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Effects of Shading on the Growth and Photosynthetic Fluorescence Characteristics of *Castanopsis hystrix* Seedlings of Top Community-Building Species in Southern Subtropical China

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Abstract: *Castanopsis hystrix* is a major community-building species in the top communities of southern subtropical China, with a high natural regeneration capacity. However, excessive logging and the introduction of exotic tree species have substantially reduced the area of natural forest patches of *Castanopsis hystrix*, and seedling regeneration is essential for the long-term continuation of *Castanopsis hystrix* populations. To explore the effects of light intensity on the seedling emergence and early growth of *Castanopsis hystrix*, shading experiments were conducted under four shading treatments (0%, 40%, 60%, and 80%). The growth, biomass accumulation, and distribution, the quality index of seedlings, the morphology and structure of the root systems of seedlings, and the leaf chlorophyll content and chlorophyll fluorescence properties of seedlings under different shading treatments were analyzed. The results displayed the following: (1) Shade intensity impacts growth of *Castanopsis hystrix* seedlings and biomass allocation, with optimal results observed at 60% shade, leading to the promotion of organic matter production in leaves and the limitation of stem growth. (2) Using a multi-indicator composite index, it was determined that seedling quality for *Castanopsis hystrix* peaks at 60% shade intensity. (3) Shade significantly impacts the morphology and structure of *Castanopsis hystrix*'s root system, with most root characteristics peaking at 60% shade, indicating a substantial increase in root development compared to no-shade conditions. (4) The D-values indicated the most suitable shade intensity for seedling growth to be 60%, suggesting that *Castanopsis hystrix* seedlings are sensitive to light and excessive light can be detrimental to their growth. (5) The 60% shade treatment showed the maximum values of chlorophyll fluorescence characteristics and photochemical activity, with variations in energy conversion efficiency and dissipation reflected in parameters like photochemical burst coefficient (qP), photochemical burst coefficient (qN), the actual photometric yield of PSII under light acclimation (YII), and the maximum photosynthetic electron transport rate in photoinhibition (ETR), thereby supporting seedling growth and maintaining the normal function of photosynthetic organs. In conclusion, 60% shade treatment can effectively improve the growth and photosynthetic characteristics of *Castanopsis hystrix* seedlings and promote the accumulation of nutrient elements, ultimately promoting their growth.

Keywords: shading; *Castanopsis hystrix*; biomass allocation; root characteristics; chlorophyll fluorescence characteristics

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1. Introduction

Light plays a critical role in plants' physiological growth, with adaptations to light environments being a primary focus of ecological studies [1]. Appropriate light intensity is fundamental to the optimal growth and developmental processes of plants. Exposure to high-intensity light can result in an overabundance of light energy, thereby diminishing the photochemical efficiency in plants and inducing photoinhibition. Such conditions can subsequently lead to detrimental effects on plants' health [2]. Under sunny and warm conditions in the south during summer, seedlings are found to struggle with adjusting to high light intensity. In shaded conditions, both solar radiation and environmental heat storage are markedly diminished. This leads to elevated atmospheric humidity. Concurrently, plants exhibit alterations in specific leaf weight, morphological attributes, physiological traits, photosynthetic characteristics, and biomass distribution across different organs [3–6]. Therefore, shade treatment has also become essential for regulating light conditions during seedling cultivation [7,8].Photosynthesis is the basis of plant growth and the essential factor of plant productivity, and the response of plant photosynthesis to environmental factors is highly sensitive [9]. Chlorophyll fluorescence, as one of the natural probes in plants, is closely related to photosynthesis and can rapidly and sensitively characterize the photosynthetic function of plants [10,11]; qP represents the efficiency of converting light energy absorbed by PSII into chemical energy, reflecting the level of photosynthetic activity and openness of the PSII reaction center [12]; qN represents a pathway by which chloroplasts in the PSII reaction center of plants dissipate energy. so understanding the characteristics of chlorophyll fluorescence is considered crucial to comprehending plants' growth, light-stress responses, and adaptation mechanisms [13]. Historically, the determination of plants' shade tolerance relied predominantly on growers' anecdotal experiences, with less emphasis placed on empirical, scientific support. Recently, systematic studies on plants' shade tolerance have begun in China. Progressively, research focusing on plants' resistance to shade is receiving attention, driven by advancements in biotechnology, initiatives towards ecological environment building, and efforts in forest plant cultivation [14].

Castanopsis hystrix Miq., belonging to the family Fagaceae and the genus *Castanopsis*, and also known as the spiny tannin, is a rare evergreen hardwood family timber species [15]. Recognized as a principal species of the evergreen broad-leaved forests of the southern subtropics and esteemed as a top community species, it is characterized by tall, straight trunks and a strong ability to adapt to various environmental conditions. *Castanopsis hystrix* is known for being evergreen, for growing at a fast rate, and for its longevity [16]. The species primarily thrives in evergreen broad-leaved forests located on slopes and mountains at elevations ranging from 30 to 1600 m in the Fujian, Hunan, Guangdong, Hainan, Guangxi, Guizhou, and Tibet regions of China [17]. The wood of *Castanopsis hystrix* is appreciated for its toughness and resistance to corrosion, its attractive light-red heartwood color, and its ease of workability, making it a popular timber choice in its regions of origin. Prospects for its use in home decoration, woodworking, and shipbuilding are promising [15]. Zhiling Huang took *Castanopsis hystrix* as the research object and used pots to study the effects of 20%, 30%, and 100% light intensity relative to natural light on the light-response curve of *Castanopsis hystrix* [18]. The results showed that 30% light intensity was more suitable for the growth of *Castanopsis hystrix*. However, to date, no scholars have explored the effects of different shade conditions on the growth, root system, and chlorophyll fluorescence of *Castanopsis hystrix*, and a comprehensive evaluation is missing. In this study, *Castanopsis hystrix* is taken as the focus to examine the effects of varying shading levels on its aboveground growth, root morphology, biomass allocation patterns, and chlorophyll fluorescence characteristics. This study addresses the following research questions: (1) What is the influence of shade on the growth, biomass accumulation, and distribution of *Castanopsis hystrix* seedlings? (2) How is the quality index of *Castanopsis hystrix* seedlings affected by shade? (3) What are the implications of shade on the morphology and structure of the root systems of *Castanopsis hystrix* seedlings? (4) How are the chlorophyll content and chlorophyll fluorescence characteristics of *Castanopsis hystrix* seedling leaves influenced by shade? The aim of this study is to provide a scientifically backed basis for optimal production and cultivation strategies for *Castanopsis hystrix* seedlings, as well as to offer insights for more effective cultivation management and forest breeding practices.

2. Materials and Methods

2.1. Experimental Site and Test Materials

The experimental site was located at the nursery of the Experimental Centre of Tropical Forestry, Chinese Academy of Forestry, Pingxiang, Guangxi, China, Guangxi Youyiguan Forest Ecosystem National Observation and Research Station (106°48′12″ E, 22°05′00″ N) (Figure 1), which is in a southern subtropical monsoon climate zone with a distinct wet and dry season. The average annual precipitation is 1400 mm, mainly in April–September. The test materials were obtained from the nursery of the Tropical Forestry Experimental Centre and were 1.5-year-old live seedlings of *Castanopsis hystrix*.

