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Effects of Canopy Microclimate on Chinese Chestnut (*Castanea mollissima* Blume) Nut Yield and Quality

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Received: 17 November 2019; Accepted: 10 January 2020; Published: 13 January 2020

Abstract: There are considerable differences in chestnut yield and quality across different chestnut-producing regions in China, indicating that environmental factors affect these properties of chestnuts. Furthermore, nut yield and quality differ depending on canopy position. Therefore, this study investigated the relationship between the canopy microclimate, nut yield, and quality. We determined microclimate factors from blossoming to ripening at different positions in the canopy. Nut yield and quality and the number of different branch types were measured at various canopy positions. The light intensity and temperature of the different canopy layers exhibited funnel-form distributions ranging from 0 to 3600 $\mu mol \cdot m^2 \cdot s^{-1}$ and from 32 to 37 °C, respectively. Canopy humidity showed an inverted funnel-shaped distribution ranging from 26% to 40%. Nut yield and quality in the top and outer canopies were higher than in the bottom and inner canopies. Branches in the top-middle and peripheral parts of the canopy also produced higher yields, especially strong branches that bore more nuts. Nut yield and quality had positive correlations with light intensity ($r = 0.735$) and temperature ($r = 0.709$), whereas they were inversely associated with humidity ($r = -0.584$). The nut yield was more than 200 gm^{-3} when the light intensity was above 1500 $\mu mol \cdot m^2 \cdot s^{-1}$, the temperature was above 34.4 °C, and the humidity was below 27.5%.

Keywords: climatic factors; breeding strategy; chestnut; correlations

1. Introduction

Chinese chestnut (*Castanea mollissima* Blume) is an important woody food crop in China, with its nuts containing sugar, starch, protein, fat, vitamins, and minerals [1]. Its biological properties include drought resistance, the ability to grow in poor soil, heliophile characteristics, and high ecological and economic value [2,3]. Chestnut quality is closely related to the cultivar [4,5], and different environmental factors in each area also affect chestnut quality [6]. Therefore, chestnut quality is determined by the cultivar and the environment, such as light intensity, temperature, and precipitation. The different climates across China mean that chestnut production areas can be divided into six regions, including the Northeast region, the North region, the Northwest region, the middle and lower reaches of the Yangtze River region, the Southeast coastal region, and the Yunnan–Guizhou Plateau region. The North region and the middle and lower reaches of Yangtze River region are the most suitable areas for chestnut cultivation [7]. Chestnut quality is affected by environmental factors, meaning that it varies widely across different regions. For example, the single nut weight from chestnut cultivars of South China is greater than the nut weight produced in the North region, while the quality of North chestnuts is better than the quality of the chestnuts grown in the South of China [8].

In the late 1980s and early 1990s, Chinese chestnuts began to be planted in high density to improve nut-bearing and yield [9]. However, improper canopy management began when chestnut trees did not bear a large amount of fruit, causing the canopy to close and thereby leading to poor light penetration. This resulted in a low yield and a decrease in nut quality [10]. Pruning is a common canopy management practice that improves fruit yield and quality [11,12] by modifying the canopy microclimate [13,14]. Therefore, increasing our understanding of the canopy microclimate is necessary if chestnut pruning practices are to improve.

The canopy microclimate is the climatic condition of a small area formed by external meteorological factors after canopy filtration. These factors include light, temperature, and humidity, which affect almost all physiological processes [15]. For example, light distribution within a canopy plays an important role in the photosynthetic capacity of leaves [16]. In a single tree crown, light availability depends on the position within canopy. Light intensity and penetration in the inner canopy are always lower than in the outer canopy [17,18]. Canopy temperature increases from the bottom to the top [19], even when the spatial distance within the canopy is short [20]. The temperature in the outer canopy is higher than in the inner canopy [21], which is in contrast to the trend of humidity [22]. In addition, the number, proportion, and spatial distribution of the branches and leaves making up the canopy structure also influences the canopy microclimate. For example, light absorption, reflection, and transmission within a canopy are easily affected by leaf interception [23]. Appropriate canopy light, temperature, and humidity levels improve the distribution and composition of the branches and leaves, which increases the ability of the tree to continuously bear fruit.

Fruit yield and quality vary greatly within the canopy due to the different microclimates that are present. Light is essential for crop growth, yield, and quality and adequate light distribution improves fruit yield and quality, whereas fruit growth, quality, and yield are poor in canopy positions where light levels are low [24]. The soluble sugar and starch contents of chestnuts in the outer canopy are significantly higher than in the inner canopy due to the high light levels that enhance photosynthesis [6]. Furthermore, the nut set percentage of peripheral branches of chestnuts with round heads is as high as 95.45%, whereas it is only 4.55% for inner branches [25]. In olive trees, over 60% of the total tree production came from fruit growing in the middle-outer and upper parts of the canopy [26], with the fruit growing in the higher layers being richer in phenol components and saturated fatty acids [27]. Fruit yield and soluble solids contents in d'Anjou pears increased with canopy height, and more anthocyanins were found in fruit growing in higher canopies because the high levels of light intensity enhanced the photosynthetic activity of the fruit, thereby promoting anthocyanin formation [18].

Canopy temperature and humidity also have significant effects on fruit characteristics [28]. More figs with lower acidity exist in the exterior canopy positions compared to the interior due to the high temperatures, which enhance fruit enlargement and decrease the acidity of fig juice [29]. In contrast, d'Anjou pear fruit grown in high-temperature areas of the canopy had high percentages of fruit blush, attributed to increased enzyme activity in the anthocyanin synthesis pathway caused by high temperatures [18]. It was reported that lower temperature and higher humidity positions within apple tree canopies increased Ca transportation from the xylem to the fruit, leading to a reduction in bitter pits and better fruit quality [30]. In contrast, low Ca concentrations in chestnut leaves may reduce yields [31].

