was determined based on the absolute value of the standardized coefficient and evaluated based on the variance inflation factor (VIF) and k, with a VIF value of $\leq$10 and a smaller k value indicating a better regression effect. The statistical significance level was set at the 5% level ($p < 0.05$) or the 1% level ($p < 0.01$) for statistical tests.

3. Results

3.1. Trees Growth under Different Site Conditions and Densities

The results seen in Table 4 and Figure 1 showed that the interaction between site condition and density had no significant effect on tree and crown growth, or biomass ($p > 0.05$). However, the site condition had a highly significant impact on DBH and V ($p < 0.01$), and density had a highly significant effect on DBH, H, V, and RDD ($p < 0.01$). Figure 1 demonstrates that the DBH of S3 was significantly larger than that of S1 ($p < 0.05$), and was 1.2 times larger than that of S1. Similarly, the V of S3 was significantly larger than that of S1 and S2 ($p < 0.05$), with values of 1.7 and 1.3 times larger, respectively. In addition, the DBH of D1 was significantly greater than that of D3 and D4 ($p < 0.05$) and was 1.2 and 1.3 times larger, respectively. The H and V of D1 were also significantly larger than those of D4 ($p < 0.05$) and were 1.2 times larger than D1. Moreover, the V of D1 was significantly larger than that of D3 and D4 ($p < 0.05$) and was 1.4 and 1.7 times larger, respectively. The RDD of D1 was significantly higher than that of D2, D3, and D4 ($p < 0.05$) and was 1.1, 1.2, and 1.2 times greater, respectively. RDD of D2 was significantly greater than that of D4 ($p < 0.05$) and was 1.1 times larger.

Table 4. Multivariate covariance analysis table.

Indicators		Site Condition (S)		Density (D)		Site Condition × Density (S × D)	
		F	*p*	*F*	*p*	*F*	*p*
Tree Growth	DBH	19.636	<0.01	28.235	<0.01	0.130	0.721
	H	3.533	0.070	7.672	<0.01	1.298	0.263
	V	18.031	<0.01	17.171	<0.01	0.749	0.394
	RHD	1.872	0.181	1.793	0.190	4.201	0.055
	RDH	2.282	0.141	3.829	0.059	0.036	0.850
	RDD	0.506	0.482	26.931	<0.01	1.583	0.218
Crown	CW	10.676	<0.01	11.588	<0.01	0.018	0.894
	CL	21.510	<0.01	6.677	0.015	0.093	0.763
	CLE	3.665	0.065	12.493	<0.01	0.565	0.458
	CDBK	7.627	<0.01	0.299	0.588	0.352	0.557
	FT	0.351	0.707	0.819	0.496	0.087	0.997
	CD	0.731	0.399	2.936	0.097	0.579	0.452
	CCSA	16.491	<0.01	25.565	<0.01	0.256	0.617
	CCV	22.988	<0.01	31.286	<0.01	1.615	0.213
	CEFF	10.887	<0.01	6.682	0.015	1.895	0.179
	CR	9.796	<0.01	0.864	0.360	3.669	0.065
	CFR	0.193	0.664	0.238	0.629	0.005	0.945
	RCD	0.473	0.497	0.168	0.685	0.000	0.989
Biomass	WS	7.709	<0.01	5.050	0.007	0.639	0.698
	WB	8.419	<0.01	4.250	0.015	0.548	0.767
	WF	8.419	<0.01	4.250	0.015	0.548	0.767
	WR	8.419	<0.01	4.250	0.015	0.548	0.767
	WT	8.150	<0.01	4.548	0.012	0.579	0.743

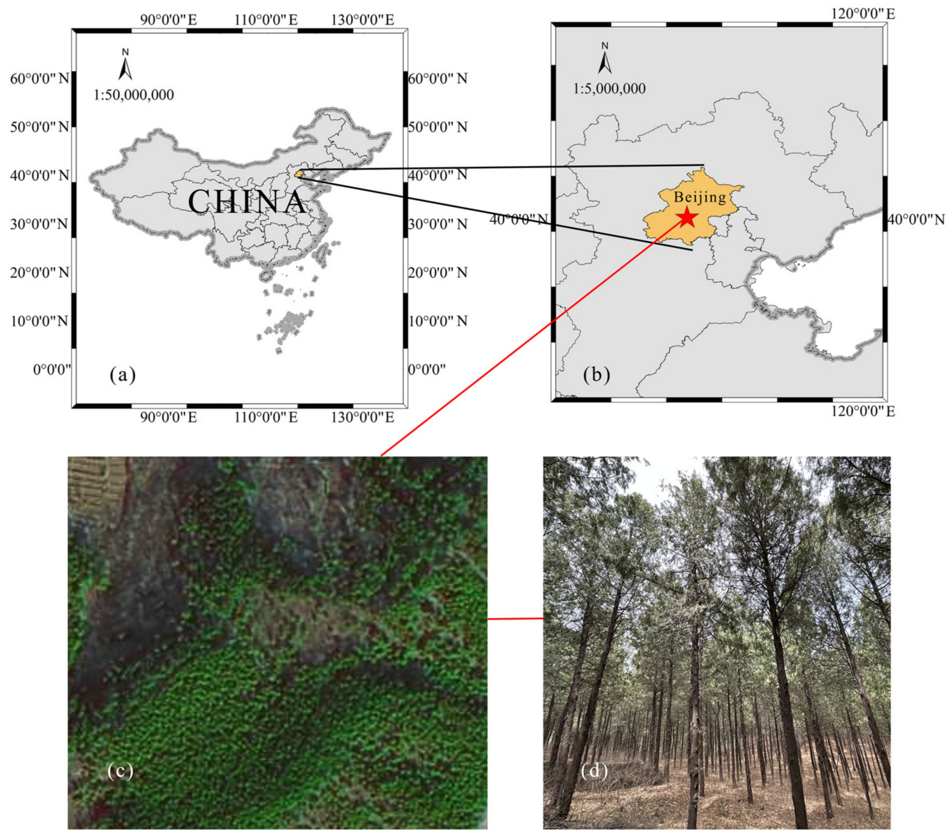

Figure 1. The geographic location of the experimental site in Beijing [yellow areas in (**a**,**b**)]. The satellite map of our experimental plantation (**c**). A photo of our experimental plantation (**d**).