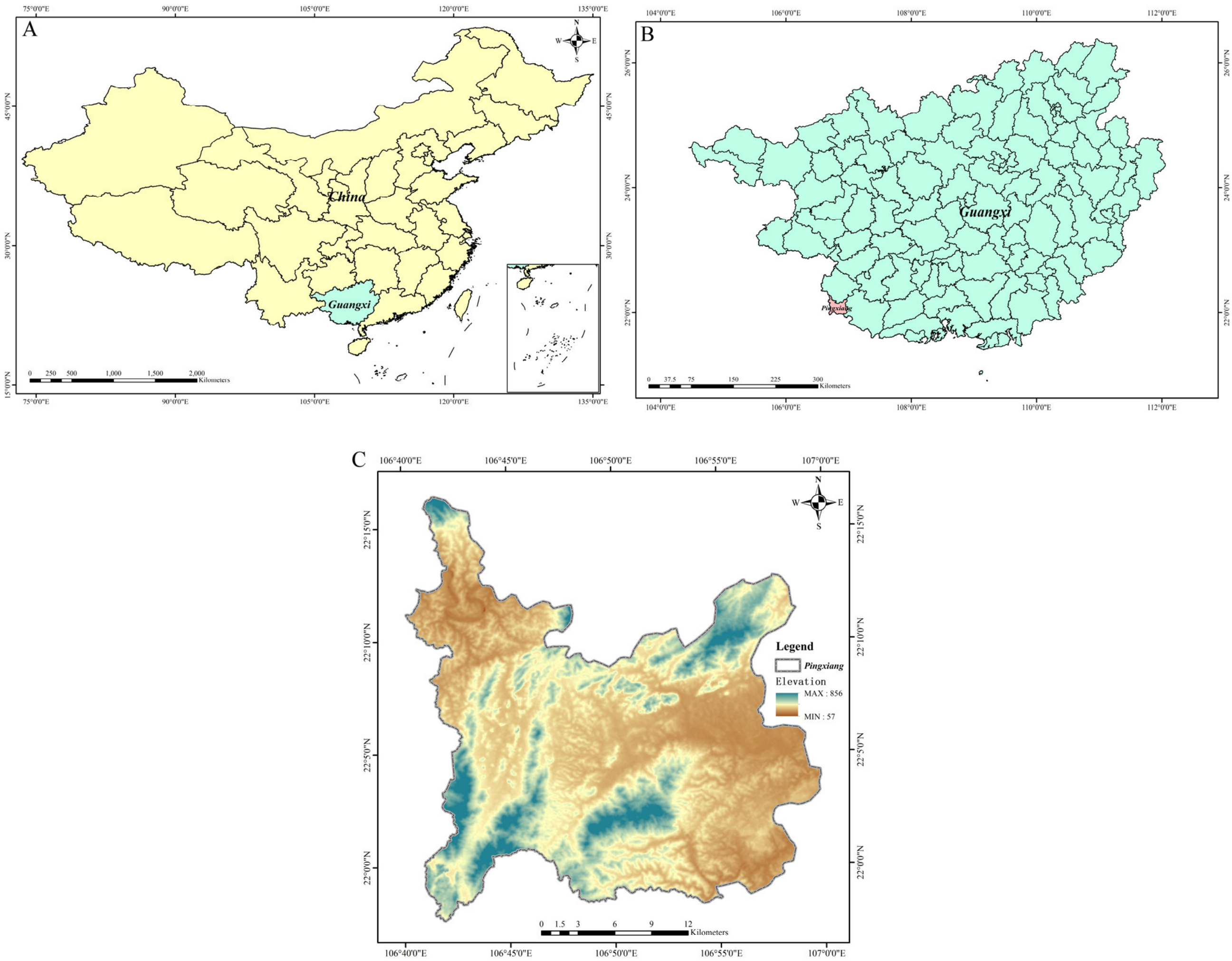

Figure 1. Location of the study area: (**A**) Position of Guangxi in China. (**B**) The location of Pingxiang city in Guangxi. (**C**) Topographic map of Pingxiang city.

2.2. Experimental Design

On 10 October 2021, we selected 120 1.5-year-old strong *Castanopsis hystrix* seedlings of continuous growth and free of pests and diseases to be planted in 60 cm diameter × 33.3 cm height × 34.5 cm bottom diameter pots. The seedlings were randomly divided into four groups using a wholly randomized trial design, with four treatments (S1: no shade, S2: 40% shade (soft shade), S3: 60% shade (medium shade), and S4: 80% shade (heavy shade)). The photosynthetic photon flux densities (PPFDs) of the 40%, 60%, 80%, and 0% shading treatments were 635.20 ± 23.95, 504.80 ± 20.66, 194.45 ± 10.89, and 1149.20 ± 40.38 μmol·m^{-2}·s^{-1}, respectively. A Taiwan Hipoint handheld spectrometer (HP350) was used to measure the light intensity, with three replicates of each treatment and ten *Castanopsis hystrix* seedlings per replicate arranged randomly and spaced at a certain distance. Shading rate = (1 − actual light intensity under the shade/natural light intensity) × 100%. The shade nets of each treatment were set up to ensure that there was no mutual shading, and the position of the pots was adjusted randomly every week to ensure that the light conditions were consistent across the treatments and to ensure ventilation all around. The treatments were managed with uniform water and fertilizer, with weed control at a later stage.

2.3. Determination Method

Growth index measurement: After seven consecutive months of incubation, 15 seedlings were randomly selected from each treatment on 10 May 2022, and seedling heights were measured using a tape measure with an accuracy of 0.1 cm; the ground diameter was measured with a Vernier caliper.

The root system was scanned and analyzed: The seedlings were removed from the pots after height and diameter measurements to avoid damage to the root system and to ensure its integrity; the root system was cut from the root neck with scissors, and the soil was washed off with tap water to obtain the whole root system; after a short drying period, the root system was quickly put into a plant root scanner to obtain a scanned map, and the root system was analyzed for total root length, root surface area, root volume, mean diameter, and root tip diameter using the WinRHIZO professional root analysis system.

Biomass determination: After the root system was scanned, each seedling was divided into three parts—root, stem, and leaf—and each part was washed with tap water to avoid dropping the parts as much as possible. After drying, they were put into envelopes and placed in an oven at 105 °C for 15 min, and then dried at 80 °C until constant weight. The biomass of a single plant was taken as the sum of the dry masses of roots, stems, and leaves, and the biomass distribution ratio of each component was calculated [19]:

Leaf biomass allocation ratio = (leaf biomass/total biomass) × 100%;

Stem biomass allocation ratio = (stem biomass/total biomass) × 100%;

Root biomass allocation ratio = (root biomass/total biomass) × 100%;

Height-to-diameter ratio = seedling height/ground diameter;

Crown-to-root ratio = (leaf biomass + stem biomass)/root biomass;

Seedling quality index = individual biomass/(height-to-diameter ratio + crown-to-root ratio);

Calculation of affiliation function values [20]:

$$U(X_j) = (X_j - X_{min})/(X_{max} - X_{min})j = 1, 2, \cdots, n.$$

where $U(X_j)$ denotes the value of the affiliation function of the j composite indicator. If an indicator is positively correlated with growth, the value of its affiliation function = $(X_j - X_{min})/(X_{max} - X_{min})$, and if it is negatively correlated its affiliation function = $1 - (X_j - X_{min})/(X_{max} - X_{min})$. X_j denotes the jth composite indicator, while X_{max} and

X_{min} denote the maximum and minimum values of the jth composite indicator, respectively.

$$\text{Calculation of weights}: \ W_j = \frac{P_j}{\sum_{j=1}^{n} P_j}, j = 1, 2, \cdots, n$$

where W_j denotes the importance of composite indicator j among all composite indicators, i.e., the weight; P_j is the contribution of composite indicator j in each shade treatment.

Calculation of the combined assessment value:

$$D = \sum_{j=1}^{n} [U(X_j) \times W_j], j = 1, 2, \cdots, n$$

where D is the combined value of seedling growth traits of cypress under different shade treatments.

Measurement of chlorophyll fluorescence parameters and chlorophyll content: On 8 May 2022, on a clear, windless morning, the leaves of the four treatments of live seedlings were measured using a modulated chlorophyll fluorometer (PAM-2500, made in Germany). The leaves were dark-adapted for at least 20 min, and then they were clamped evenly in the dark-adapted clips for Fv/Fm mode measurements. The chlorophyll fluorescence parameters measured included the maximum photochemical efficiency (Fv/Fm) of photosystem II (PSII), the potential photochemical activity (Fv/Fo) of PSII, the electron transfer efficiency (Fm/Fo) of PSII, the actual photometric yield of PSII under light acclimation (YII), the maximum photosynthetic electron transport efficiency during light suppression (Fv/Fo), and the maximum photosynthetic electron transport efficiency (Fm/Fo) of PSII, along with the maximum photosynthetic electron transport rate in photoinhibition (ETR), photochemical burst coefficient (qP), and photochemical burst coefficient (qN).

The chlorophyll content index (CCI) was determined by using a CCM-200 chlorophyll meter (ADC BioScientific Ltd., Hoddesdon, UK) to determine the chlorophyll content index of leaves [21]. For each treatment, 15 seedlings were randomly selected, and the 5th to 10th leaves from the top were measured. Three measurement points were selected for each leaf at the base, middle, and tip of the leaf, avoiding the leaf veins, and the average was taken.