Previous studies on chestnut mainly focused on its photosynthetic characteristics [32,33], distribution, and nut yields of different chestnut tree structures [6,34]. These studies only provided details regarding light; they did not include other canopy microclimate factors, such as temperature and humidity. In this study, we chose cultivar Zun Da chestnut trees from the Yanshan region as the material and determined the light intensities, temperatures, and humidities of different canopy positions from the blossoming to ripening stages. Nut quality and yield and the number of different branch types were also measured at these positions. The purposes of this study were (i) to investigate the distribution of microclimate, branches, and nut yield and quality, (ii) to obtain correlations between the microclimate and nut yield and quality, and (iii) to propose suitable canopy microclimate conditions during the blossoming to ripening stages of Chinese chestnut trees.

2. Materials and Methods

2.1. Experimental Site Description and Plant Materials

The experiment was conducted at the Fine Cultivar Breeding Center of Chestnut located at Weijinghe forest farm in Zhunhua, China (39°55′–40°22′ N, 117°34′–118°14′ E, 173 m in altitude). The experimental site is the core area for planting high-quality chestnut in China. The annual rainfall was 760 mm and the average temperature was 0.40 °C, with an average temperature ranging from −7.5 °C in January to 25.4 °C in July. The soils were leached cinnamon soil and meadow drab soil at 50–100 cm depth. The soil parent materials were sandy and slight acidic. The soil characteristics were as follows: pH, 6.5; organic matter content, 1%; available nitrogen, 30 mg kg^{-1}; available phosphorus, 2–4 mg kg^{-1}; available potassium, 30–45 mg kg^{-1}. There were also areas with good drainage. According to our investigation, the single-plant yield of chestnut low-yield orchard was 50 gm^{-3} and the single-plant yield of high-yield orchard was 200 gm^{-3}.

Cultivar Zun Da chestnut trees aged 10 years with round heads were used for the experiments. The trees were pruned into a round-head shape, and were 3 m high, spaced at 2 m × 3 m, and had a crown diameter of 2.0 × 2.0 m. Six chestnut trees with strong growth and no disease and pest problems were chosen for this study. All of the trees were grown under the same site conditions, and had the same growth strength, shape, and canopy structure.

2.2. Canopy Microclimate

Centered on the trunk, the tree canopy was divided into eight directions, namely, south, southwest, west, northwest, north, northeast, east, and southeast. Each crown was divided into horizontal and vertical directions as well. The horizontal direction was then divided into inner (0–60 cm away from the center of the trunk) and outer canopies (60–100 cm away from the center of the trunk) (Figure 1a). The canopy was considered to start at 120 cm from the base of the trunk. A vertical layer was identified at every 60 cm. The vertical extent was divided into three layers, which were the lower layer (0–60 cm), middle layer (60–120 cm), and top layer (120–180 cm) (Figure 1b). There were 48 areas in total.

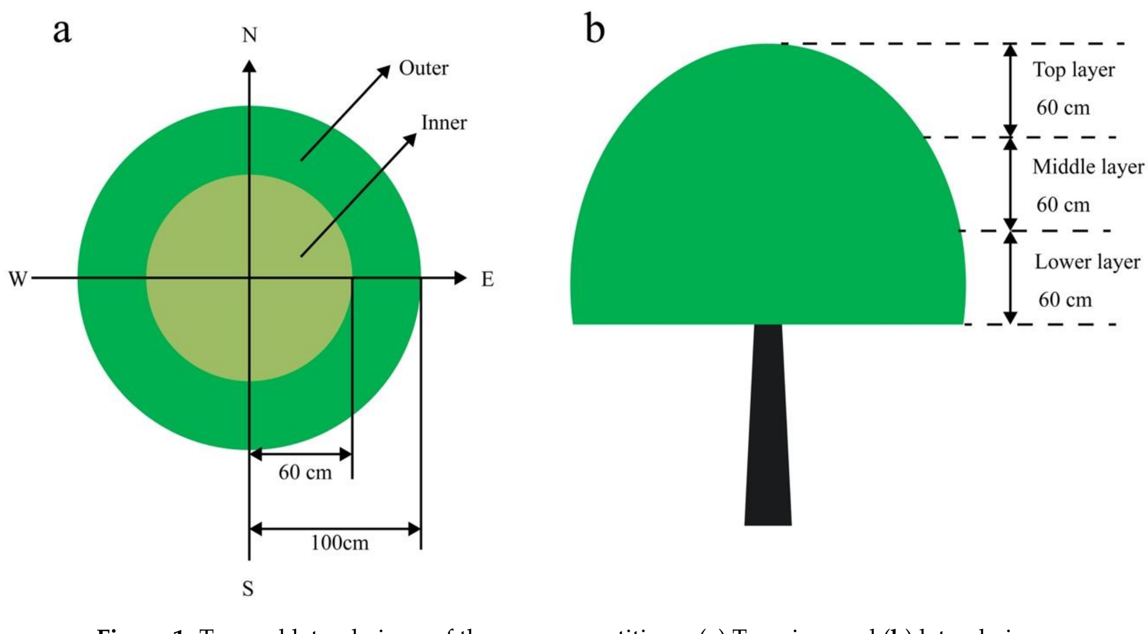

Figure 1. Top and lateral views of the canopy partitions. (**a**) Top view and (**b**) lateral view.

Light intensity, temperature, and humidity levels were measured every 7 days from blossoming to the ripened nut stage of the trees on wind-free, clear days. The canopy microclimate shown in Figure 1 was recorded from 08:00 to 17:00 at hourly intervals throughout the observation days. The measurements were repeated three times at any fixed time and the averages were taken. The averages of six repetitions were used to analyze the differences in microclimates of the different canopy areas during the fruit development period. An LI-250 light meter (Li-COR, lnc.; Lincoln, NE, USA) was used to determine the light intensity, while the temperature and humidity were measured using a portable meteorograph (Kestrel 4000, Nielsen Kellerman, Boothwyn, PA, USA).

