Research Article

Optimal Utilization of Light Energy in Semiclosed Greenhouse Using Three-Dimensional Cucumber Model

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Received 24 April 2020; Revised 16 June 2020; Accepted 9 July 2020; Published 1 August 2020

Academic Editor: Chenxi Huang

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In the east of China, low temperature and light energy in winter are the main factors for the decline in cucumber yield, as well as in greenhouses without supplementary light. Optimal utilization of light energy is critical to increase cucumber yield. In this study, experimental measurements were conducted in two scenarios, April to May (Apr-May) and November to December (Nov-Dec) 2015, respectively, to analyze leaf development, dry matter accumulation, and yield of cultivated cucumber. Statistical analysis showed that leaves grew in Nov-Dec had larger leaf area and lower dry matter than leaves grew in Apr-May. This revealed that the dry matter accumulation rate per unit area was lower in winter. To be precise, the yield 0.174 kg/m² per day in Nov-Dec was 35.3% lower than the yield in Apr-May. Environmental monitoring data showed that there was no significant difference in the average temperature between two scenarios, but the light intensity in Nov-Dec was only 2/3 of that in Apr-May. Three-dimensional (3D) cucumber canopy models were used in this study to quantify the effects of weak light on dry matter production in Nov-Dec. Three 3D canopies of cucumber were reconstructed with 20, 25, and 30 leaves per plant, respectively, by using a parametric modeling method. Light interception of three canopies from 8:00 to 15:00 on 4 November 2015 was simulated by using the radiosity-graphic combined model (RGM) with an hourly time step. CO₂ assimilation per unit area was calculated using the FvCB photosynthetic model. As a result, the effects of light intensity and CO₂ concentration on the photosynthetic rate were considered. The leaf photosynthesis simulation result showed that during the daytime in winter, the RuBP regeneration-limited assimilation A_j was always less than the Rubisco-limited assimilation A_c . This means that the limiting factor affecting the photosynthesis rate in winter was rather light intensity. As the CO₂ concentration in the greenhouse was utmost in the morning, increasing the light intensity and therefrom increasing the canopy light interception at this time will be highly beneficial to increase the yield production. Through a comparative analysis of photosynthetic characteristics in these three virtual 3D canopies, the 25-leaf canopy was the best-performed canopy structure in photosynthetic production in winter. This study provides an insight into the light deficiency for yield production in winter and a solution to make optimal use of light in the greenhouse.

1. Introduction

Cucumber is one of the most popular crops grown in facility agriculture. It requires relatively high light intensity and temperature. Low temperature and deficient light energy in winter in the east and north of China are the main factors for the decline of cucumber yield. With the promotion and application of semiclosed greenhouses in China, the excess

solar energy in summer was collected and stored, and this energy should be reused to heat the greenhouse in winter [1]. As a result, the impact of low temperature in winter on yield has been greatly improved [2]. Nevertheless, in greenhouses without supplementary light, low light intensity remains an important cause affecting winter production [1]. For most greenhouse vegetables, 1% light increment results in 0.7–1% increase in harvestable product [3]. Therefore, optimal

utilization of light energy should be critical for increasing the yield of cucumber in winter.

Optimization and control of the light environment in greenhouse have been widely studied. In order to increase the incident light intensity, supplementary light sources are often added on top of the canopy during the growing period as early as the 1980s [4]. For most greenhouse fruiting vegetables, such as cucumber and tomato, vegetative growth is concentrated on the top and middle of the canopy while reproductive growth occurs at the middle and bottom. In recent years, lighting strategies including light source type and distribution, spectral composition, and lighting duration have been widely studied. Hovi et al. [5] have shown that interlighting by using HPS (high-pressure sodium) can increase by 10% of cucumber fruit yield. However, these kinds of light sources are very difficult to be used as interlighting in narrow row arrangements, as they produce high heat. Hao et al. [6] studied the effect of HPS and LED (light-emitting diodes) light source and light position (on the top or inside of the canopy) on mini-cucumber growth rate and fruit yield. The result shows that the plants grown with LED interlighting achieved higher energy use efficiency than that with the top HPS. And, once canopy closure achieves, increasing total canopy light interception, especially increasing middle and lower light interception, is more conducive to yield [7].