The mean DBH and V of the S3 were significantly larger than those of S1 and S2, and the average DBH, H, and V decreased with increasing density. Moreover, the RDD was greater in the low-density stands, indicating a higher level of stand diameter differentiation than in other densities.

3.2. Crown Growth under Different Site Conditions and Densities

Table 4 indicates that the interaction between site condition and density had no significant effect on crown objective, subjective, and composite indicators ($p > 0.05$). However, site condition had a highly significant effect ($p < 0.01$) on CW, CL, and CDBK, and density has a significant impact ($p < 0.05$) on CW, CL, and CLE. Figure 2 demonstrates that the CW and CL of S2 and S3 were significantly larger than those in S1 ($p < 0.05$); the CDBK of S1 was significantly larger than that in S3 ($p < 0.05$). No significant differences ($p > 0.05$) were observed in CLE, CD, and FT under each site condition. Additionally, the CW of D1 was significantly larger than that in D3 and D4 ($p < 0.05$). CL of D1 was significantly larger than D3 ($p < 0.05$). CLE of D1 was significantly larger than D3 and D4. No significant differences ($p > 0.05$) were noted in CDBK and CD at any density. In conclusion, crown growth was significantly inhibited under thin soil and high density on the sunny slope, as evidenced by the significant reduction of CD and CL.

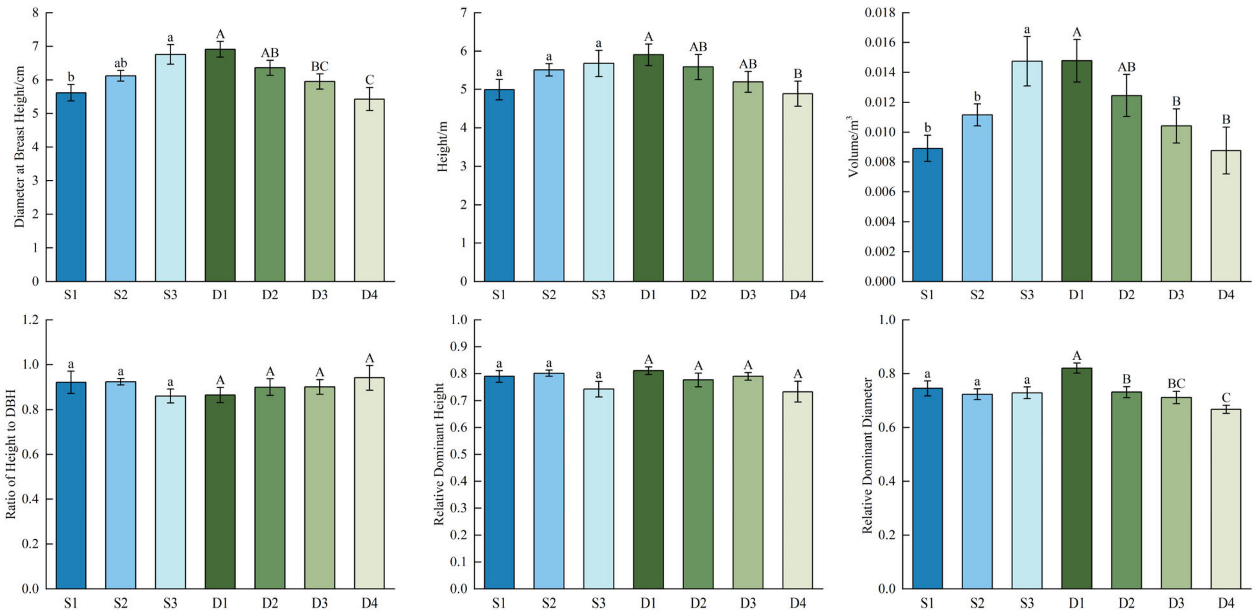

Figure 2. Tree growth indicators of different site conditions and densities (Mean ± Standard Error). The lowercase letters a and b in the figure represent the significant difference between the tree growth indicators under different site conditions ($p < 0.05$), and the capital letters A, B, and C represent the significant difference between the tree growth indicators under different densities ($p < 0.05$).

The results in Table 4 indicate no significant effect of the interaction between site condition and density on crown composite indicators ($p > 0.05$). However, a highly significant effect of site condition ($p < 0.01$) on CCSA, CCV, CEFF, and CR were observed, while density had a highly significant impact ($p < 0.01$) on CCSA and CCV, and a significant impact ($p < 0.05$) on CEFF. Furthermore, Figure 3 shows that the CCSA and CCV of S3 and S2 were significantly larger than those in S1 ($p < 0.05$). The CEFF in S1 was significantly higher than that in S2 and S3 ($p < 0.05$). Additionally, the CR in S3 and S2 was significantly larger than S1 ($p < 0.05$). However, there was no significant difference in CFR and RCD among the site conditions ($p > 0.05$). Moreover, the CCSA at D1 was significantly greater than D2, D3, and D4 ($p < 0.05$). The CCV at D1 was also significantly larger than that at D3 and D4 ($p < 0.05$). In addition, the CEFF at D4 was significantly higher than that at D1

($p < 0.05$), and the CR of D4 was significantly larger than that at D3 ($p < 0.05$). There was no significant difference ($p > 0.05$) in CFR and RCD at each density gradient.