2.3. Distribution of Different Branch Types

All of the basal diameters and lengths of the 1-year-old branches were measured in the areas shown in Figure 1 and classified as follows: a diameter and length of >0.5 cm and 20 cm, respectively, indicated a strong branch, a diameter and length of <0.3 cm and 10 cm, respectively, indicated a weak branch, and those with intermediate values were classified as moderate branches [35]. The numbers of each type of branch were then counted. An electronic vernier caliper (TESA-CAL IP67, TESA Tech., Renens, Switzerland) and diameter tape were used to determine the basal diameters and lengths, respectively.

2.4. Flesh Nut Yield and Quality

The nuts were picked at the maturation stage from the areas shown in Figure 1, and the flesh yield, weight, and nutritional quality of the nuts were determined. Multiple different parameters were used to evaluate the quality of the nuts, including starch, fat, total sugar, and protein. These parameters were determined using enzymatic hydrolysis, soxhlet extractions, direct titration, and the Kjeldahl method, respectively, in accordance with Chinese National Standards GB/T5009.9-2003, GB/T5009.6-2003, GB/T5009.7-2003, and GB/T5009.5-2003. Four repetitions for each of the nut quality parameters were recorded and the averages were taken.

2.5. Statistical Analysis

Differences in the microclimate, nut yield, and quality between the different areas were analyzed using one-way ANOVA (SPSS 18.0, SPSS Inc., Chicago, IL, USA). Multiple comparisons of the means were conducted using an LSD test at $\alpha = 0.01$. Design expert (version 8.0) software (Stat-Ease Inc., Minneapolis, MN, USA) was used to draw the distributions for the nut yield, the canopy microclimate, and the different types of branches in the top, middle, and lower layers. Pearson's (parametric) test was used for all of the correlations, with additional analysis using SPSS.

3. Results

3.1. Nut Yield and Quality at Different Positions within the Canopy

There were significant differences in the nut yield and quality between the different canopy positions (Figure 2, Supplementary Table S1) ($p < 0.01$). Nut yield and quality improved as the canopy height increased and from the inner to outer canopy. The change in nut yield was the greatest, ranging from 131.65 (TO) to 15.79 gm^{-3} (LI) (Figure 2a). Nut weight, starch content, total sugar, fat, and protein levels in the outer canopy of the top layer were 1.05, 1.54, 1.12, 1.05, and 1.17 times larger than those in the inner canopy of the lower layer, respectively (Figure 2b–f). A very significant difference in nut weight was observed between the outer canopy of the top layer and the inner canopy of the lower layer ($p < 0.01$). In addition, very significant differences in starch content, total sugar, and protein levels were observed in top and lower layers of both the inner and outer canopies ($p < 0.01$), respectively.

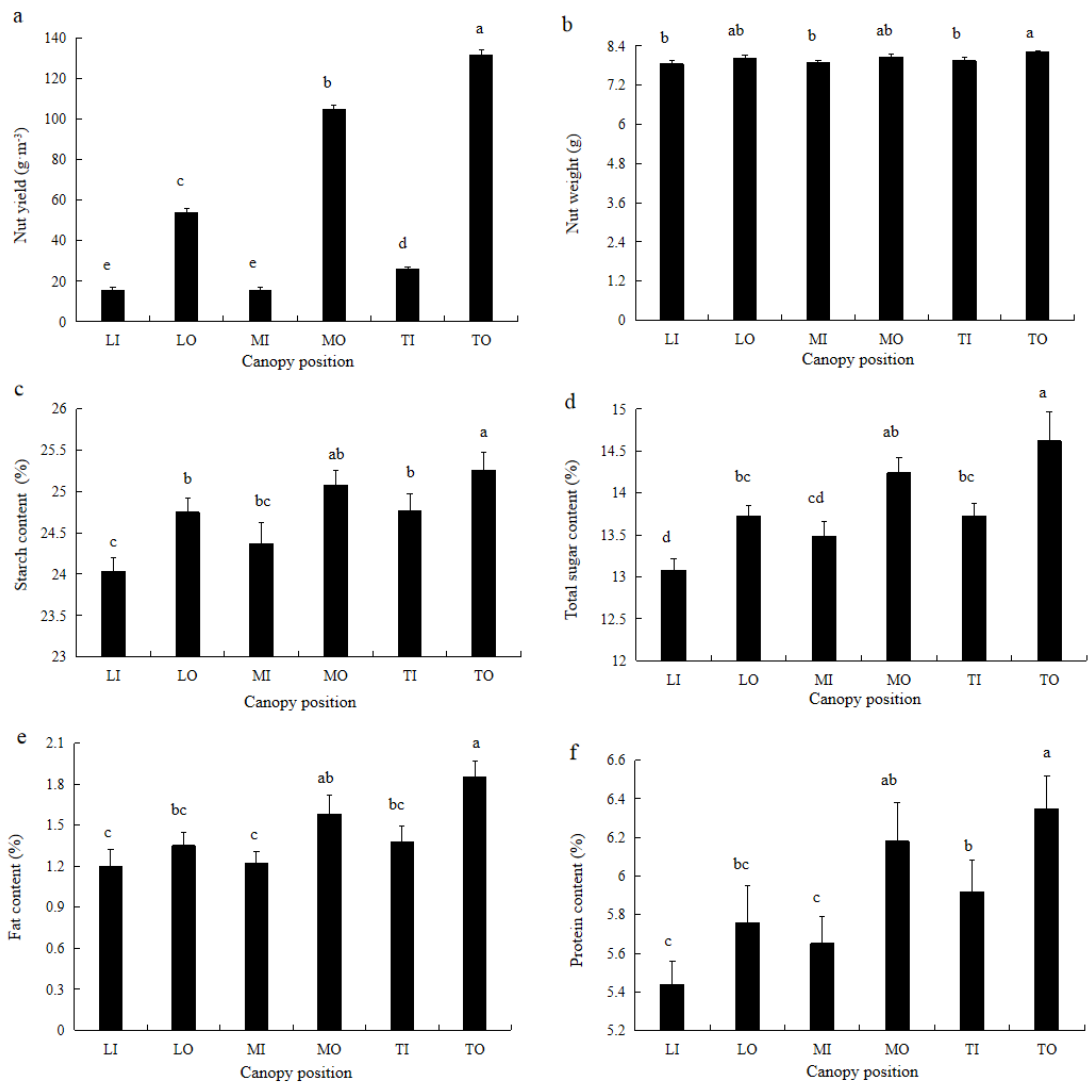

Figure 2. Nut yield and quality at different positions within the canopy. LI: inner canopy of the lower layer; LO: outer canopy of the lower layer; MI: inner canopy of the middle layer; MO: outer canopy of the middle layer; TI: inner canopy of the top layer; TO: outer canopy of the top layer. (**a**) Nut yield; (**b**) nut weight; (**c**) starch content; (**d**) total sugar content; (**e**) fat content; (**f**) protein content. Significant differences are highlighted as a–e. Bars with different letters differ statistically according to LSD's test, where $\alpha = 0.01$.