In cucumber canopy, light interception is directly affected by canopy structure, which depends on plant growth and cultivation management. Accurate measurement of total light interception in the canopy has always been a great challenge. In previous studies, Beer–Lambert’s law was widely used to calculate canopy light interception, but this law assumes that the canopy is a uniform medium, and ignored the influence of leaf distribution and inclination angle on light transmission [8]. For horticultural crops planted in rows, the canopy structure exhibits distinct heterogeneity. Since light distributes significantly different between and within crop rows, the orientation of the leaf directly determines its light interception [9]. The 3D structural model, which delivers a structure close to the real canopy, can accurately describe the distribution and location of organs in 3D space. Combining with ray casting, radiosity, and Monte Carlo ray-tracing approaches, local light conditions and light interception can be simulated at the leaf level and upscale to the canopy level [10]. Thus, the accuracy of the light interception estimation can be greatly improved.

Recent studies have shown that the 3D structural model is extremely useful for light interception-related calculation, for example, evaluating the effect of leaf area distribution and leaf angles on canopy light interception for “ideotype” selection [11, 12] and optimizing canopy structure pruning management [13]. In many FSPM (functional and structural plant models) research studies, 3D structural models were always combined with photosynthetic models and dry matter distribution models at the aim to design crops with higher yield potential and to enhance resource use efficiency [14–16].

In the present study, we combined 3D cucumber canopy model, ray-tracing method, and photosynthesis model

together to analyze light conditions inside the canopy. By virtual experiments, we discussed a solution in greenhouse management to increase the photosynthetic production of cucumber crops in winter.

2. Materials and Methods

2.1. Field Experiments and Measurement on Plants. Field experiments were conducted in May and November 2015, respectively, in a semiclosed Venlo-type greenhouse at Shanghai Chongming Island (lat. $31^{\circ}34'N$, long. $121^{\circ}41'E$). The detailed information of the experimental greenhouse can be referenced in Ding et al. [2]. Mini-cucumbers (*Cucumis Sativus* L. cv. Deltastar) were planted on rockwool slabs along two parallel lines and each plant is located with a growing wire at a stem density of 2.8 stems/m^2 . Air temperature, relative humidity, and CO_2 concentration in the greenhouse were recorded automatically at 5 min intervals using one climate sensor (Priva, De Lier, the Netherlands) per greenhouse, placed at the top of the canopy.

2.1.1. Measurement 1: Organ Developing Measurement. Two measurements were conducted in 2015 from 15th April to 14th May and from 4th November to 3 December, and for convenience, Apr-May and Nov-Dec will be used to refer the two experimental scenarios, respectively, hereinafter. Every day in the experiment, five newly appeared phytomers, including an internode with the directly attached leaves and petioles, were selected to be marked as the initial point of organ expansion. In total, 150 phytomers corresponding to 450 organs were marked in the thirty consecutive days. Morphological measurements were performed on all marked phytomers, respectively, on May 16, 2015, and December 3, 2015. The measurement contents include leaf length (LL), leaf width (LW), petiole length (PL), petiole diameter (PD), internode length (IL), and internode diameter (ID). Leaf length was measured from the lamina tip to the intersection end of petiole along the lamina midrib. Leaf width was measured from tip to tip between the widest lamina lobes, as referenced in Cho et al. [17]. The diameter of the petiole and internode was measured in the middle of the organ. The manual measurement error is $\pm 1 \text{ mm}$. After the measurement, the leaves and petioles were destructively dried and weighed.

2.1.2. Measurement 2: Canopy Structure Measurement. Canopy structure measurements were conducted on 4 November 2015. A total of 8 cucumber plants from 2 (rows) $\times$ 4 (plants) adjacent plants were selected, and all organs of the whole plant were measured manually. The measurement contents include leaf length, leaf width, petiole length, petiole diameter, internode length, and internode diameter. After the measurement, organs were segmented, dried, and weighed one by one.