2.4. Data Analysis

Microsoft Excel 2019 software with R software was used to analyze the data. R software and Origin 2021 (OriginLab Corporation, Northampton, MA, USA) were used to create data graphs. The differences between treatments were assessed using a one-way analysis of variance and Duncan's multiple ratio method test, with a significance level of 0.05.

3. Results

3.1. Effects of Shading on the Growth and the Biomass Accumulation and Distribution of Castanopsis hystrix Seedlings

As shown in Figure 2, after 6 months of shade treatment, among the four shade treatments, the ground diameter and seedling height of *Castanopsis hystrix* seedlings in the 60% shade treatment were the largest, and the ground diameter of *Castanopsis hystrix* seedlings in the 80% shade treatment was the smallest. The minimum diameter of seedling height was recorded in the no-shade treatment, as was the maximum seedling height. All differences were significant ($p < 0.05$). *Castanopsis hystrix* seedlings in the 60% shade treatment had maximum roots, stems, leaves, and plant biomass. There were significant differences ($p < 0.05$) in root biomass and stem biomass between the 60% shade treatment and the no-shade treatment. There were significant differences ($p < 0.05$) in leaf biomass and main biomass between the 60% shade treatment, 40% shade, and no-shade treatments. As shown in Figure 2, the biomass distribution of various organs in *Castanopsis hystrix* seedlings under shading conditions has a certain regularity. The root biomass distribution ratio of *Castanopsis hystrix* seedlings was the largest in the 60% shade treatment and the smallest in the 40% shade treatment. The stem biomass distribution ratio was the smallest in the 60% shade treatment and the largest in the 40% shade treatment. The leaf biomass allocation ratio was the largest in the 80% shade treatment and the smallest in the 40% shade treatment. The allocation of biomass to the organs in the 60% shade treatment compared to the other shade treatments showed that root > stem > leaf, with the 60% shade treatment significantly limiting the growth of leaves and stems compared to natural light. The 60% and 80% shade treatments promoted organic matter production and accumulation in leaves and limited the allocation of stem biomass.

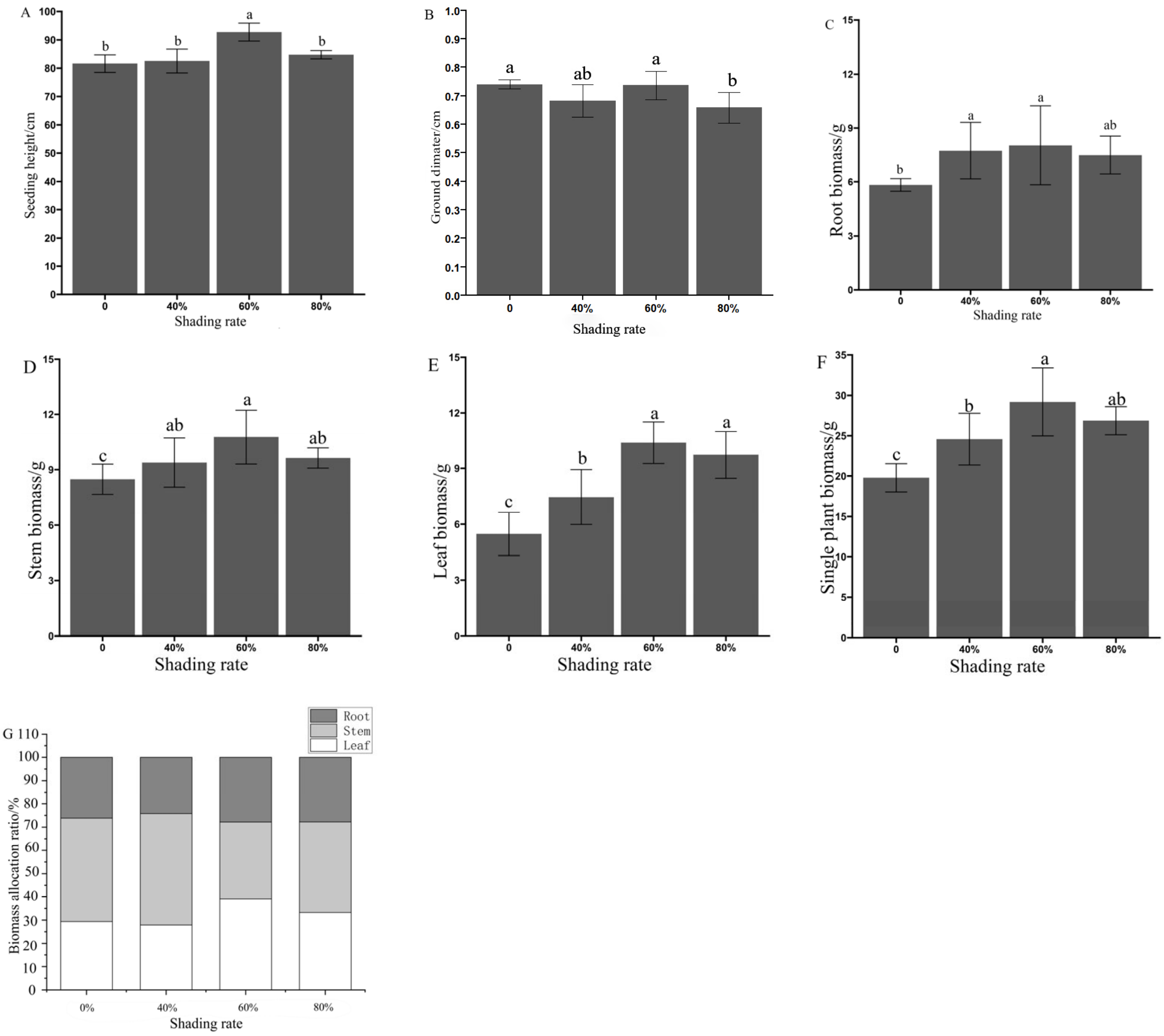

Figure 2. Effects of shading percentage on the growth and biomass of *C. hystrix* seedlings, and effects of shading on the biomass distribution of *C. hystrix* seedlings: (**A**) seedling height; (**B**) ground diameter; (**C**) root biomass; (**D**) stem biomass; (**E**) leaf biomass; (**F**) single-plant biomass; (**G**) biomass allocation ratio. Note: Different lowercase letters indicate significant differences between different shading treatments ($p < 0.05$).

3.2. *Effect of Shading on the Quality Index of Castanopsis hystrix Seedlings*

As shown in Figure 3, the height-to-diameter ratio increased with increasing shade intensity, and the difference between the no-shade and other shade treatments was significant ($p < 0.5$). The crown-to-root ratio was the largest at 60% shade and the smallest at 40% shade, and the difference between the shade treatments was not significant. The seedling quality index was the largest in the 60% shade treatment and the smallest in the no-shade treatment, and there was a significant difference between the 60% shade and no-shade treatments.

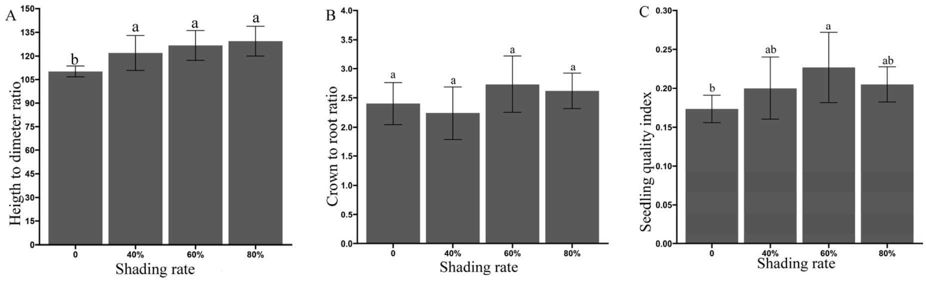

Figure 3. Effect of shading percentage on the quality index of *C. hystrix* seedlings: (**A**) height-to-diameter ratio; (**B**) crown-to-root ratio; (**C**) seedling quality index. Note: Different lowercase letters indicate significant differences between different shading treatments ($p < 0.05$).