There were significant and positive correlations between the nut yield and quality (Table 1). Nut yield was the most highly correlated with total sugar content (0.726) followed by fat content (0.628), but it was less well-correlated with protein content (0.577). The correlations between nut weight and total sugar content and starch content were as high as 0.871 and 0.884, respectively. In addition, the correlations between the starch content, fat content, total sugar, and protein content were all very significant at more than 0.790 ($p < 0.01$).

The nut yield gradually declined from the top to the bottom and from the outer to the inner canopies (Figure 3). Furthermore, a funnel-shaped nut yield distribution for the different layers showed that the nuts were mainly distributed in the outer canopy of the top layer and that there were nearly no nuts in the inner canopy of the lower layer. Nut yields from the upper and middle layers varied greatly between the different directions (Figure 3a,b), whereas direction had little effect on nut yield in the lower layer (Figure 3c). In a given layer, nut yield in the South sector was far higher than in the North sector.

Table 1. Correlation analysis of nut yield and quality.

Nut Characteristic	Nut Yield	Nut Weight	Starch Content	Total Sugar Content	Fat Content	Protein Content
Nut yield	1					
Nut weight	0.615 **	1				
Starch content	0.598 **	0.884 **	1			
Total sugar content	0.726 **	0.871 **	0.893 **	1		
Fat content	0.628 **	0.759 **	0.793 **	0.790 **	1	
Protein content	0.577 **	0.764 **	0.823 **	0.849 **	0.830 **	1

"**" significant correlations at the $p \leq 0.01$ level.

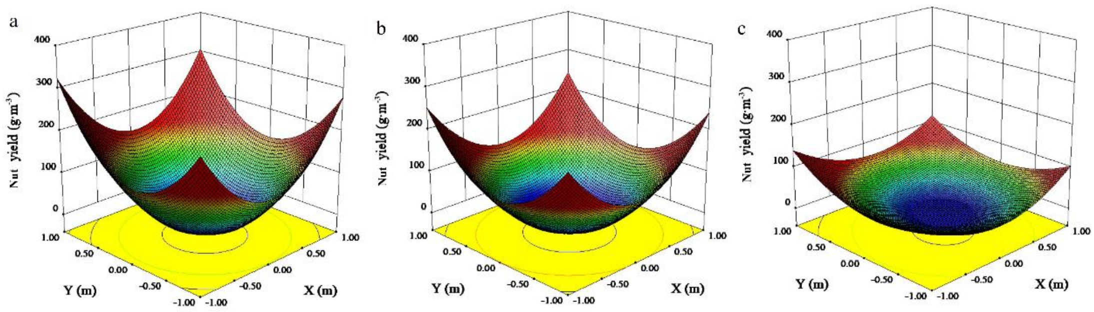

Figure 3. Distribution of nut yields in the different layers. The *x*-axis shows the distance in the east (+) and west (−) directions from the trunk. The *y*-axis shows the distance in the south (+) and north (−) directions from the trunk. The *z*-axis represents the nut yield. (**a**) Top layer; (**b**) middle layer; (**c**) lower layer.

3.2. Microclimate Distribution within the Canopy

There were significant differences in the microclimate between the different positions of the canopy (Table 2 and Supplementary Tables S2–S4). The light intensity and temperature levels in the outer canopy of the top layer were the highest of all of the positions, with the highest values appearing in August (1475.22 μmol·m^2·s^{-1} and 33.56 °C), while the lowest values for light intensity and temperature were recorded in the inner canopy of the lower layer, with the minimum values appearing in October (635.27 μmol·m^2·s^{-1}) and May (24.01 °C), respectively. In addition, the highest humidity level was recorded in the inner canopy of the lower layer and the lowest value was in the outer canopy of the top layer. The highest humidity was in July at 48.23% in the inner canopy of the lower layer and 44.71% for the outer canopy of the top layer. The lowest humidity was observed in May, ranging from 24.94% at the outside of the top layer to 28.61% inside the lower layer.

Table 2. Monthly variations in the canopy microclimate of the different positions.

Month	Position	Light Intensity (μmol·m^2·s^{-1})	Temperature (°C)	Humidity (%)
5	LI	692.12 ± 5.43 f	24.01 ± 0.01 e	28.61 ± 0.02 a
	LO	1390.92 ± 13.21 c	24.82 ± 0.14 c	25.92 ± 0.02 d
	MI	732.09 ± 7.23 e	24.31 ± 0.04 d	28.51 ± 0.04 b
	MO	1432.23 ± 7.71 b	25.71 ± 0.04 b	25.80 ± 0.03 e
	TI	764.22 ± 9.18 d	24.63 ± 0.15 c	27.17 ± 0.02 c
	TO	1468.89 ± 10.56 a	25.90 ± 0.10 a	24.94 ± 0.04 f
6	LI	680.09 ± 5.66 e	25.13 ± 0.07 e	43.81 ± 0.09 a
	LO	1359.11 ± 16.31 c	26.16 ± 0.14 b	40.20 ± 0.05 d
	MI	736.21 ± 9.32 d	25.41 ± 0.11 d	41.92 ± 0.07 b
	MO	1409.21 ± 18.42 b	26.92 ± 0.10 a	38.93 ± 0.02 e
	TI	743.23 ± 12.85 d	25.90 ± 0.10 c	41.17 ± 0.05 c
	TO	1450.21 ± 14.32 a	27.01 ± 0.16 a	38.15 ± 0.03 f