2.2. 3D Reconstruction of the Canopy

2.2.1. Organ Expansion Modeling. Based on measurement 1, the least-squares method was used to fit statistical models for

organ development. We used logistics function for leaf length, leaf width, petiole diameter, and internode diameter and Boltzmann function for petiole length, internode length, leaf dry weight (LDW), and petiole dry weight (PDW). The parameters of descriptive models for organ development are listed in Tables 1 and 2. The sum of the thermal time (GDD) is calculated independently: $GDD = \sum (T - T_{base})/288$, where T is the temperature measured by the sensor, T_{base} is the base temperature, 10°C for mini-cucumber, and 288 is an invariant for the number of measurements per day. The duration is from the initial date till the end of measurement and valid temperature ranging from 10 to 40°C is applied for cucumber.

2.2.2. Parametric Construction of 3D Cucumber Model.

Parameterized modeling method was used to construct the 3D cucumber canopies. The shape of each organ was determined by morphological parameters, which were generated by using the equations described above. Organ morphology was composed of skeletons and triangular mesh. B-splines curve was used to represent these skeletons in the computer. The control points on B-spline curve can determine the size of the organs (Figure 1), and the spatial distance of the control points was determined by the organ morphological parameters, which in turn determined the topology of the plant [18, 19].

2.2.3. 3D Canopy Construction for Cucumber. Three 3D canopies of cucumber were reconstructed with 20, 25, and 30 leaves per plant, respectively, by using the parameterized modeling method. Each virtual canopy was consisted of sixteen plants (4 rows*4 plants). The interplant distance in one line was 40 cm, the line spacing was 70 cm (inside) and 110 cm (path), respectively (Figure 2).

2.3. Light Interception Modeling. Light interception of three canopies from 8:00 to 15:00 on 4 November 2015 was simulated by using the radiosity-graphic combined model (RGM) with an hourly time step. Distribution of 3D diffuse photosynthetically active radiation (DPAR) in the canopy was simulated discretely by dividing the sky hemisphere into a grid of fine cells that allowed for the anisotropic distribution of DPAR over the sky hemisphere. Diffuse radiation was calculated using the method of Wen et al. [10]. It was assumed that a leaf absorbs 87%, transmits 7%, and reflects 6% of the incident photosynthetically active radiation [15]. Total PAR and proportion of diffuse light intensity were measured using SunScan Canopy Analysis System (Delta Company, UK).

2.4. Leaf Photosynthesis Modeling. FvCB model (Farquhar-von Caemmerer-Berry biochemical photosynthesis model) was applied in leaf photosynthesis modeling. According to Farquhar et al. [20], assimilation rate A is the minimum of the Rubisco-limited (A_o , $\mu\text{mol}\cdot\text{CO}_2\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) or RuBP regeneration-limited (A_j , $\mu\text{mol}\cdot\text{CO}_2\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) photosynthesis rate:

$$A_c = \frac{V_{c\max} \cdot (C_c - \Gamma^*)}{[C_c + K_c \cdot (1 + O/K_o)] - R_d}, \quad (1)$$

$$A_j = \frac{J \cdot (C_c - \Gamma^*)}{(4C_c + 8\Gamma^*) - R_d}, \quad (2)$$

where C_c (chloroplastic CO_2 concentration, $\mu\text{mol}\cdot\text{mol}^{-1}$) is calculated by using the following equation:

$$C_c = \frac{C_i - A}{g_m}. \quad (3)$$

When substituting equation (3) into equations (1) and (2), we get the quadratic equation of variable A_c and A_j , and the solutions are as follows:

$$A_c = \frac{-b - \sqrt{b^2 - 4ac}}{2a}, \quad (4)$$

$$\begin{aligned} a &= \frac{1}{g_m}, \\ b &= \frac{(R_d - V_{c\max})}{g_m - C_i - K_c(1 + O/K_o)}, \\ c &= V_{c\max}(C_i - \Gamma^*) - R_d \left[C_i + K_c \left(\frac{1 + O}{K_o} \right) \right], \end{aligned} \quad (5)$$

$$A_j = \frac{-b - \sqrt{b^2 - 4ac}}{2a},$$

$$\begin{aligned} a &= \frac{4}{g_m}, \\ b &= \frac{(4R_d - J)}{g_m - 4C_i - 8\Gamma^*}, \\ c &= J(C_i - \Gamma^*) - 4R_d(C_i + 2\Gamma^*). \end{aligned}$$