3.3. Effects of Shading on the Morphology and Structure of the Root System of Castanopsis hystrix Seedlings

As shown in Figure 4, under different shade treatments, the total root length, total root surface area, total root volume, number of root branches, number of root crosses, and number of root tips reached their maxima at 60% shade, and the average root diameter reached its maximum at 40% shade and its minimum with no shade. There were significant differences in total root length, total root surface area, total root volume, number of root branches, number of root crosses, and number of root tips between no shade and 60% shade, as well as between 40% shade and no shade. The total root length, total root surface area, total root volume, number of root branches, number of root crosses, and number of root tips were 1.91, 2.48, 3.88, 1.85, 1.73, and 1.62 times higher in the 60% shade treatment than in the no-shade treatment, respectively.

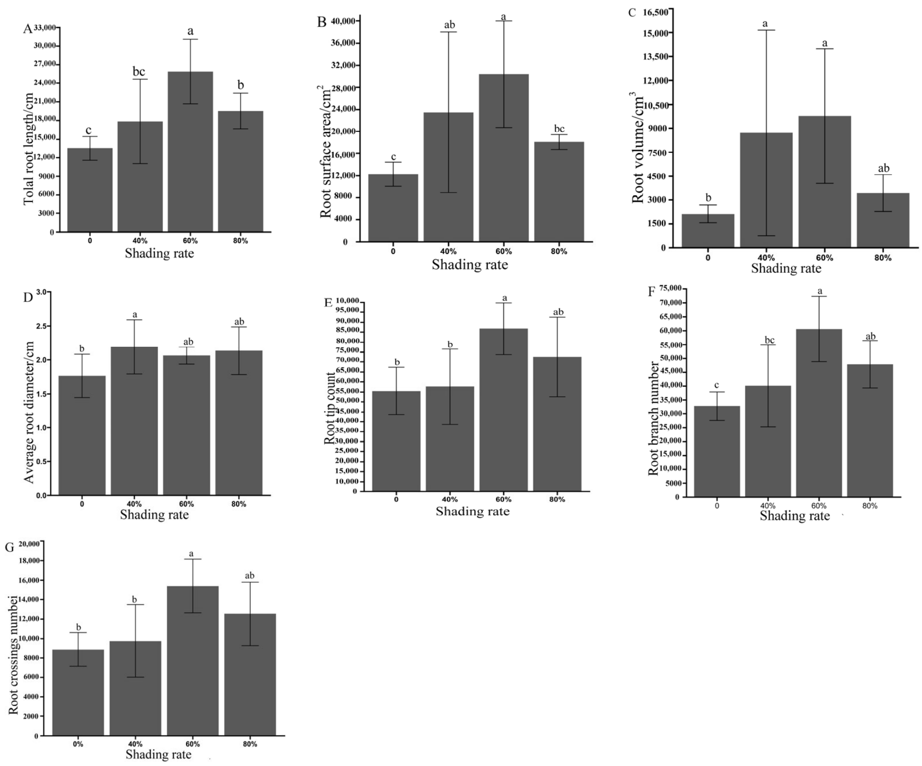

Figure 4. Effects of shading on the root growth of *C. hystrix* seedlings: (**A**) total root length; (**B**) root surface area; (**C**) root volume; (**D**) average root diameter; (**E**) root tip count; (**F**) root branch number; (**G**) root crossing number. Note: Different lowercase letters indicate significant differences between different shading treatments ($p < 0.05$).

3.4. Correlation between Growth Traits of *Castanopsis hystrix* Seedlings

As can be seen from Figure 5, there were different degrees of correlation among the growth traits of seedlings of cypress under shade treatment. There were significant or highly significant correlations between total root length and seedling height, leaf biomass, stem biomass, root biomass, individual biomass, and seedling quality index; significant or highly significant correlations between root surface area and seedling height, leaf biomass, and individual biomass; significant correlations between root volume and seedling height; significant or highly significant correlations between total root tip number and seedling height, leaf biomass, root biomass, individual plant biomass, and seedling quality index; significant or highly significant correlations between root branch number, root cross number, and seedling height, leaf biomass, stem biomass, root biomass, individual plant biomass, and seedling quality index; and overlapping information between the remaining evaluation indicators in terms of correlation, some of which were not significantly correlated with one another. The overlap of information among the other relevant evaluation indicators was not significant or noticeable. Therefore, it is not easy to obtain objective results when evaluating the growth of *Castanopsis hystrix* seedlings based on individual growth trait indicators, so other multivariate statistical methods were further used for analysis on this basis.

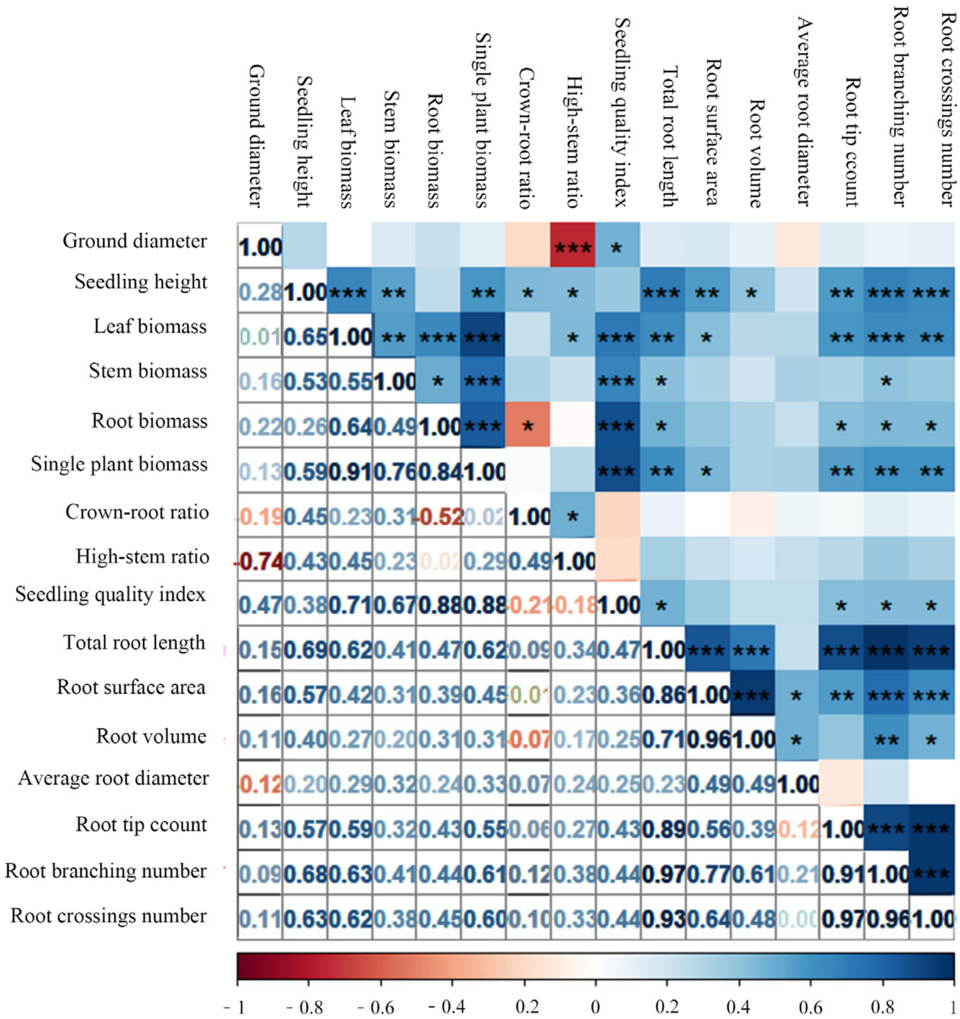

Figure 5. Correlation of growth, biomass index, and root morphology index of *C. hystrix* seedlings. * Represents $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

3.5. Comprehensive Evaluation of the Growth Traits of Castanopsis hystrix Seedlings under Shade Conditions

The values of the affiliation functions of the composite indicators of the growth traits of *Castanopsis hystrix* seedlings under different shade treatments are shown in Table 1. For index 1, tthe value of 80% shade treatment was the largest, indicating that 80% shading gave the best performance of the *Castanopsis hystrix* seedling growth traits in index 1, with the worst in 40% shade treatment. For index 2, the value of 80% shade treatment was the largest, indicating that 80% shade treatment gave the best performance of the seedling growth traits in index 2, with the worst in unshaded conditions. For index 3, the value of 80% shade treatment was the largest, indicating that 80% shade provided the best performance of *Castanopsis hystrix* seedling growth traits in ndex 3, it showed the worst performance under unshaded conditions. For index 4, 40% shade treatment was the highest, indicating that the 40% shade treatment *Castanopsis hystrix* seedling growth traits performed best in index 4, but still the worst in unshaded conditions. For index 5, the value of 60% shade treatment was the largest, indicating that the 60% shade *Castanopsis hystrix* seedling growth traits performed best in index 5, with the worst in the 40% shade treatment condition. The D-values were ranked as 60% shade > 80% shade > 40% shade > no shade treatment. This demonstrates that *Castanopsis hystrix* seedlings exhibited superior growth under the 60% shade treatment, suggesting that this shade intensity is optimal for their development. Both full light and 40% shade treatment impede seedling growth; however, the deleterious effect of full light is more pronounced than that of reduced light. Furthermore, these observations indicate that *Castanopsis hystrix* seedlings are particularly light-sensitive, with full light exposure being especially detrimental to their growth.