Table 2. *Cont.*

Month	Position	Light Intensity (μmol·m^2·s^{-1})	Temperature (°C)	Humidity (%)
7	LI	667.24 ± 6.90 f	26.71 ± 0.10 f	48.23 ± 0.11 a
	LO	1330.89 ± 15.11 c	29.62 ± 0.11 c	46.03 ± 0.07 d
	MI	710.09 ± 9.91 e	27.34 ± 0.13 e	47.92 ± 0.09 b
	MO	1389.23 ± 10.39 b	30.93 ± 0.08 b	45.15 ± 0.07 e
	TI	740.22 ± 11.56 d	28.10 ± 0.10 d	47.27 ± 0.10 c
	TO	1439.30 ± 23.11 a	31.57 ± 0.12 a	44.71 ± 0.12 f
8	LI	674.78 ± 10.45 e	28.71 ± 0.09 f	44.51 ± 0.07 a
	LO	1343.79 ± 23.57 b	32.32 ± 0.16 c	41.30 ± 0.10 d
	MI	722.66 ± 13.21 d	29.00 ± 0.14 e	43.46 ± 0.08 b
	MO	1413.13 ± 20.34 a	33.10 ± 0.09 b	41.22 ± 0.02 d
	TI	757.10 ± 17.21 c	30.10 ± 0.08 d	42.29 ± 0.10 c
	TO	1475.22 ± 14.55 a	33.56 ± 0.16 a	40.10 ± 0.09 e
9	LI	656.56 ± 9.12 f	27.11 ± 0.14 e	37.71 ± 0.05 a
	LO	1325.96 ± 21.32 c	29.42 ± 0.11 c	35.80 ± 0.07 d
	MI	717.45 ± 10.31 e	27.60 ± 0.17 d	36.53 ± 0.04 b
	MO	1395.36 ± 20.81 b	30.09 ± 0.09 b	35.22 ± 0.10 e
	TI	750.89 ± 14.81 d	27.81 ± 0.12 d	36.01 ± 0.07 c
	TO	1452.11 ± 20.11 a	30.52 ± 0.11 a	34.93 ± 0.08 f
10	LI	635.27 ± 8.31 f	26.13 ± 0.12 f	33.60 ± 0.07 a
	LO	1310.35 ± 20.11 c	28.14 ± 0.15 c	30.11 ± 0.08 d
	MI	703.02 ± 9.99 e	26.80 ± 0.14 e	32.53 ± 0.09 b
	MO	1372.11 ± 13.01 b	28.91 ± 0.19 b	29.55 ± 0.11 e
	TI	732.96 ± 11.87 d	27.15 ± 0.10 d	31.20 ± 0.08 c
	TO	1410.33 ± 18.34 a	29.26 ± 0.17 a	28.17 ± 0.12 f

Data are presented as means ± standard deviations. Different small letters in a column indicate significant differences according to the LSD test at $p \leq 0.01$ in microclimates between the different positions within the canopy in each month. LI: inner canopy of the lower layer; LO: outer canopy of the lower layer; MI: inner canopy of the middle layer; MO: outer canopy of the middle layer; TI: inner canopy of the top layer; TO: outer canopy of the top layer.

The light intensity and temperature properties in the different canopy layers showed funnel-form distributions and increased from the inner to the outer canopies (Figure 4a–f). However, humidity exhibited an inverted funnel-shaped distribution and decreased from the inner to the outer canopies (Figure 4g–i), with a variation range of 26%–40%. The canopy microclimate changes according to the different directions in the outer canopy were greater than those observed in the inner canopy. In addition, the humidity distribution in the lower layer varied more than in the top and middle layers, but the light intensities and temperatures in the lower, middle, and top layers showed very similar variations.

3.3. Canopy Microclimate Effects on Nut Yield

Table 3 shows the different nut yields for a range of microclimates. The yield and microclimate distributions were continuous, therefore allowing the microclimate that led to a certain yield range to be defined. When the nut yield ranged from 150 to 200 gm^{-3} and from 100 to 150 gm^{-3}, the light intensity, temperature, and humidity levels ranged from 1125.0 to 1500.0 μmol·m^2·s^{-1} and 750.0 to 1125 μmol·m^2·s^{-1}, 33.8 to 34.4 °C and 33.2 to 33.8 °C, and from 27.5% to 30% and 30% to 32.5%, respectively. However, when the light intensity was lower than 375 μmol·m^2·s^{-1}, the temperature below 32.6 °C, and the humidity above 35%, the nut yield tended to be lower than 50 gm^{-3}.