J (rate of electron transport, $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) was calculated by the following equation:

$$J = \frac{\left(K \cdot I + J_{\max} - \sqrt{(K \cdot I + J_{\max})^2 - 4\theta \cdot J_{\max} \cdot K \cdot I} \right)}{2\theta}, \quad (6)$$

where $V_{c\max}$ is the maximum rate of Rubisco carboxylation ($130.84 \mu\text{mol}\cdot\text{CO}_2\cdot\text{m}^{-2}\cdot\text{s}^{-1}$); Γ^* is the CO_2 compensation point in the absence of dark respiration ($43.02 \mu\text{mol}\cdot\text{mol}^{-1}$); K_c ($404 \mu\text{mol}\cdot\text{mol}^{-1}$) and K_o ($278 \text{mmol}\cdot\text{mol}^{-1}$) are Michaelis-Menten constants of Rubisco for CO_2 and O_2 ; O is the mole fraction of O_2 at the site of carboxylation ($210 \text{mmol}\cdot\text{mol}^{-1}$); R_d is the respiration rate ($1.08 \mu\text{mol}\cdot\text{CO}_2\cdot\text{m}^{-2}\cdot\text{s}^{-1}$); g_m is mesophyll conductance ($0.8 \text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$); C_i is ambient CO_2 concentration measured by CO_2 sensor; $J_{\max}$ is the maximum electron transport rate ($125.66 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$); K is a constant describing the conversion efficiency of intercepted PAR (I) to J ($0.425 \text{mol}\cdot\text{mol}^{-1}$ photon); and θ is a constant convexity factor describing the response of J to I (0.7) [15].

2.5. Model Calibration and Validation. The structural parameters measured in measurement 2 were used for model

TABLE 1: Equations and parameter values of organ expansion in Apr-May.

Equation	Dependent variables (y)	Independent variables (x)	Parameter value			R^2	
			a	b	k		
$y = a/1 + be^{-kx}$	LL	GDD	26.30	4.21	0.025	0.983	
	LW	GDD	31.78	5.38	0.029	0.980	
	PD	GDD	7.91	2.61	0.003	0.915	
	ID	GDD	8.13	2.81	0.039	0.951	
$y = A_1 - A_2/1 + e^{(x-x_0)/dx} + A_2$			A_1	A_2	x_0	dx	
	PL	GDD	-8.01	32.17	67.08	47.69	0.989
	IL	GDD	-4.09	11.69	20.62	48.84	0.862
	LDW	GDD	-0.09	1.91	90.04	33.05	0.958
	PDW	GDD	-0.04	0.68	124.9	41.35	0.974

TABLE 2: Equations and parameters of organ expansion in Nov-Dec.

Equation	Dependent variables (y)	Independent variables (x)	Parameter value			R^2	
			a	b	k		
$y = a/1 + be^{-kx}$	LL	GDD	29.43	4.21	0.030	0.986	
	LW	GDD	33.49	5.40	0.035	0.977	
	PD	GDD	7.65	2.28	0.022	0.981	
	ID	GDD	7.69	1.98	0.094	0.898	
$y = A_1 - A_2/1 + e^{(x-x_0)/dx} + A_2$			A_1	A_2	X_0	dx	
	PL	GDD	-7.92	28.52	51.72	41.88	0.982
	IL	GDD	1.04	11.33	26.97	12.20	0.802
	LDW	GDD	-0.003	1.38	67.73	22.98	0.964
	PDW	GDD	-0.01	0.44	92.92	26.00	0.984

FIGURE 1: The workflow of reconstruction based on statistical models. The geometric parameters of blade, petiole, and internode came from equations of Tables 1 and 2, while the topology parameters of the angle between organs came from our former study of Qian et al. [18]. The spatial shape of the blade was determined by LL, LW, θ_L , and φ_L ; the spatial shape of the petiole was determined by PL and PD and δ_L ; the spatial shape of the internode was determined by IL and ID.