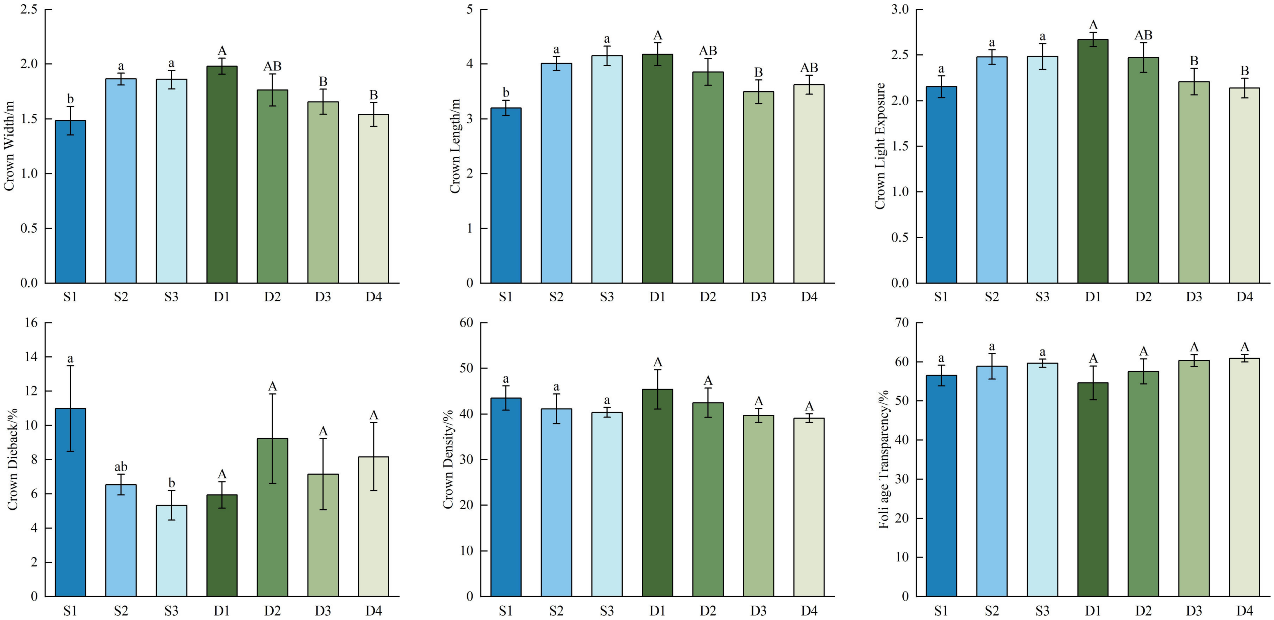

Figure 3. Crown objective and subjective indicators of different site conditions and densities (Mean ± Standard Error). The lowercase letters a and b in the figure represent the significant difference between the crown indicators under different site conditions ($p < 0.05$), and the capital letters A and B represent the significant difference between the crown indicators under different densities ($p < 0.05$).

It was observed that crown growth was more pronounced in sites with thin soil on shaded slopes than those on sunny slopes with thin soil; however, it was not significantly different from those with thick soil on sunny slopes. Additionally, CW, CL, CCSA, and CCV decreased with increasing density while CEFF increased. These results indicated that crown growth was limited under high-density conditions, with the profile of the crown narrowing as CW decreased due to the high-density effect.

3.3. Biomass Accumulation and Distribution at Different Site Conditions and Densities

Table 4 and Figure 4 demonstrate that the interaction of site condition and density had no significant effect ($p > 0.05$) on stem, branch, leaf, root, and individual biomass. Additionally, site condition had a highly significant effect ($p < 0.01$) on organ and individual biomass, with S3 being significantly higher than S1 and S2; 1.6 and 1.3 times, respectively. Moreover, density significantly affected biomass ($p < 0.05$), with D1 being significantly higher than D3 and D4; 1.4 and 1.6 times, respectively.

Figure 4 demonstrates the biomass and percentage of each organ under varying site conditions and densities. The WS in S1 and S3 was significantly higher ($p < 0.05$) than the WB, WF, and WR. Similarly, the WS in S2 was significantly higher ($p < 0.05$) than the WB. The WB was significantly higher than the WF and WR ($p < 0.05$). Moreover, Figure 4 shows that the biomass ratios of each organ followed the same pattern, with the WS and WB ratios of S1, S2, and S3 being 47.91%, 46.09%, 44.40%, and 21.02%, 21.45%, and 21.99%, respectively. WS ratios were significantly higher than WB ratios ($p < 0.05$). In comparison, WB ratios were significantly higher than the WF and WR ($p < 0.05$). The biomass and biomass ratio of the same organ varied significantly ($p < 0.05$) among different site conditions, as demonstrated by Figure 5A. The WS in S3 was significantly higher ($p < 0.05$) than that in S1. The results in Figure 5B indicate that the WB, WF, and WR in S3 was significantly higher ($p < 0.05$) than that of S2 and S1. The percentage of WS in S1, S2, and S3 were 47.91%, 46.09%, and 44.40%, respectively. The WS in S3 was significantly lower than that in S1. However, the WB, WF, and WR percentages in S3 were significantly higher than in S2 and S1. It appears that *P. orientalis* has the highest biomass in shady slopes with thin soil conditions, and the site condition less influenced the biomass distribution of each organ.