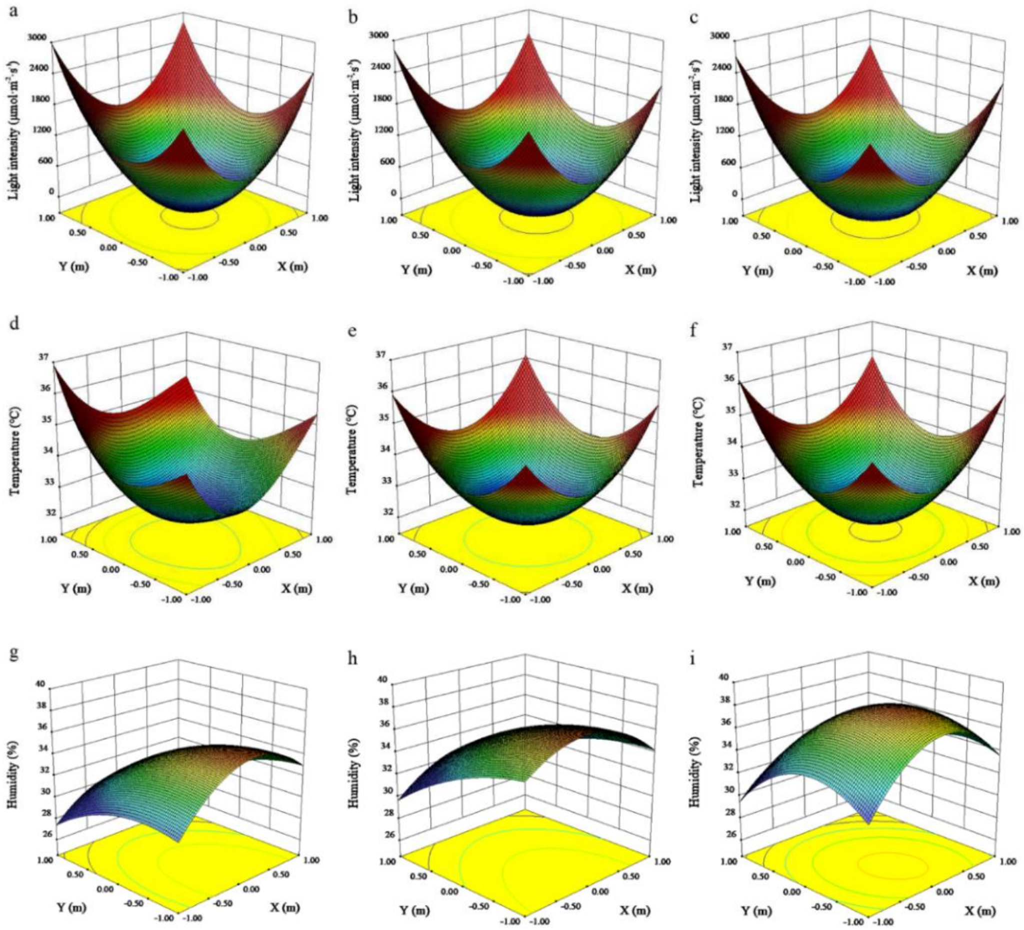

Figure 4. Distributions of canopy microclimates in the different layers over the whole fruit development period. The *x*-axis shows the distance in the east (+) and west (−) directions from the trunk. The *y*-axis shows the distance in the south (+) and north (−) directions from the trunk. The *z*-axis represents each microclimate factor. (**a**) Light intensity in the top layer; (**b**) light intensity in the middle layer; (**c**) light intensity in the lower layer; (**d**) temperature in the top layer; (**e**) temperature in the middle layer; (**f**) temperature in the lower layer; (**g**) humidity in the top layer; (**h**) humidity in the middle layer.; (**i**) humidity in the lower layer.

Table 3. Relationship between microclimatic factors and nut yield.

Nut Yield ($g \cdot m^{-3}$)	Microclimate Factor		
	Light Intensity ($\mu mol \cdot m^2 \cdot s^{-1}$)	Temperature (°C)	Humidity (%)
200	1500.0	34.4	27.5
150	1125.0	33.8	30.0
100	750.0	33.2	32.5
50	375.0	32.6	35.0

3.4. Distribution of Different Branch Types within the Canopy

Branch distributions within the different layers were similar to the light intensity and temperature trends (Figure 5). In the vertical direction, the total number of branches was distributed differently within the layers, with the top layer having the most (138) (Figure 5a), followed by the middle layer (100) (Figure 5b), and the lower layer having the least (80) (Figure 5c). The branches were mostly distributed in the outer canopy, with far more branches present in the outer canopy than in the inner canopy. In addition, the largest number of branches appeared in the southeast area, where there were 34, 25, and 21 branches in the top, middle, and lower layers, respectively.

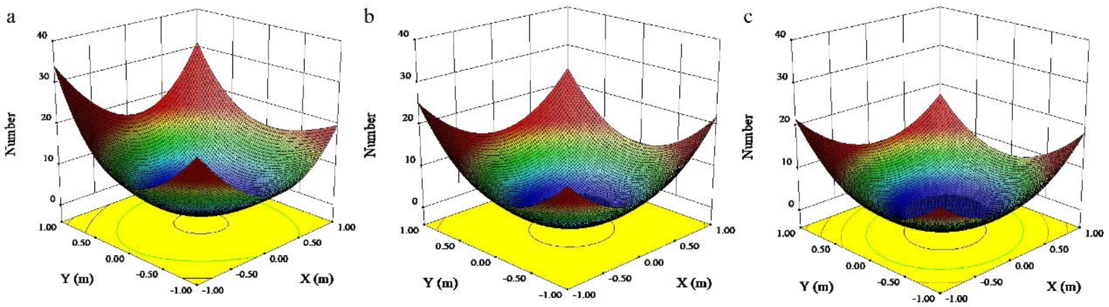

Figure 5. Number of branches in the different layers. The x-axis is the distance in the east (+) and west (−) directions from the trunk. The y-axis shows the distance in the south (+) and north (−) directions from the trunk. The z-axis represents the number of branches. (**a**) Top layer; (**b**) middle layer; (**c**) lower layer.

The numbers of each branch type in each layer all showed funnel distributions, except for the weak branches in the top layer (Figure 6). The weak branches were mainly distributed in the inner canopy of the top layer. The numbers of strong and moderate branches increased with canopy height and together accounted for 81.25% and 76.92% of the branches in the upper and middle layers, respectively. Furthermore, there were clearly variation differences between the directions in these layers (Figure 6a–e), but there were no obvious differences in the lower layer (Figure 6c,f). The southeast area had the highest number of strong branches, which were located in the top-middle layers (Figure 6a,b), but there were more moderate-strength branches than strong branches in the east and northwest sectors of the top layer compared (Figure 6d).

3.5. Relationships between the Canopy Microclimate and Nut Yield and Quality

There were large positive correlations between nut yield, quality, and light intensity and temperature within the canopy (Table 4). Light intensity was correlated with nut yield (0.796), nut weight (0.789), protein content (0.785), starch content (0.742), total sugar content (0.657), and fat content (0.639). The correlations between the temperature and the nut yield and quality were very similar to those observed for light intensity. However, humidity was negatively correlated with nut yield and quality, and had the highest and lowest correlations with nut weight (−0.756) and fat content (−0.473).