FIGURE 2: 3D canopies of sixteen cucumbers with 20, 25, and 30 leaves per plant, respectively.

validation. The root-mean-squared deviation (RMSD), bias, and accuracy (%) were determined following the approach described by Kahlen and Stützel [21]:

$$\text{RMSD} = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - y_i)^2}, \quad (7)$$

$$\text{bias} = \frac{1}{n} \sum_{i=1}^n (x_i)^2 - \frac{1}{n} \sum_{i=1}^n (y_i)^2, \quad (8)$$

$$\text{accuracy} = 1 - \frac{\text{RMSD}}{(1/n) \sum_{i=1}^n y_i}, \quad (9)$$

where x_i and y_i are the simulated and measured values, respectively. n is the number of simulated or measured values.

3. Results

3.1. Organ Development Analysis. The growth of cucumber organs conforms to the sigmoid growth curve. The maximum asymptote ($y = \max$), the maximum growth rate point (x_0, y_0), and the slope (y'_0) at the inflection point can be used as characteristic values describing its growth process (Figure 3). The curve characteristic values based on the results of measurement 1 are shown in Table 3 and Figure 4. The y'_0 of the leaf area expansion curves in Apr-May was

4.58, while the maximum expansion rate of leaf area occurs when the GDD reaches 92.75 Cd (Figure 4(a)). The maximum expansion rate of the petiole and internode length in Apr-May was 0.21 and 0.30, while the maximum expansion rate of the petiole appears at 67 Cd, and the maximum expansion rate of the internode appears at 41 Cd (Figure 4(c)). It indicated that internode reaches the maximum expansion rate before leaf and petiole reaching the maximum expansion rate, and the elongation of the internode is nearly completed. The dry matter accumulation of the petiole was less than that of the leaf, and the maximum values were 0.68 g and 1.91 g, respectively (Figure 4(b)). The dry matter of the leaf was 3 times the weight of the petiole.

The leaf expansion curve of cucumber in Nov-Dec was similar to that of Apr-May, and the leaf length expansion rate was lower than that of leaf width. Different from Apr-May, the maximum leaf expansion rate in Nov-Dec occurred when GDD reached 76 Cd, earlier than Apr-May. The maximum expansion rates of petiole length and internode length were both 0.21. The maximum expansion rate of the petiole appeared at 52 Cd, while the maximum expansion rate of the internode appeared at 27 Cd. In Nov-Dec, the maximum dry matter accumulation of petiole was 0.44 g and 1.38 g, and the maximum dry matter accumulation in winter leaf was significantly smaller than that in Apr-May (Table 3).

3.2. Analysis of Differences in Organ Development in Different Scenarios. The rate of leaf area expansion in Apr-May was

FIGURE 3: Sigmoid growth curve of organ expansion. $y = \max$ is the asymptote at the top of the curve, which represents the theoretical maximum value of organ expansion; (x_0, y_0) is the inflection point of the curve, which represents the point when the organ expansion reaches the maximum rate; y_0' is the slope at the inflection point and represents the maximum rate of organ expansion.

TABLE 3: Characteristic parameters of the organ expansion curve.

	Parameters	$y = \max$	y_0'	x_0, y_0
Apr-May	Leaf area	625.95	4.58	92.75, 312.97
	Leaf dry matter	1.91	0.02	90.05, 0.91
	Petiole length	32.17	0.21	67.08 12.08
	Internode length	10.75	0.30	41.92 6.07
	Petiole diameter	7.91	0.04	53.78, 3.95
	Internode diameter	8.13	0.08	26.70, 4.06
Nov-Dec	Leaf area	730.09	6.83	76.58, 365.05
	Leaf dry weight	1.38	0.01	67.73, 0.69
	Petiole length	28.52	0.21	51.72, 10.30
	Internode length	11.33	0.21	26.97, 6.19
	Petiole diameter	7.65	0.04	40.37, 3.82
	Internode diameter	7.69	0.18	7.13, 3.84

less than that in Nov-Dec, while the dry weight of leaves was greater in Apr-May than in Nov-Dec (Figure 4). That is, the leaf dry matter per unit area in Apr-May was greater than that in Nov-Dec. From the changing trend of the dry matter accumulation curve, there was unobvious difference between the dry matter accumulation in the early Apr-May and Nov-Dec, but the rapid growth period of the dry matter accumulation curve in Apr-May was obviously longer than that in Nov-Dec. Therefore, the accumulation ratio of leaf dry weight per unit area was greater in Apr-May than in Nov-Dec (Figure 5). The elongation of the petiole and internode had no significant difference in the two scenarios. Although the diameter change of the petiole and internode was slightly different during the expansion period, the final diameter was still relatively close, with no obvious difference.