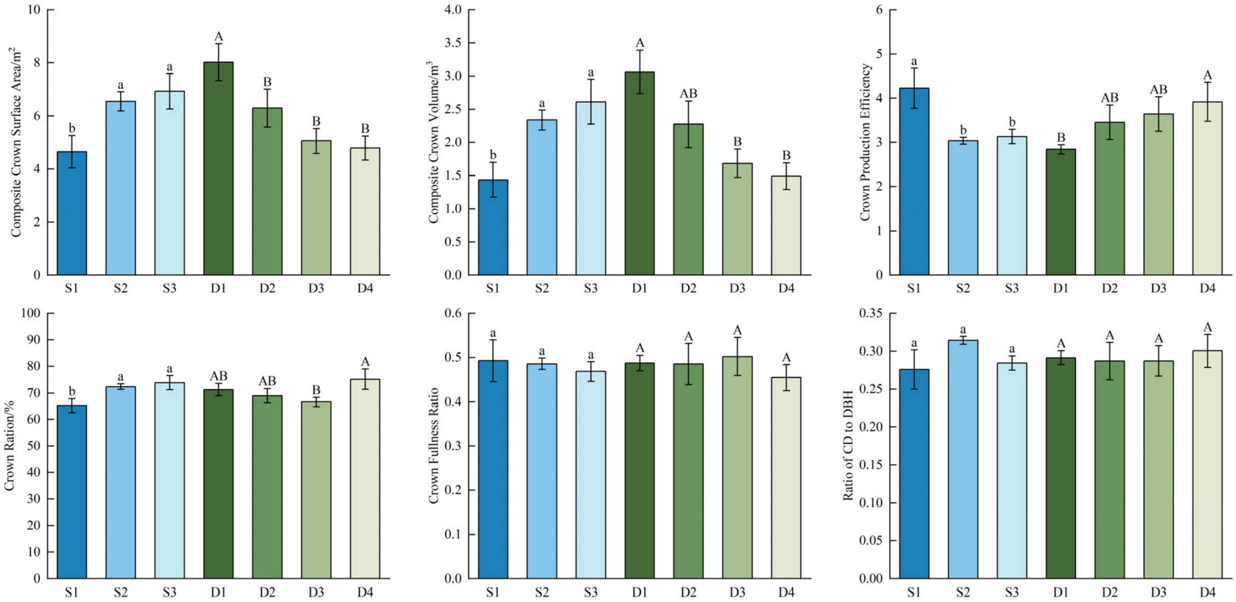

Figure 4. Crown composite indicators of different site conditions and densities (Mean ± Standard Error). The lowercase letters a and b in the figure represent the significant difference between the crown indicators of different site conditions ($p < 0.05$), and the capital letters A and B represent the significant difference between the crown indicators of different densities ($p < 0.05$).

As shown in Figure 4, there were significant differences ($p < 0.05$) in biomass and its distribution among different organs at the same density. WS was significantly higher ($p < 0.05$) than the branch, leaf, and WR for D1, D2, D3, and D4. Additionally, Figure 5D revealed that the percentage of WS was significantly higher than the percentage of branch biomass ($p < 0.05$). In comparison, the percentage of branch biomass was significantly higher than the percentages of leaf biomass and WR ($p < 0.05$). The highest percentage of WS was observed in D1, D2, D3, and D4, at 44.51%, 45.43%, 46.60%, and 48.01%, respectively. As demonstrated in Figure 5C, the WS at D1 was significantly higher than that of D3 and D4. Furthermore, WB, WF, and WR at D1 were not significantly different from that of D2 and D3 ($p > 0.05$). In contrast, WB, WF, and WR at D1 were significantly higher than that of D4 ($p < 0.05$). Figure 5D indicated that the percentage of WS at D4 was significantly higher than that of D1 ($p < 0.05$). However, the percentage of D4 WB and WF was significantly lower than that at D1. Additionally, the percentage of WR at D4 was significantly lower than that at D1 and D2.

In conclusion, the biomass of *P. orientalis* was affected by the different site conditions and densities. However, the proportion of biomass distribution among the organs remained relatively constant. Generally, the biomass allocation of each organ had a similar pattern, with the WS being notably higher than the other organs. It was observed that the biomass accumulation was greater under thin soil on shady slopes compared to thin soil on sunny slopes and thick soil on sunny slopes, and it was higher under low density than high density.

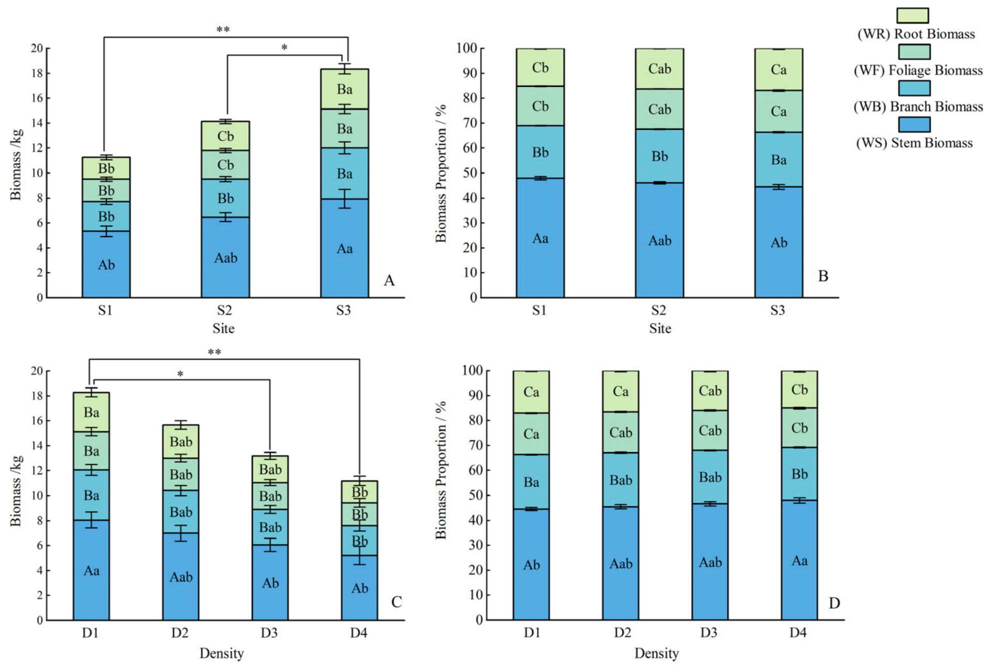

Figure 5. Biomass allocation of different site conditions and densities (Mean ± Standard Error). Biomass allocation and proportion of different site conditions (**A**,**B**). Biomass allocation and proportion of different densities (**C**,**D**).The lowercase letters a and b represent the significant difference between the biomass of the same organ at different site conditions or densities ($p < 0.05$), and the capital letters A, B, and C represent the significant difference between the biomass of different organs at the same site condition or density ($p < 0.05$). * is the significant difference in biomass at different site conditions or densities ($p < 0.05$), and ** is the extremely significant difference of biomass at different site conditions or densities ($p < 0.01$).