Table 4. Correlations between the canopy microclimate and nut yield and quality.

Quality Factor	Correlation Coefficients		
	Light Intensity	**Temperature**	**Humidity**
Nut yield ($g{\cdot}m^{-3}$)	0.796 **	0.836 **	−0.593 **
Nut weight (g)	0.789 **	0.804 **	−0.756 **
Starch content (%)	0.742 **	0.674 **	−0.519 **
Fat content (%)	0.639 **	0.583 **	−0.473 *
Total sugar content (%)	0.657 **	0.671 **	−0.596 **
Protein content (%)	0.785 **	0.684 **	−0.564 **

"**" significant correlations at the $p \leq 0.01$ level.

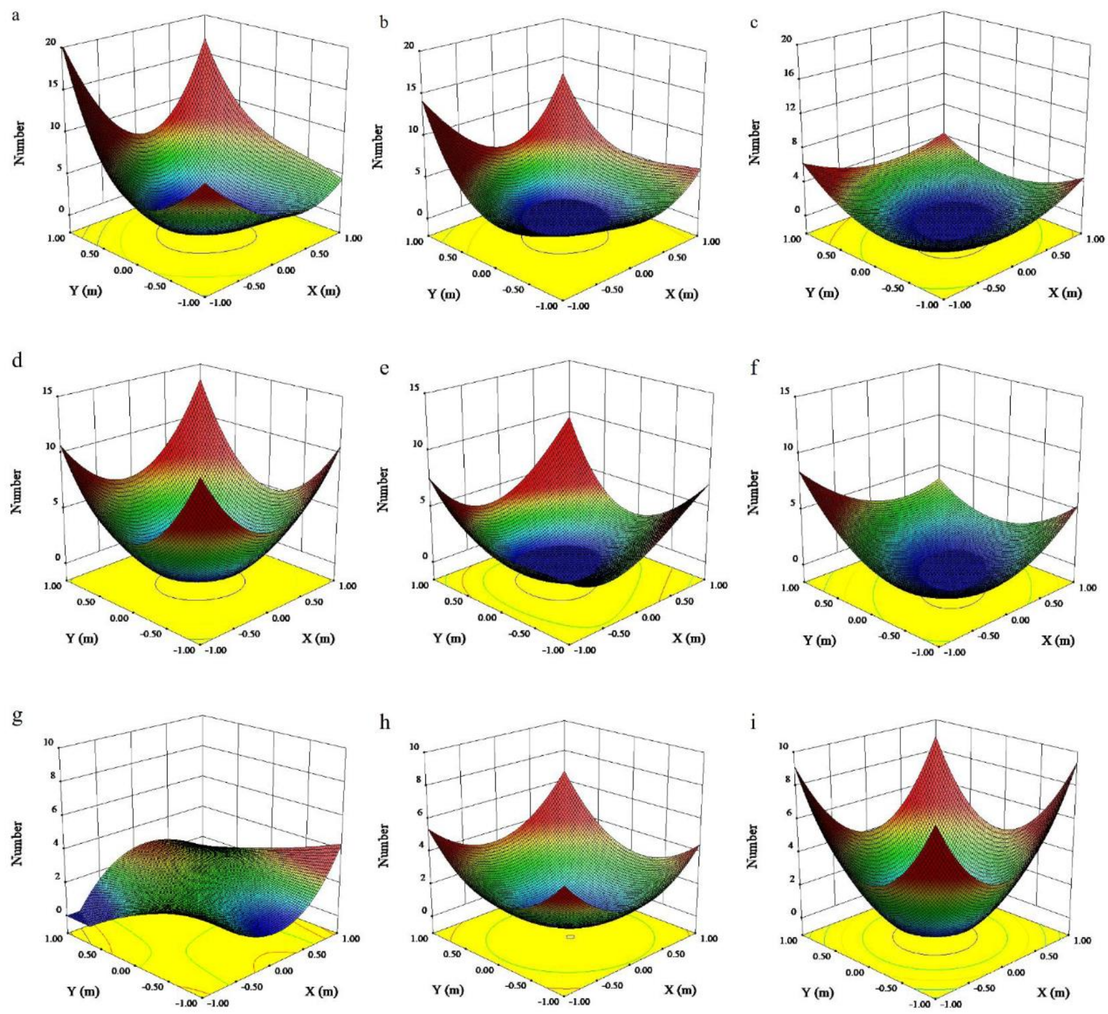

Figure 6. Distribution of the different branch types in the three layers. The *x*-axis is the distance in the east (+) and west (−) directions from the trunk. The *y*-axis shows the distance in the south (+) and north (−) directions from the trunk. The *z*-axis represents the number of branches. (**a**) Strong branches in the top layer; (**b**) strong branches in the middle layer; (**c**) strong branches in the lower layer; (**d**) moderate branches in the top layer; (**e**) moderate branches in the middle layer; (**f**) moderate branches in the lower layer; (**g**) weak branches in the top layer; (**h**) weak branches in the middle layer; (**i**) weak branches in the lower layer.

4. Discussion

4.1. Yield and Quality of Nuts from Different Positions within the Canopy

Nut yield and quality increased with canopy height, an observation which agreed with He et al. [17], who concluded that peaches were mostly distributed in the upper canopy, which was where relatively well-developed apples were also found [36]. It was also reported that peaches and pears in upper canopies weighed more compared to those found in the lower canopy [37,38]. In the horizontal direction, chestnut yield in the outer canopy was higher than in the inner canopy and produced better quality nuts, probably due to improved illumination. These results were similar to those reported by Lewallen and Marini [39], who investigated peaches.