3.3. Methodological Accuracy of Organ Expansion Models.

The data obtained in experiment 2 was used for model verification. The relationship between the measured and simulated values of leaf length, leaf width, petiole length, and internode length is shown in Figure 6, while the bias, RMSD, and accuracy of the model simplifications are shown in Table 4. The

simulated value was close to the measured value, and the accuracy of the four simulations was higher than 0.99.

3.4. Analysis of Leaf Light Interception and Photosynthetic Characteristics in 3D Canopies. Comparing the temperature and light environment conditions between Apr-May and Nov-Dec, the temperature difference was small, but the light difference was large. Since light directly participates in photosynthetic reactions during the accumulation of dry matter, there was a significant difference in yield in Apr-May and Nov-Dec (Figure 7). The yield was 0.174 kg/m^2 per day in Nov-Dec and it was 35.3% lower than the yield in Apr-May. To further analyze the canopy photosynthesis characteristics, it is necessary to combine the canopy radiation interception model and photosynthesis model.

In this study, light interception of three canopies from 8:00 to 15:00 on 4 November 2015 was simulated by using the radiosity-graphic combined model. Combining the 3D structure model and the radiosity-graphic combined model, the instantaneous light interception of each cucumber leaf in the canopy was calculated. The light interception data of the leaves of 4 plants inside the canopy were selected for analysis. The blocking effect of the surroundings was fully considered. The average light interception of a single leaf is shown in Figure 8. The light interception of the middle and lower canopy leaves was significantly lower than that of the upper part, and the light of the top leaves was relatively small due to the small leaf area. The lower leaves in the 20-leaf canopy have lower light interception than the other two canopies. The difference in light interception between the three upper canopy leaves was not obvious.

FvCB photosynthesis model was used in leaf assimilation rate modeling considering carbon dioxide assimilation mechanisms. The light interception of each blade calculated from the light interception simulation is input into the FvCB model as the incident light intensity (I). The FvCB model calculates the assimilation rate of Rubisco-limited (A_c , $\mu\text{mol}\cdot\text{CO}_2\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) and RuBP regeneration-limited (A_j , $\mu\text{mol}\cdot\text{CO}_2\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), respectively. The data showed that during the daytime in Nov-Dec, the A_j value was always less than the A_c value. It means that the limiting factor affecting the photosynthesis rate in Nov-Dec was light intensity. The high concentration of CO_2 in the morning can also promote photosynthesis (Figure 9). In the morning and afternoon, light intensity was only about half of the noon, while the photosynthesis rate was about 85% of noon. High CO_2 concentration can make up part of the effect of low light intensity on the photosynthetic rate in Nov-Dec. There was no significant difference in the photosynthetic rate of the upper leaves of the three canopies, but affected by the light interception of the leaves, the photosynthetic rate of the lower leaves of the 20-leaf canopy was significantly lower than that of the other two canopies.

4. Discussion

4.1. The Contribution of 3D Model in Simulation Research.

In the light interception calculation, the consistency of the 3D model and the true structure of the canopy is a crucial

FIGURE 4: Leaf area expansion (a) and dry matter accumulation (b), petiole and internode length (c) and diameter increasing (d) following thermal time accumulation in Apr-May 2015 and Nov-Dec 2015. Measured data of leaf expansion and petiole and internode diameter increasing were fitted by logistic curves, while measured data of leaf dry matter accumulation and petiole and internode length increasing were fitted by Boltzmann curves.

factor that determines the reliability of the simulation results. At the field level, many research studies were conducted on 3D point cloud acquisition of field crop canopy based on UAV (unmanned aerial vehicle) and LiDAR [22, 23]. Based on these 3D point clouds, plant height, ground cover, and above-ground biomass were obtained [24, 25]. But these methodologies presented an underestimation of biomass and leaf area index and cannot extract the architecture parameters of individual plants from the canopy. In order to obtain more detailed 3D point clouds at the

individual plant level, 3D laser scanner, 3D digitizing, and multiview imaging were used in plant and organ 3D point cloud acquisition [26, 27]. Using these methods, many specific morphological parameters of various crops have been achieved, such as leaf azimuthal angle, leaf length, and leaf area of maize [28]. Since the last few years, many 3D point cloud acquisition methods were used in plant 3D structural model construction at different scales, such as LIDAR, 3D laser scanner, 3D digitizing, and multiview imaging [29]. However, there are still many challenges in

FIGURE 5: Correlation between leaf dry matter accumulation and leaf area expansion in different scenarios.