Table 1. Comprehensive evaluation of growth characteristics of *C. hystrix* seedlings under shading.

Shading Treatment	Comprehensive Index Value					Subordinate Function Values					D	Sort
	C (1)	C (2)	C (3)	C (4)	C (5)	U (1)	U (2)	U (3)	U (4)	U (5)		
0%	−3.09	−0.59	−0.77	−0.68	0.54	0.00	0.00	0.00	0.00	0.91	0.10	4
40%	−0.59	−0.30	−0.17	1.21	−0.44	0.40	0.37	0.37	1.00	0.23	0.41	3
60%	3.22	0.24	0.05	−0.49	0.66	1.00	0.50	0.50	0.10	1.00	0.63	1
80%	0.46	0.66	0.89	−0.04	−0.76	0.56	1.00	1.00	0.34	0.00	0.61	2
Weighting						0.31	0.25	0.14	0.12	0.11		

3.6. Effects of Shading on Leaf Chlorophyll Content and Chlorophyll Fluorescence Properties of Castanopsis hystrix Seedlings

It was observed that the leaves of *Castanopsis hystrix* seedlings grown under full-light conditions were light green, while those under intense shade (80% shade) were dark green. The chlorophyll content index (CCI) measurements (Figure 6) showed significant differences between the full-light treatment, 40% shade treatment, and 60% and 80% shade treatments. The 80% shade treatment showed the highest chlorophyll content index, significantly higher than the other treatments.

As shown in Figure 6, the variation in chlorophyll fluorescence characteristics of *Castanopsis hystrix* seedlings with shade intensity varied somewhat, with some shade treatments reaching significant levels of variation. Fm/Fo represents the efficiency of PSII electron transfer. Compared with natural light, Fv/Fm, Fv/Fo, and Fm/Fo increased to different degrees in the 60% and 80% shade treatments, with Fv/Fm increasing by 7.88% and 6.82% in the 60% and 80% shade treatments, respectively, Fv/Fo increasing by 27.03% and 21.39% in the 60% and 80% shade treatments, respectively, and Fm/Fo increasing by 19.02% and 13.21%, respectively. This shows that the maximum values of Fv/Fm, Fv/Fo, and Fm/Fo were also found in the 60% shading treatment, and the potential photochemical activity of PSII was also higher in the 60% shading treatment. Fv/Fm, Fv/Fo, and Fm/Fo all reached significant levels ($p < 0.05$) between natural light and shading at 60% and 80%.

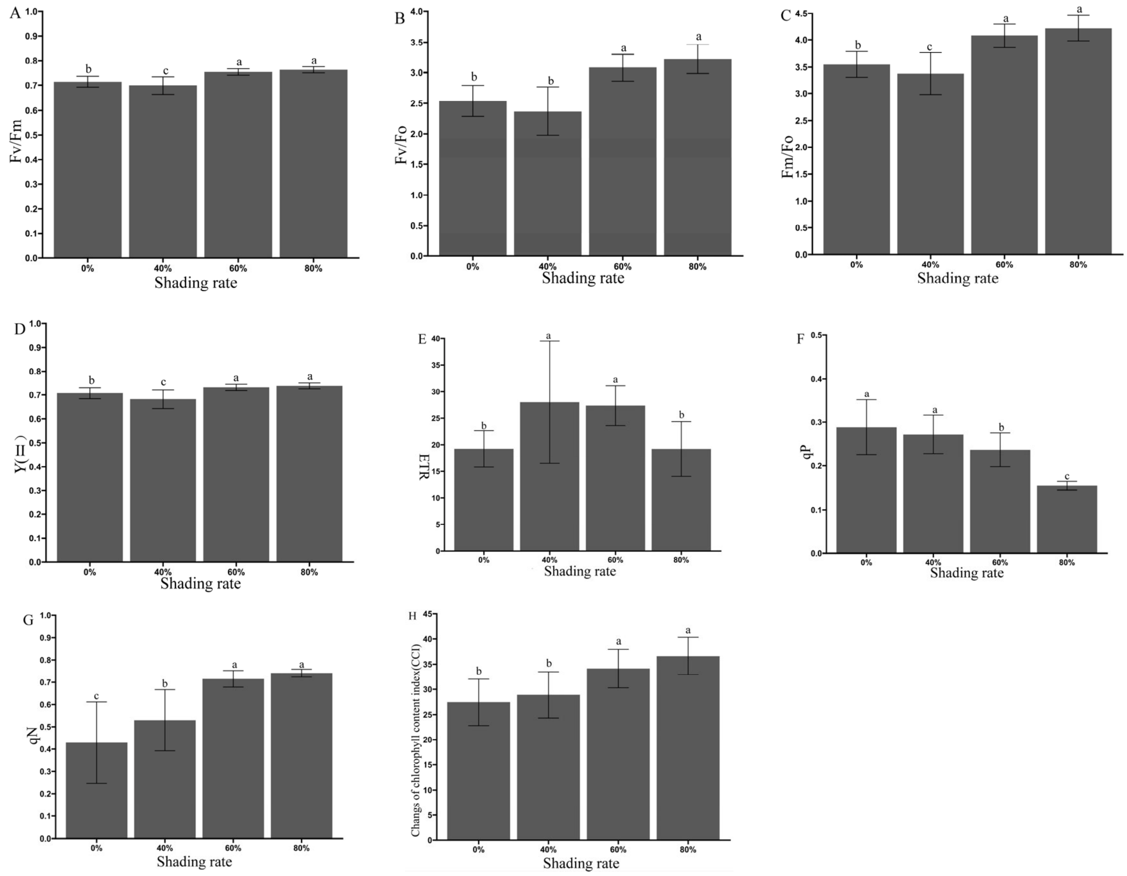

Figure 6. Effects of shading intensity on the chlorophyll fluorescence parameters of leaves of *C. hystrix seedlings*: (**A**) Fv/Fm. (**B**) Fv/Fo; (**C**) Fm/Fo; (**D**) Y(II); (**E**) ETR; (**F**) qP; (**G**) qN; (**H**) change in chlorophyll content index. Note: Different lowercase letters indicate significant differences between different shading treatments ($p < 0.05$).

Compared with natural light, qP decreased by 21.91% and 46.47% in the 60% and 80% shade treatments, respectively, while qN increased by 66.64% and 72.63%, respectively; qP was most significant in the unshaded condition; qN increased in all other shade treatments compared with natural light; qP significantly differed between the unshaded and 40% shade treatments and between the 60% and 80% shade treatments ($p < 0.05$). Compared with no shading, YII increased by 3.53% and 4.41% in the 60% and 80% shading treatments, respectively, while ETR increased by 42.23% and 45.55% in the 60% and 40% shading treatments, respectively. Significant differences ($p < 0.05$) existed between no shade and the other three shade treatments.

4. Discussion

4.1. Growth, Biomass Accumulation, and Distribution of Castanopsis hystrix Seedlings under Varying Light Intensities

Compared to full sunlight, treating *Castanopsis hystrix* seedlings with a 60% shade rate stimulated growth in both the ground diameter and seedling height. Conversely, growth in ground diameter was inhibited under treatments with 40% and 80% shade. This corroborates the results of Qian Huang [22], who found that medium-intensity lighting benefits the growth of *Parashorea cathayensis* seedlings, with seedling height and stem diameter often growing best under moderate shading with 60% light conditions [12]. Light serves as one of the requisite environmental factors for plants' growth and development, with the intensity of illumination directly impacting every facet of plants' growth, morphology, and various physiological and biochemical properties [23]. Light intensity primarily governs plant growth in two ways. Firstly, plants' growth, development, and morphogenesis are regulated through signals like photosensitive pigments. Secondly, the efficiency of plants' photosynthesis is directly controlled by the intensity of light, which, in turn, regulates plants' biological activity. Both exceedingly intense and weak light conditions are suboptimal for plant growth. Overly intense light may lead to photoinhibition, causing a decline in photosynthesis and a slowdown in plants' growth rate. Conversely, weak light intensity can lead to a deficiency of light, ultimately hampering normal plant growth and development [24]. Appropriate light is pivotal for plants' growth and development, and shading can influence the morphological traits of plants [25]. Exposure to light stress can result in diminished photosynthesis and a reduction in photosynthetic product content, leading plants to exhibit discernible damage symptoms. In terms of a plant's external morphology, attributes such as seedling height, diameter, and biomass accumulation are susceptible to photoinhibition [26].