3.4. Biomass Allometric Relationship at Different Site Conditions and Densities

Table 5 indicates that the biomass allocation of *P. orientalis* varied significantly with site condition and density. The WS in S3 was significantly higher than WB, and WF ($p < 0.05$), the allometric growth index was significantly greater than that in S2 ($p < 0.05$), and S2 was significantly greater than that in S1 ($p < 0.05$). Additionally, the WB in S1 was significantly higher than that of WF and WR ($p < 0.05$), and the allometric growth index was significantly greater than that in S2 and S3 ($p < 0.05$). Meanwhile, there was no significant difference in WB and WR allocation between S2 and S3; however, the WF and WR allocation was not significantly different between S1 and S2, but S1 was significantly greater than S3 ($p < 0.05$). The weakest allometric growth relationship was observed in WB and WF, with a mean value of 1.045.

Table 5. Effects of site condition and density on biomass distribution among different organs.

		Site Condition						Density							
y	x	S1	S2	S3	S1	S2	S3	D1	D2	D3	D4	D1	D2	D3	D4
		Slope			Intercept			Slope				Intercept			
LnWS	LnWB	1.190 c	1.250 b	1.270 a	−1.160 A	−1.250 B	−1.270 B	1.300 a	1.280 a	1.240 b	1.200 c	−1.350 C	−1.310 C	−1.230 B	−1.170 A
LnWS	LnWF	1.269 c	1.303 b	1.314 a	−1.575 A	−1.629 B	−1.642 B	1.333 a	1.321 a	1.297 b	1.272 c	−1.685 C	−1.661 C	−1.619 B	−1.580 A
LnWS	LnWR	1.620 a	1.620 a	1.580 a	−2.220 A	−2.230 A	−2.190 A	1.460 c	1.520 bc	1.680 a	1.630 a	−1.940 A	−2.050 AB	−2.330 C	−2.240 C
LnWB	LnWF	1.060 a	1.042 b	1.034 c	−0.340 A	−0.326 B	−0.325 B	1.023 c	1.030 c	1.045 b	1.058 a	−0.306 A	−0.315 A	−0.330 B	−0.339 C
LnWB	LnWR	1.350 a	1.290 b	1.230 b	−0.647 B	−0.605 A	−0.602 A	1.120 b	1.180 b	1.340 a	1.350 a	−0.425 A	−0.502 A	−0.652 B	−0.654 B
LnWF	LnWR	1.280 a	1.240 a,b	1.200 b	−0.213 A	−0.204 A	−0.217 A	1.100 b	1.150 b	1.290 a	1.280 a	−0.091 A	−0.143 A	−0.232 B	−0.221 B

The lowercase letters a, b, and c indicate the significant difference in the slope of biomass relationship between two organs at different site conditions or densities ($p < 0.05$), and the capital letters A, B, and C indicate the significant difference in the intercept of biomass relationship between two organs at different site conditions or densities ($p < 0.05$).

At all densities, the biomass allocated to the stem was greater than that of branches and leaves. Allometric growth indices were significantly higher for D1 and D2 than D3 ($p < 0.05$) and D3 than D4 ($p < 0.05$). Most biomass was allocated to the stem, branches, and leaves than the roots. Allometric growth indices at D3 and D4 were significantly higher than those of D1 and D2 ($p < 0.05$), while the difference between D1 and D2 was insignificant. Compared to leaves, branches accumulated more biomass, with D4 being significantly higher than D3, D3 being significantly higher than D1 and D2, and D1 and D2 were not significant. The weakest correlation with allometric growth was observed for branch and leaf biomass, with a mean value of 1.039.

3.5. Effect of Crown Indicators on Biomass Allocation under Different Site Conditions and Densities

The ridge regression model R^2 between the crown indicators and the biomass of different organs under various site conditions was presented in Figure 5, with R^2 ranging from 0.818 to 0.962. The contribution of crown indicators to the biomass of different organs varied significantly among site conditions (Figure 6). CL, CCSA, CR, CFR, and RCD contribute significantly to WS accumulation across various site conditions ($p < 0.01$). The WS in S2 was significantly raised by CLE, CD, FT, and CEFF ($p < 0.01$). In S3, CW significantly contributes to WS ($p < 0.01$). Crown indicators contribute similarly to the WB, WF, and WR. CL was significant to all stands' WB, WF, and WR ($p < 0.01$). CCSA, CEFF, CR, and RCD in S1 significantly impact WB, WF, and WR ($p < 0.01$). CLE in S2 was significant to WB, WF, and WR ($p < 0.01$). CDBK, CCSA, CCV, CR, CFR, and RCD in S3 significantly contribute to WB, WF, and WR ($p < 0.01$). CD, CCV, CEFF, CD, FT, CLE, and CDBK appeared only once in the ridge regression model, but their contributions to biomass allocation were significant ($p < 0.05$) or highly significant ($p < 0.01$), indicating that these crown indicators were the factors causing variations in the biomass allometric growth relationship under different site conditions.