High correlations were observed between nut yield and quality, and there were also close relationships among various nut quality parameters. Generally, sugar and starch can be converted to one another. The highest correlation was recorded between the starch content and the total sugar content, which also highlighted that there was a close relationship between starch and sugar. In our study, starch had a high correlation with other quality parameters and the starch content often determines the taste of chestnuts because it adjusts the glutinosity of the nut, suggesting that the starch content could become an important parameter for measuring chestnut quality. In addition, there was a strong positive correlation between the nut weight and the nut quality parameters. Alcobendas et al. [40] also found significant correlations among peach fruit quality parameters, although the correlation coefficients were small. Lin [31] reported that there was also a correlation between Ca concentration and chestnut yield (0.613). Therefore, more research on mineral nutrients, such as nitrogen, phosphorus, potassium, and calcium, which are also deemed to be quality parameters for chestnut, is needed.

4.2. Microclimate Distribution within the Canopy

It appears that canopy microclimate varies in both time and space. Spatial variation refers to the microclimate changes caused by canopy orientation (east, west, north, and south), horizontal direction (outer and inner canopies), and vertical direction (upper, middle, and lower layers). In this study, the chestnut leaves and branches redistributed the visible light from solar radiation, causing significant differences in the light intensity distribution among the different canopy locations. Furthermore, light intensity distribution was heterogeneous and declined from top to bottom and from the periphery to the inner canopy. The distributions of light intensity, temperature, and humidity could have reflected the microclimate variations in different chestnut canopy locations. Similar results were obtained regarding the spatial light distributions of other types of trees [41–43].

4.3. Distribution of Different Branch Types within the Canopy

The strong branches on the trees that could bear more nuts were mostly in the top and middle layers of the canopy, a result which was consistent with a study by Wang and Cheng [44], who concluded that the main bearing branches of chestnut were always found in the outer canopies. Greater numbers of stronger branches form when light is abundant, however, upper branches block the sunlight, thereby preventing the light intensity from reaching the inner and lower layers and leading to more weak branches. In addition, the number of branches and leaves also influences leaf photosynthesis. Large numbers of branches and leaves lead to poor ventilation and low light transmittance within the canopy, causing lower temperatures, higher humidities, and a reduction in photosynthesis. Fewer branches and leaves combined with high light intensities might lead to high temperatures within the canopy, which would also inhibit photosynthesis. Therefore, a reasonable distribution of branches and leaves is key to nut production. The management of leaf and branch numbers is usually achieved by pruning. In this study, we only investigated the distribution of different branch types in chestnut trees, however, the microclimate was mainly filtered by the leaves; therefore, leaf area index should also be considered. Further studies on the nut-bearing branches and cultivation of reasonable shapes for Chinese chestnut trees will be summarized in our next study.

4.4. Relationships between the Canopy Microclimate and Nut Yield and Quality

The results showed that canopy microclimate had a considerable impact on chestnut yield and quality. The nut yield and quality parameters exhibited significantly greater correlations with light intensity than with temperature and humidity. This indicated that light intensity had the greatest impact on nut yield and quality, which agreed with previous studies showing that light plays a crucial role in the growth and development of fruit trees and crops [45]. The top and middle layers of the canopy had higher light intensities and produced larger nut yields of higher quality than the lower layer. This was probably because the moderate–high light levels caused an increase in photosynthesis by enhancing photosynthetic efficiency [46], therefore leading to the formation of more flower buds. Increased light levels may also raise the percentage of set nuts [47]. In contrast, insufficient light may lead to physiological nut drop [48]. Xiong et al. [6] concluded that no nuts formed on the branches when the relative light intensity of the inner canopy was less than 25%.

Besides nut yield, improved light distribution within the canopy also increased chestnut quality, especially the nut weight, which had the highest correlation coefficient with light intensity (0.789). The outer leaves were exposed to more sunlight, which meant that they always had a high photosynthetic productive efficiency. Furthermore, photoassimilates supplied by peripheral leaves are first transported to nearby sinks, such as buds and nuts, which could also lead to improved nut quality in the outer canopy. The results also showed that the quality of the chestnuts produced in the south direction was superior to that of those from the north direction because more light came from the south than from the north. With apple trees, it is generally accepted that an invalid light area occurs when the relative light intensity is less than 30%, causing poor fruit quality and low yield in the area [49]. Our data confirmed that light intensity was clearly related to fruit quality characteristics [50,51]. The linear relationships between fruit production, quality, and light exposure were also established for apple trees [47]. In addition, correlations between canopy temperature and humidity indicated that a large amount of canopy light, high temperature, and low humidity improved nut yield and quality. The results also implied that temperature and humidity affected the chestnuts yield and quality. However, it was not clear how temperature and humidity influenced nut yield and quality, and this area requires further study.

5. Conclusions

The distribution of Chinese chestnut nut yield and quality within the canopy was influenced by microclimatic factors, particularly light intensity; therefore, an optimal canopy microclimate should be encouraged to improve chestnut production. This could be achieved by better pruning in order to control the crown size and improve ventilation and light distribution, thereby maximizing microclimate benefits. Furthermore, a large amount of canopy light, high temperature, and low humidity improved nut yield and quality. A nut yield of over 200 gm^{-3} could be achieved when the canopy microclimate characteristics include a light intensity above 1500 $\mu mol \cdot m^2 \cdot s^{-1}$, a temperature above 34.4 °C, and humidity levels below 27.5%.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/11/1/97/s1, Table S1: Effects of canopy position on nut yield and quality indicated by degree of freedom (DF), F and *p* values derived from ANOVA analyses, Table S2: Effects of canopy position on light intensity during each month indicated by degree of freedom (DF), F and *p* values derived from ANOVA analyses, Table S3: Effects of canopy position on temperature during each month indicated by degree of freedom (DF), F and *P* values derived from ANOVA analyses, Table S4: Effects of canopy position on humidity during each month indicated by degree of freedom (DF), F and *p* values derived from ANOVA analyses.

Author Contributions: S.S. conceived the structure and idea of the paper. H.Z. was involved in collecting data. Y.W. took charge of data processing, data analysis, and writing the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Key Research & Development Program of China (2018YFD1000605).

Conflicts of Interest: The authors declare that they have no conflict of interest.

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