As the intensity of shading increased, the *Castanopsis hystrix* biomass of roots, stems, leaves, and individual plants all reached their maxima at a shading rate of 60%, with leaf, stem, and individual biomass being lowest under unshaded conditions. The total biomass of *Castanopsis hystrix* seedlings exhibited an inverse "U"-shaped trend, increasing initially with shading intensity and subsequently decreasing. Research by Li Donglin revealed that under mild shading, seedlings can maintain a relatively high photosynthetic efficiency, ensuring good growth of *Emmenopterys henryi* Oliv., but severe shading can lead to nutrient deficiency, seriously restricting its growth and development [27]. Zhang Ling found that heavy shading has a significant inhibitory effect on *Phellodendron amurense* Rupr., reducing its biomass, which is consistent with the results of this study [28]. This suggests that both full sunlight and excessive shading reduce the photosynthetic efficiency of the seedlings, reducing the accumulation of photosynthetic products. Overshading enhances seedlings' photorespiration, increasing the consumption of organic matter [29], which is consistent with the results of this study. There were significant differences in the biomass of *Castanopsis hystrix* components and individual plants between a 60% shading rate and no shading treatment. The maximum leaf biomass was 11.9 times the minimum leaf biomass, while the maximum biomass of stems and roots were 1.27 and 1.38 times the minimum biomass, respectively. This indicates that leaf growth is the most sensitive under shading treatment, and the leaves are the organs most sensitive to environmental changes, with high variability and plasticity [30]. Under moderate shading intensity, the total biomass increases with the intensity of light but decreases when the light intensity continues to increase [31].

Under a 60% shade treatment, the organ allocation ratio showed that leaf > stem > root, indicating that the 60% shade treatment significantly promotes leaf growth and somewhat restricts stem growth. *Castanopsis hystrix* seedlings under moderate shading increase their root biomass to absorb more water and nutrients, adapting to weaker light intensity, but when the shading intensity increases (shading rate 80%), the biomass allocation of leaves, stems, and roots is more uniform. This is consistent with the study of Kishore K, where the accumulation and distribution of biomass were optimal under moderate shading conditions [32]. Evidently, *Castanopsis hystrix* seedlings have a high degree of shade tolerance and have strict requirements for their living environment, not tolerating high light exposure.

The results of this study indicated that the height-to-diameter ratio was at its highest at a 60% shade rate; under natural light conditions, the height-to-diameter ratio was too small. *Castanopsis hystrix* seedlings had the highest quality index under the 60% shade treatment, and there was a significant difference between this and the no-shade treatment.

Under shade conditions, the ability of a plant to survive light limitation is usually expressed in the ratio of biomass distribution between its aboveground and belowground parts. The height-to-diameter ratio reflects the balance between seedling height and thickness, and maintaining this ratio within a certain range can ensure robust growth of the seedlings [33]. Plants with a higher height-to-stem ratio often have higher growth rates and photosynthetic efficiency. They typically occupy a dominant position in environments with intense light competition. On the other hand, a lower height-to-stem ratio may mean that plants invest more in root system development to acquire more water and nutrients. In comparison to no shading, the crown-to-root ratio showed no significant changes under the different shading treatments. The seedling quality index is an important indicator to assess the health and growth status of seedlings. Healthy seedlings typically have a larger biomass, a developed root system, and normal leaf morphology. By measuring the seedling quality index, the growth condition and adaptability of seedlings can be evaluated, providing a scientific basis for the selection and planting of seedlings.

4.2. Morphological Changes in Castanopsis hystrix Seedling Roots under Different Light Intensities

Many studies have found significant differences in the morphological and physiological responses of plant roots due to the interplay of environmental influences and the plant's genetic traits [34–37]. This aligns with our findings, where under shading conditions the total root length, total root surface area, total root volume, root branching number, and root crossing number all peaked under the 60% shade treatment. Full light exposure and intense shading significantly affected the growth and development of *Castanopsis hystrix* seedling roots, inhibiting the seedlings' ability to utilize soil nutrients and water, which, in turn, limited the accumulation and growth of organic matter in the whole plant. This is consistent with the research findings on Fujian cypress seedlings by Chen Qian et al. [38]. This study also found that while some indicators correlated under shading conditions, there was little overlap in the information between some indicators. A single index is inadequate to measure the comprehensive characteristics of *Castanopsis hystrix* seedlings under shading treatment. Morphological indices are the most effective indicators to assess the growth status of seedlings. Hence, principal component analysis and the membership function method were used to perform a comprehensive evaluation of the growth characteristics of Fujian cypress seedlings under shading conditions, yielding differences in the comprehensive characteristics of *Castanopsis hystrix* seedlings under different shading conditions. The optimal comprehensive characteristics were found under the 60% shading treatment, while the worst were under full light exposure. This study used potted experiments, which may differ from natural growth conditions, potentially influencing the research results.

4.3. Changes in Chlorophyll Fluorescence of Castanopsis hystrix Seedlings under Different Light Intensities

In this study, the chlorophyll content in the leaves of *Castanopsis hystrix* seedlings increased as the light intensity decreased, with the highest chlorophyll content in the 80% shade treatment. Chlorophyll, the photosynthetic pigment of plants, absorbs and transmits photons, and its content is an indicator of a plant's ability to utilize light energy. Moreover, photosynthesis in plants is closely related to their chlorophyll content. Generally, leaves with appropriate shading have higher chlorophyll contents than those under full light exposure. This study's findings are consistent with the results of previous studies [39–41]. Under low-light conditions, the total amounts of chlorophyll a, b, and total chlorophyll all increased. This is advantageous for the plant to better absorb light energy and perform photosynthesis more effectively. This shows that shade treatment has a beneficial effect on chlorophyll synthesis in *Castanopsis hystrix*, enhancing the ability of *Castanopsis hystrix* leaves to capture and absorb light as a physiological adaptation to the light environment, with similar responses having been found in many plants [42–44].

In this study, as shading increased, the primary light energy conversion efficiency of PSII (Fv/Fm) and the potential activity of PSII (F_v/Fo) increased, but both remained below 0.77, indicating that Fv/Fm was slightly inhibited under both shading and full light exposure. Fv/Fm is the efficiency of the open PSII reaction center in capturing excited light energy, i.e., intrinsic photochemical efficiency. Fv/Fo represents the potential activity of the PSII reaction center during photosynthesis. Under non-light-inhibiting conditions, Fv/Fm generally ranges between 0.75 and 0.85 [45]. Under natural light, the Fv /Fm value was only 0.71, which was significantly lower than in the other shade treatments, indicating that moderate shade is beneficial to maintaining the normal function of photosynthetic organs and seedling growth in *Castanopsis hystrix* leaves. This suggests that the shading treatment improved the photochemical efficiency and potential activity of the PSII reaction center. This could be due to the shading treatment allowing more light energy absorbed by PSII to be allocated to photosynthetic electron transfer for leaf photosynthesis, thereby exhibiting a higher electron transfer rate. This is an embodiment of the *Castanopsis hystrix* seedlings' adaptability to low-light environments.