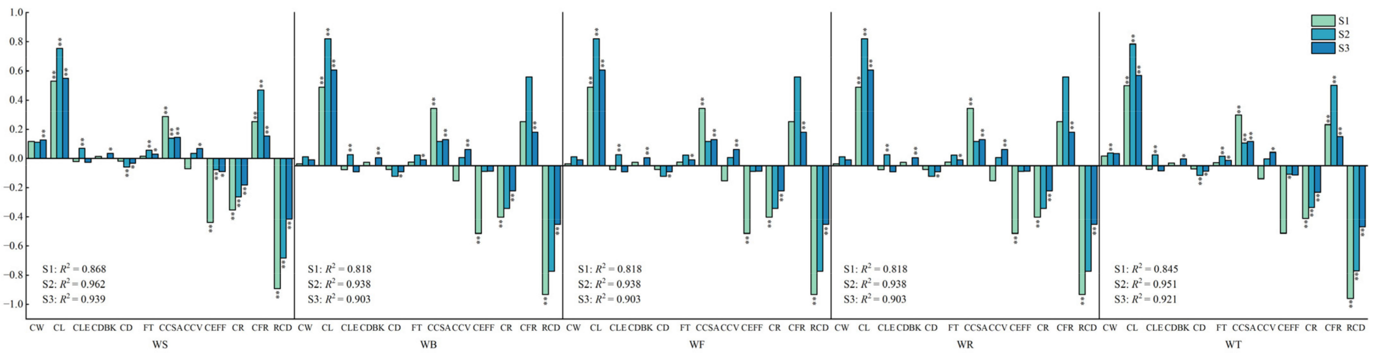

Figure 6. R^2 of crown and biomass ridge regression models under different site conditions. *, $p < 0.05$; **, $p < 0.01$.

Figure 7 shows the ridge regression model R^2 between crown indicators and the biomass of different organs under different densities, with R^2 ranging from 0.808 to 0.957. Significant differences in the contribution of crown indicators to the biomass allocation of different organs varied significantly across different densities. CL, CR, CFR, and RCD all significantly contribute to the biomass of various organs at each density ($p < 0.01$). In D1, CW, CD, FT, CCSA, and CEFF significantly impacted WS ($p < 0.01$). Similarly, in D2, CW, CCSA, and CCV all significantly affected WS ($p < 0.01$). Additionally, in D3, CW, CD, FT, CCSA, and CEFF all significantly influenced WS ($p < 0.01$). Lastly, in D4, CD, FT, and CEFF all significantly contributed to WS ($p < 0.01$). Crown indicators contribute to WB, WF, and WR at the same rate. WB, WF, and WR in D1 was significantly affected by CCSA and CEFF ($p < 0.01$). Moreover, CCV was influential in the WB, WF, and WR in D2 ($p < 0.01$). CEFF was also significant to WB, WF, and WR in D3 and D4 ($p < 0.01$). CW, CCV, and CDBK appeared only once in the ridge regression model and contributed at significant ($p < 0.05$)

or highly significant ($p < 0.01$) levels, indicating that these crown indicators altered the biomass allometric growth relationship at different densities.

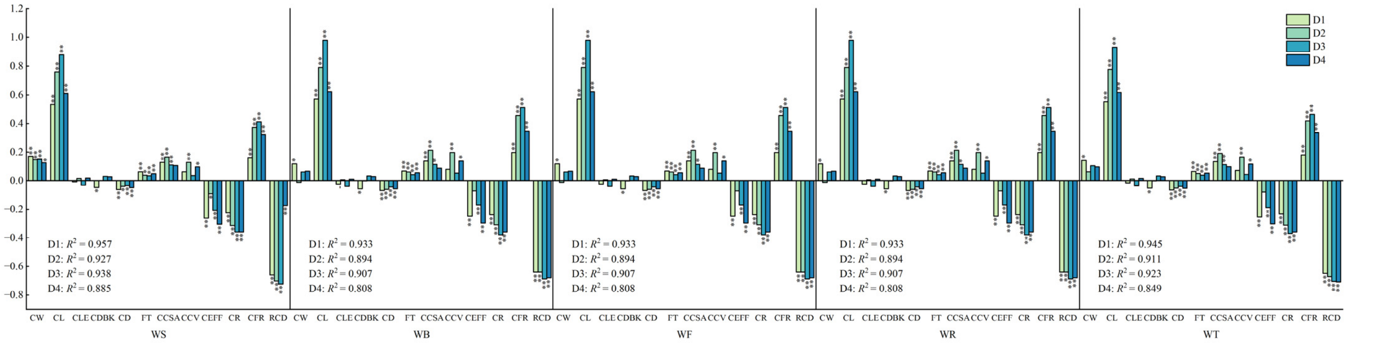

Figure 7. R^2 of crown and biomass ridge regression models under different densities. *, $p < 0.05$; **, $p < 0.01$.

4. Discussion

4.1. Effect of Site Condition and Density on Tree and Crown Growth

Site condition is one of the key factors determining tree growth and crown structure [41]. Consistent with previous studies [65,66], our study indicated that *P. orientalis* growth was poorer on sunny slopes than on shady slopes. This is primarily due to the higher intra-forest temperature on sunny slopes versus shady slopes [47], which results in higher soil water evaporation and transpiration rates [67,68]. Additionally, in water-stressed areas such as Beijing, trees growing on sunny slopes are more susceptible to water stress than those growing on shady slopes [45,65,69]. Furthermore, the soil layer in S2 is deeper, and more water can be absorbed by the tree root [70,71], and S2 has better tree growth condition than S1 (Figure 1). RHD showed no difference between site conditions (Figure 1), consistent with previous research [72]. The crown indicators CW, CL, CCSA, CCV, and CR were significantly lower in S1 than in S2 and S3 (Figure 2). At the same time, CEFF in S1 was significantly higher than in S2 and S3, suggesting that the crown size of S1 was smaller and that the tree growth necessitated a more efficient formation of photosynthetic products by the crown (Figure 1).