In this study, shading led to a decrease in qP, indicating that shading reduced the photosynthetic electron transfer activity of PSII. The photochemical quenching coefficient (qP) of chlorophyll fluorescence represents the proportion of open PSII reaction centers, reflecting the efficiency of the photosynthetic pigments in PSII converting light energy into chemical energy. qN is the non-photochemical quenching coefficient, reflecting the proportion of light energy absorbed by the PSII antenna pigments that cannot be used for photosynthetic electron transfer and is instead dissipated as heat [46]. ETR reflects the maximum potential relative electron transfer efficiency under light inhibition, i.e., the apparent electron transfer efficiency under actual light exposure. An increase in qN indicates that a certain degree of shading can help improve the photochemical efficiency of the plant and the electron transfer efficiency of the light reaction, reduce heat dissipation, and enhance the adaptability of the photosynthetic components to a low-light environment. A decrease in ETR indicates that shading resulted in a decrease in the relative electron transfer efficiency of the *Castanopsis hystrix* seedlings. Therefore, *Castanopsis hystrix* seedlings enhance their light energy conversion efficiency under shading conditions by improving the photochemical activity of the PSII reaction center and reducing heat dissipation, thereby adapting to photosynthesis in a low-light environment and ensuring the growth of seedlings.

5. Conclusions

In this study, *Castanopsis hystrix* seedlings showed a certain tolerance to shading and were able to adapt to different shading conditions by changing their growth mode. In the South Asian subtropics, the intense summer sunlight renders moderate shading advantageous for seedlings to sustain regular photosynthesis. Consequently, it is advisable to employ suitable shading techniques during the cultivation of seedlings. Notably, intense shading impedes the accumulation of dry matter in *Castanopsis hystrix*. The root biomass, stem biomass, leaf biomass, height-to-diameter ratio, and seedling quality index were the smallest in the no-shade treatment. The crown-to-root ratio, F_V/F_M, Fv/Fo, and Fm/Fo in the 40% shade treatment were the smallest. The ground diameter, total root length, root volume, and qP of the 80% shading treatment were the smallest. Therefore, appropriate silvicultural thinning practices are recommended to maintain the understory with 60% shade, thus promoting natural regeneration of *Castanopsis hystrix*. Maintaining more than 60% natural light under the forest can significantly influence the morphological growth and biomass distribution of *Castanopsis hystrix* seedlings, effectively promoting the growth of *Castanopsis hystrix* seedlings, and is beneficial for the natural renewal of seedlings. Shade at 60% can significantly affect the physiological characteristics and chlorophyll fluorescence characteristics of *Castanopsis hystrix* seedlings during the seedling stage. Under 60% shade treatment, the chlorophyll content of *Castanopsis hystrix* seedlings significantly increased, enhancing the utilization of light, and the leaf color also changed from yellow-brown to green. Compared to natural light, shading treatment can significantly improve the fluorescence parameters of *Castanopsis hystrix* seedlings, enhancing the photosynthetic capacity of the seedlings. Future research will focus on the systematic and in-depth study of the physiological and ecological impacts of the interaction of shading with soil, water, and nutrients on *Castanopsis hystrix* seedlings. This will reveal the adaptive strategies of *Castanopsis hystrix* seedlings to different environments and provide a scientific basis for the cultivation and management of *Castanopsis hystrix* seedlings.

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References

1. Rezvi, H.U.A.; Tahjib-Ul-Arif, M.; Azim, M.A.; Tumpa, T.A.; Tipu, M.M.H.; Najnine, F.; Dawood, M.F.A.; Skalicky, M.; Brestič, M. Rice and Food Security: Climate Change Implications and the Future Prospects for Nutritional Security. *Food Energy Secur.* **2023**, *12*, e430. [CrossRef]
2. Carreiras, J.; Cruz-Silva, A.; Fonseca, B.; Carvalho, R.C.; Cunha, J.P.; Proença Pereira, J.; Paiva-Silva, C.; A. Santos, S.; Janeiro Sequeira, R.; Mateos-Naranjo, E.; et al. Improving Grapevine Heat Stress Resilience with Marine Plant Growth-Promoting Rhizobacteria Consortia. *Microorganisms* **2023**, *11*, 856. [CrossRef] [PubMed]
3. Ahmed, H.A.; Tong, Y.; Yang, Q.; Al-Faraj, A.A.; Abdel-Ghany, A.M. Spatial Distribution of Air Temperature and Relative Hu midity in the Greenhouse as Affected by External Shading in Arid Climates. *J. Integr. Agric.* **2019**, *18*, 2869–2882. [CrossRef]
4. Tang, Y.; Yang, P.; Lu, N. Effects of shade on growth and photosynthetic characteristics of fir seedlings. *J. Appl. Environ. Biol.* **2023**, 1–15. (In Chinese)
5. Han, Z.; Tian, X.; Zhang, F. Effects of shade on growth, physiological characteristics and quality of Northeast Clematis. *J. Jilin Agric. Univ.* **2021**, *43*, 303–309. (In Chinese)
6. Fang, Z.; Zhong, C.; Cheng, C. Effects of shading on growth and biomass allocation of seedlings of Tetragonolobus rosa-sinensis. *Mol. Plant Breed.* **2023**, 1–20. Available online: https://kns.cnki.net/kcms2/detail/46.1068.S.20230612.1151.004.html (accessed on 28 June 2023). (In Chinese).
7. Guo, X.; Luo, Y.-J.; Xu, Z.-W.; Li, M.-Y.; Guo, W.-H. Response Strategies of Acer Davidii to Varying Light Regimes under Different Water Conditions. *Flora* **2019**, *257*, 151423. [CrossRef]
8. Zhang, N.; Van Westreenen, A.; Anten, N.P.R.; Evers, J.B.; Marcelis, L.F.M. Disentangling the Effects of Photosynthetically Active Radiation and Red to Far-Red Ratio on Plant Photosynthesis under Canopy Shading: A Simulation Study Using a Functional–Structural Plant Model. *Ann. Bot.* **2020**, *126*, 635–646. [CrossRef]
9. Lizana, C.; Wentworth, M.; Martinez, J. Differential adaptation of two varieties of common bean to abiotic stress: I. Effects of drought on yield and photosynthesis. *J. Exp. Bot.* **2006**, *57*, 685–697.
10. Krause, G.; Weis, E. Chlorophyll fluorescence as a tool in plant physiology. *Photosynth. Res.* **1984**, *5*, 139–157. [CrossRef]
11. Baker, N. Chlorophyll fluorescence: A probe of photosynthesis in vivo. *Annu. Rev. Plant Biol.* **2008**, *59*, 89–113. [CrossRef]
12. Chen, T.; Zhang, H.; Zeng, R.; Wang, X.; Huang, L.; Wang, L.; Wang, X.; Zhang, L. Shade Effects on Peanut Yield Associate with Physiological and Expressional Regulation on Photosynthesis and Sucrose Metabolism. *IJMS* **2020**, *21*, 5284. [CrossRef]
13. Toscano, S.; Trivellini, A.; Cocetta, G.; Bulgari, R.; Francini, A.; Romano, D.; Ferrante, A. Effect of Preharvest Abiotic Stresses on the Accumulation of Bioactive Compounds in Horticultural Produce. *Front. Plant Sci.* **2019**, *10*, 1212. [CrossRef] [PubMed]
14. Ren, Y.; Chen, G.; Pu, T.; Chen, C.; Zeng, J.; Peng, X.; Ma, Y.; Yang, W.; Wang, X. Response of Photosynthetic Characteristics of Maize Ear Leaves in Narrow Rows of High-light Efficiency Maize to Low-light Stress in Maize-Soybean Strip Intercropping. *Acta Agron. Sin.* **2019**, *45*, 728–739. (In Chinese) [CrossRef]
15. Xue, G.; Deng, Z.; Zhu, X.; Wu, J.; Dong, S.; Xie, X.; Zeng, J. Characterization and Phylogenetic Analysis of the Chloroplast Genome of *Castanopsis hystrix*. *Chin. J. Biotechnol.* **2023**, *39*, 670–684. (In Chinese)
16. Guo, W.; Cai, D. Analysis of the Applicability of Near-Natural Cultivation of Large Diameter *Castanopsis hystrix* Timber. *Hunan For. Sci. Technol.* **2015**, *42*, 79–82. (In Chinese)
17. Liao, Y.; Hong, W.; Chen, F.; Zhang, G.; Li, S.; Li, Z.; Zhuang, X.; Xing, F.; Wang, F. Study on Species Composition and Diversity of *Castanopsis hystrix—Acacia mangium* Forest in Guangzhou. *J. Trop. Subtrop. Bot.* **2021**, *29*, 494–502. (In Chinese)
18. Huang, Z.; Jiang, Y.; Hao, H. The effect of different light intensities on the response curve of red cone light. *J. Cent. South Univ. For. Technol.* **2014**, *34*, 30–33. (In Chinese)
19. Thorne, G.N. The Quantitative Analysis of Plant Growth. By G. Clifford Evans. *Ann. Appl. Biol.* **1973**, *73*, 357. [CrossRef]
20. Rogosinski, W. *On Subordinate Functions In Mathematical Proceedings of the Cambridge Philosophical Society*; Cambridge University Press: Cambridge, UK, 1939; Volume 35, pp. 1–26.
21. Ghasemi, M.; Arzani, K.; Yadollahi, A.; Ghasemi, S.; Sarikhani Khorrami, S. Estimate of Leaf Chlorophyll and Nitrogen Content in Asian Pear (*Pyrus serotina* Rehd.) by CCM-200. *Not. Sci. Biol.* **2011**, *3*, 91–94. [CrossRef]