Density had a considerable effect on the growth of *P. orientalis* in terms of stem and crown, as reported by Duan Jie et al. [44] and Wang Yan et al. [73]. Our study revealed that DBH, H, V, and RDD decreased with increasing density (Figure 1), which aligns with previous studies' results [44]. It is believed that changes in density can modify various environmental factors, such as light, temperature, and humidity [74]. High density can decrease the nutrients available for trees and intensify competition between trees [75]. In terms of stand differentiation, the difference between the DBH of dominant trees and the DBH of average trees increased with increasing density (Figure 1). Still, there was little change in the H of dominant trees, which is consistent with the results of previous studies [74]. Density also affects crown growth, affecting stand resource utilization and allocation [76]. Under high density, tree branches cannot fully extend, and crown growth is inhibited both vertically and horizontally [26,44], and the lower branches of the crown are permanently shaded by neighboring trees, which inhibits their photosynthetic capacity and triggers self-pruning [77]. This study also found that CW, CL, CLE, CCSA, and CCV all significantly decreased with increasing density (Figures 2 and 3), consistent with the findings of previous authors [44,53], but CEFF increased with increasing density (Figure 3). Overall, it appeared that *P. orientalis* adapted to low soil moisture, high density, and low light by decreasing crown size and increasing crown productivity in both S1 and S2, which are relatively poor site conditions, and high density. Additionally, the CDBK of *P. orientalis* under different site conditions and densities was less than 15%, indicating that it is in good health as a native tree species in Beijing. As a result, our first hypothesis is confirmed.

4.2. Effect of Site Condition and Density on Biomass Accumulation

Site condition is an important basis of forest productivity and is closely related to biomass accumulation and distribution [78]. In this study, we found that the WS was the largest among all organs, followed by WB, WF, and WR, which is consistent with the findings of Lu, Leichang, et al. [79] on a plantation forest of *P. orientalis* in the Zhongshan region of Shandong Province. The available resources available to trees differ from one site condition to another, and the resource limitation makes the biomass show different differences from one site to another [24]. *P. orientalis* plantations allocate more biomass to the stem (Figure 4), which is consistent with the findings of Lei-Chang Lu et al. [80] and Quan-Quan Jia et al. [81] on *P. orientalis* and *P. tabuliformis*. The stem plays a vital role in the tree support and transport system [11], allocating higher biomass to the stem can improve the stability of the tree growth. *P. orientalis* roots received less biomass than other organs, which is likely attributed to its shallow-rooted characteristics [81].

The biomass of individual trees and their organs was found to be smaller in the thin soil of the sunny slope than in the thin soil of the shady slope, which agrees with the findings of Leichang Lu et al. [79]. This difference in biomass was attributed to the topographic factors such as slope orientation and soil thickness, as well as the ecological factors such as higher light, higher temperature, and faster water evaporation in the poorer thin soil stand of the sunny slope [80]. Furthermore, the proportion of tree biomass allocated to WS decreased, and the proportion allocated to branches, leaves, and WR increased in the better site condition (Figure 4), which follows the results of Cheng, Jemin et al. [47]. Additionally, the insignificant variation in the allometric growth relationship between stem and WR in different site conditions is consistent with the findings of Niklas et al. [11]. This allocation strategy suggests that the allometric growth relationship between branch and leaf, branch and root, and leaf and WR is reduced, and the allometric growth relationship between stem and branch and stem and leaf biomass is increased in the shaded-slope thin-soil *P. orientalis* plantations on better sites, thus promoting better tree growth.

Changes in density can significantly affect plant organ biomass differences and allocation [3,82]. This was demonstrated by Li Zongying et al. [83] in their study of *Picea schrenkiana*, which showed that as density increased, the competition for limited resources among individual trees also increased [84]. Similarly, Jia Quanquan et al. [81] and Li Zongying et al. [83] found that each organ's biomass trend as a percentage of total biomass varied with increasing density. Moreover, stand density can also change the water content and wood density in individual trees, which in turn affects biomass [3,4,85]. This suggests that trees adapt to changes in density by adjusting the biomass allocation of each organ to ensure their normal growth and development. In the present study, it was observed that as density increased, young plantations of *P. orientalis* allocated more biomass to the stem and suppressed the growth of branches, leaves, and roots, which is in line with the findings of Nilsson et al. [86] on biomass allocation in *P. sylvestris* forests of different densities. This suggests trees can adapt to increased density by promoting WS, enhancing competition, and obtaining more light [83].

It was observed that the biomass distribution of individual trees varied depending on the density. In the case of higher density of *P. orientalis* plantations, the allometric growth relationships between WS and WR, WB and WF, WB and WR, and WF and WR increased, while the allometric growth relationships between stem and branch and stem and leaf biomass decreased (Figure 4, Table 5). This result is similar to that obtained by Kellomali et al. [87], who found that trees investing mainly in aboveground branch and leaf biomass under high density and weaker light conditions can help trees to better absorb and utilize light and improve tree growth vigor. Therefore, our second hypothesis is validated. It was worth noting that the accuracy of the calculation of biomass using the anisotropic growth model is dependent on factors such as the selection of model independent variables and the form of the equations [88].

4.3. Relationship between Crown and Tree Growth

Studies have shown a correlation between crown and tree growth, which varies depending on the site conditions [89–91]. The crown can provide necessary energy and nutrients for key physiological processes, including photosynthesis and respiration. However, if the crown is compromised, these metabolic activities can be disrupted and in extreme cases, can cause the death of the tree [92]. This study has also revealed correlations between crown and tree growth in different site conditions, particularly in thick soils on sunny slopes and thin soils on shady slopes, which are more robust than those in thin soils on sunny slopes. Previous studies have demonstrated that the moisture condition of stands in thin soils on sunny slopes is lower to that in thick soils on sunny slopes and thin soils on shady slopes [15,91,93]. Tree height was significantly and positively correlated with CL and significantly and negatively correlated with CFR and RCD. At the same time, V was only significantly and positively correlated with CL. Most of the crown indicators were not significantly correlated with tree growth indicators. In S2, DBH, H, and V were significantly or highly significantly correlated with crown objective indicators, and negatively correlated with CDBK and CD. In S3, DBH was significantly and positively correlated with CW, CL was significantly and positively correlated with DBH, H, and V, and was also significantly or positively correlated with CCSA and CCV. This suggests that *P. orientalis* trees and crowns demonstrate different adaptation strategies to different site conditions.

It has been demonstrated that, under water-deficient conditions, trees allocate more biomass to their leaves and roots in response to stress rather than mainly to their stems, which increases their capacity to absorb water and decreases water usage [92,94]. The root systems of *P. orientalis* plantations under better site conditions, S2 or S3, can easily expand to deeper soil layers, which is beneficial for making full use of soil resources [95] and promoting tree and crown growth. Moreover, the increase in CCSA and CCV will promote the effective photosynthetic area of the trees [15], thus promoting tree growth [96]. On the other hand, CL under S3 in this study showed a significant negative correlation with tree growth. CEFF under S2 also showed a highly significant negative correlation with V, indicating that larger crowns are not necessarily better, as they consume energy while forming biomass [97].

The correlation between crown and tree growth was affected by density. Lower density is associated with greater light, water, and soil nutrient availability, which can enhance the tree photosynthetic and respiratory capacity, resulting in an increased positive correlation between CW, CL, and FT and tree growth indicators [98–100]. At higher density, the vertical direction of crown growth was more strongly correlated with tree growth, suggesting that taller crowns are needed to maximize light interception capacity [99,101,102]. However, larger crowns consume more photosynthetic products and are more likely to suffer from crown dieback [38,101].

4.4. Influence of Crown on Biomass Allometric Growth Relationship

Biomass is a measure of forest productivity, and crown size and shape are closely linked to the photosynthetic capacity of trees. Crown characteristics directly impact the accumulation and distribution of tree biomass [103]. Crown indicators are often used to construct models of tree growth or biomass [104]. It has been observed that the correlation between crown and tree biomass is affected by different site conditions [105,106]. This research also revealed that the relationship between crown indicators and tree organ biomass in *P. orientalis* plantations varied between site conditions, with the crown's contribution to biomass being notably higher in good soil quality sites than in those with poor soil quality.

In the same way that site condition affects crown growth, there is a trade-off between crown and tree growth in different site conditions. This study also revealed that lower density crown indicators had a more significant impact on biomass than higher density indicators, which is in line with the findings of Konopka et al. [107]. The density of stands can influence tree growth, with lower density stands having less competition, thus allowing for more vigorous growth [108]. Conversely, increased density can lead to restricted tree growth due to a lack of light and resources, affecting biomass accumulation and allocation patterns [2]. Thus, our third hypothesis is also confirmed.

Ou Jiande et al. [104] and He Peng et al. [109] have both shown that the integration of crown indicators such as CD and CR into biomass prediction models of *Taxus yunnanensis* and *Pinus massoniana* can significantly enhance the accuracy of the predictions, thereby emphasizing the significance of crown morphology and structure in tree growth and productivity. Limei [110] determined that the correlation between CW, CL, and biomass of each organ was more significant than that of tree height when constructing a biomass model for *Pinus kesiya*, and Fan Shaohui et al. [50] noted a highly significant correlation between biomass and crown relationship in small black poplar forests in North China. Crown objective indicators reflect crown size, crown subjective indicators reflect leaf vigor and crown health, and crown composite indicators reflect the three-dimensional properties of the crown [15]. Thus, combining these three types of crown indicators can more accurately quantify and assess tree growth and productivity.

4.5. Policy Recommendations and Managerial Implications

Policymakers and forest managers may use the findings of this study to inform their decision-making processes. The selection of site conditions and planting density has been demonstrated to have a substantial influence on the vitality and productivity of *P. orientalis* plantations [44,111]. This research has implications for the adaptation of forest management to climate change, emphasizing the need to adjust forest management strategies to changing environmental conditions. Moreover, the study provides substantial guidance on biomass and carbon management, equipping forest managers with vital knowledge to make informed decisions concerning harvesting and thinning operations. The identified indicators of crown growth and tree health, which encompass objective, subjective, and composite indicators, are beneficial tools for continual monitoring and evaluation [62,112].

It is essential, however, that policymakers and forest managers also take into account the active involvement of local communities and stakeholders in the decision-making process. This will ensure that forest management is in line with environmental, social, and economic objectives, thus promoting a comprehensive approach to sustainable and efficient management practices. Moreover, it is important to recognize that this study only focused on young forests, and there is still room for improvement in terms of the age range and length of monitoring.

5. Conclusions

This study investigated the effects of different site conditions and densities on tree and crown growth and biomass accumulation in young *P. orientalis* plantations. Results showed different site conditions and densities all affect tree and crown growth. Tree and crown growth was poorer when site conditions were poor and density was high, and better when site conditions were good and density was low. Research showed that, at good quality sites and lower densities, crown growth and tree volume had no correlation, due to the fact that larger crowns needed more energy. Correlations between crown and biomass were stronger at lower density and better site conditions and weaker at poorer site conditions and higher densities. Additionally, various crown indicators were found to explain the biomass accumulation of various organs. It was observed that young *P. orientalis* plantations adopted different growth strategies depending on the site conditions and densities, with poorer sites and higher densities adopting strategies to reduce crown width and length and increase productivity. In comparison, crown growth under better site condition and lower density showed strategies to increase crown width and length but with relatively lower crown productivity. Furthermore, subjective and composite indicators showed a rich response to tree growth under different site condition and density compared to common objective indicators of the crown, which can be used as reference indicators to characterize tree growth and health status. This research offers insight into how crown growth and its effect on tree biomass allometric strategy varies with different site conditions and densities, thus providing a basis for informed plantation management in the face of changing environmental conditions.

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