22. Huang, J.; Wei, L.; Zhou, H.; Yuan, H.; Tian, Y.; Wang, Q. Effects of Shading on the Growth and Physiological and Biochemical Characteristics of *Parashorea cathayensis*. *J. Southwest Norm. Univ. (Nat. Sci. Ed.)* **2021**, *46*, 74–79. (In Chinese)
23. Dai, Y.; Shen, Z.; Liu, Y.; Wang, L.; Hannaway, D.; Lu, H. Effects of Shade Treatments on the Photosynthetic Capacity, Chlorophyll Fluorescence, and Chlorophyll Content of Tetrastigma Hemsleyanum Diels et Gilg. *Environ. Exp. Bot.* **2009**, *65*, 177–182. [CrossRef]
24. Szechyńska-Hebda, M.; Karpiński, S. Light Intensity-Dependent Retrograde Signalling in Higher Plants. *J. Plant Physiol.* **2013**, *170*, 1501–1516. [CrossRef] [PubMed]
25. Sultan, S.E. Phenotypic Plasticity for Plant Development, Function and Life History. *Trends Plant Sci.* **2000**, *5*, 537–542. [CrossRef] [PubMed]
26. Pokhrel, A.; Snider, J.L.; Virk, S.; Sintim, H.Y.; Hand, L.C.; Vellidis, G.; Parkash, V.; Chalise, D.P.; Lee, J.M. Quantifying Physiological Contributions to Nitrogen-Induced Yield Variation in Field-Grown Cotton. *Field Crops Res.* **2023**, *299*, 108976. [CrossRef]
27. Li, D.; Jin, Y.; Cui, M.; Huang, L.; Pei, W. Effects of Shading on Physiological Characteristics and Ultrastructure of Mesophyll Cell of *Emmenopterys henryi* Leaves. *Bull. Bot. Res.* **2020**, *40*, 29–40. (In Chinese)
28. Zhang, L.; Zhang, D. Gender Differences in Growth and Physiological Respond of *Phellodendron amurense* Rupr. in Condition of Overshadow. *Bull. Bot. Res.* **2020**, *40*, 735–742. (In Chinese)
29. Bilen, C.; El Chami, D.; Mereu, V.; Trabucco, A.; Marras, S.; Spano, D. A Systematic Review on the Impacts of Climate Change on Coffee Agrosystems. *Plants* **2022**, *12*, 102. [CrossRef]
30. Xu, F.; Guo, W.; Xu, W.; Wei, Y.; Wang, R. Leaf Morphology Correlates with Water and Light Availability: What Consequences for Simple and Compound Leaves? *Prog. Nat. Sci.* **2009**, *19*, 1789–1798. [CrossRef]
31. Guenni, O.; Romero, E.; Guédez, Y.; Bravo De Guenni, L.; Pittermann, J. Influence of Low Light Intensity on Growth and Biomass Allocation, Leaf Photosynthesis and Canopy Radiation Interception and Use in Two Forage Species of *Centrosema* (DC.) Benth. *Grass Forage Sci.* **2018**, *73*, 967–978. [CrossRef]
32. Kishore, K.; Rupa, T.R.; Samant, D. Influence of Shade Intensity on Growth, Biomass Allocation, Yield and Quality of Pineapple in Mango-Based Intercropping System. *Sci. Hortic.* **2021**, *278*, 109868. [CrossRef]
33. Mailly, D.; Kimmins, J.P. Growth of *Pseudotsuga Menziesii* and *Tsuga Heterophylla* Seedlings along a Light Gradient: Resource Allocation and Morphological Acclimation. *Can. J. Bot.* **1997**, *75*, 1424–1435. [CrossRef]
34. Wang, L.; Yan, Z.; Li, J.; Wang, J.; He, Q.; Su, Y.; Chen, B.; Ma, J.; Dong, J. Effects of Exponential Fertilization on Biomass Allocation and Root Morphology of *Catalpa bungei* Clones. *Acta Ecol. Sin.* **2012**, *32*, 7452–7462. (In Chinese) [CrossRef]
35. Wei, R.; Hu, D.; Chen, J.; Shi, J. Study on the Response of Root Morphology and Nutrient Utilization of *Cunninghamia lanceolata* Clones under Low Phosphorus Stress. *J. Nanjing For. Univ. (Nat. Sci. Ed.)* **2018**, *42*, 1–8. (In Chinese)
36. Liu, S.; Chen, L.; Yang, B.; Jia, H.; Pang, S.; Zhang, P.; Wang, H. Effects of Nitrogen and Phosphorus Fertilizers on Biomass Allocation and Root Morphology of *Betula albosinensis* Clones. *J. Nanjing For. Univ. (Nat. Sci. Ed.)* **2019**, *43*, 23–29. (In Chinese)
37. Cao, P.; Ren, Y.; Zhang, K.; Teng, W.; Zhao, X.; Dong, Z.; Liu, X.; Qin, H.; Li, Z.; Wang, D.; et al. Further Genetic Analysis of a Major Quantitative Trait Locus Controlling Root Length and Related Traits in Common Wheat. *Mol. Breed.* **2014**, *33*, 975–985. [CrossRef]
38. Chen, Q.; Huang, X.; Jiang, D.; Ren, K.; Rong, J.; Chen, L.; Zheng, Y. Effects of Shading on the Growth and Biomass of *Fokienia hodginsii* Seedlings. *J. Fujian Agric. For. Univ. (Nat. Sci. Ed.)* **2020**, *49*, 796–802. (In Chinese)
39. Li, D.; Xiang, Q. The Influence of Light Conditions on the Growth and Photosynthetic Characteristics of *Phoebe chekiangensis* Seedlings. *J. Nanjing For. Univ. (Nat. Sci. Ed.)* **2004**, *5*, 27–31.
40. Zhang, L.; Zhang, J.; Jiao, Z.; Hao, R. Diurnal Changes in Photosynthetic Characteristics of Three Ilex Species under Different Light Conditions. *J. Northwest Bot.* **2006**, *26*, 490–495. (In Chinese)
41. Sun, X.; He, J.; Huang, X.; Ping, J.; Ge, J. The Effect of Different Light Intensities on the Growth and Chlorophyll Fluorescence of *Solidago canadensis*. *J. Northwest Bot.* **2008**, *4*, 4752–4758. (In Chinese)
42. Glasby, T.M. Effects of Shading on Subtidal Epibiotic Assemblages. *J. Exp. Mar. Biol. Ecol.* **1999**, *234*, 275–290. [CrossRef]
43. Steckel, L.E.; Sprague, C.L.; Hager, A.G.; Simmons, F.W.; Bollero, G.A. Effects of Shading on Common Waterhemp (*Amaranthus rudis*) Growth and Development. *Weed Sci.* **2003**, *51*, 898–903. [CrossRef]
44. Wang, Z.; Wang, C. Individual and Interactive Responses of Woody Plants' Biomass and Leaf Traits to Drought and Shade. *Glob. Ecol. Biogeogr.* **2023**, *32*, 35–48. [CrossRef]
45. Chen, M.; Tang, Y. Chlorophyll Fluorescence Characteristics of *Amaranthus* under High Temperature Stress. *Chin. J. Ecol.* **2013**, *32*, 1813–1818. (In Chinese)
46. Yuan, Y.; Wu, C.; Liu, L.; Ma, Q.; Yang, Q.; Feng, B. Unravelling the Distinctive Growth Mechanism of Proso Millet (*Panicum miliaceum* L.) under Salt Stress: From Root-to-leaf Adaptations to Molecular Response. *GCB Bioenergy* **2022**, *14*, 192–214. [CrossRef]