FIGURE 6: Continued.

FIGURE 6: Comparison between the simulated and the measured value of leaf length, leaf width, petiole length, and internode length. Error bars indicate the SD.

TABLE 4: The bias, RMSD, and accuracy of the model simplifications for leaf length, leaf width, petiole length, and internode length.

Structural parameters	Simulated		
	Bias (cm ²)	RMSD (cm)	Accuracy
Leaf length	-7.14	0.28	0.99
Leaf width	-19.26	0.21	0.99
Petiole length	23.59	0.72	0.99
Internode length	0.97	0.57	0.99

FIGURE 7: Measured cucumber yield per day in Nov-Dec and Apr-May.

building a sufficiently accurate 3D model because plant morphologies are diverse for different species, and there is none uniform solution for all kinds of plants [28]. The

FIGURE 8: Light interception per leaf in the three canopies.

parametric modeling method applied in this study is also one of the alternative methods for constructing three-dimensional plants. Based on the descriptive model of organ expansion, a plant population with any number stands can be constructed. However, since the organ expansion model is a regression model, its adaptability is limited, and the simulation of the three-dimensional structure model is also constrained by the model. Therefore, we separately constructed the organ expansion curve equations in different scenarios (Apr-May and Nov-Dec) to construct the canopy growth accordingly.

FIGURE 9: Diurnal variation of carbon dioxide assimilation rate per plant.

4.2. Light Energy on Cucumber Development. The effect of light on plant growth and development not only directly affects the photosynthetic reaction of leaves, but also affects plant morphogenesis. In most of the plant growth models, leaf area is an important parameter directly related to biomass accumulation and structural development [30]. However, the results of this study showed that leaf area is not completely positively related to dry matter. Cucumber grown in winter has larger leaf area but less dry matter, resulting in a smaller specific leaf area (SLA). Therefore, growth is more directly related to specific leaf area than to leaf area [31].

4.3. Photosynthesis Modeling. The photosynthetic capacity of leaves is affected not only by the amount of light intercepted, but also by the age of the leaves and the ambient temperature. In particular, cucumbers belong to C3 type plants, which have stronger photorespiration and growth respiration. They consume more assimilates than C4 plants to maintain growth and protect photosynthetic organs. In many research studies, various forms of equations were used to describe the response of FvCB model parameters to temperature, such as temperature sensitivity (Q_{10}), polynomials, exponential functions, and normal distribution functions [32]. The change in temperature dependence of photosynthesis is caused by several factors such as C_i , J_{max} , and J_{max} to V_{cmax} ratio, which were also reported to change with growth temperature. The response of each factor to

temperature seems to differ among species, and there is no report yet in cucumber. In the research of Zhou et al. [33], it is found that leaf aging significantly affected A_m , A_g , R_{dark} , V_{cmax} , J_{max} , R_{dark}/A_m , and g_s , but leaf aging had little effect on the J_{max}/V_{cmax} ratio, suggesting coordination between V_{cmax} and J_{max} processes regardless of leaf age. Further studies are needed to reconfirm the leaf aging effect on the temperature sensitivity of R_{dark} and to elucidate the mechanisms involved.

4.4. Optimal Utilization of Light Energy. In a semiclosed greenhouse, the CO_2 concentration in the morning is significantly higher than at noon and afternoon (Figure 9). The main reason is that the respiration of plants at night accumulates a lot of CO_2 . From the photosynthesis simulation results, the high concentration of CO_2 in the morning can obviously promote the leaf photosynthesis rate (Figure 9). At this stage, light intensity is the main factor limiting the assimilation rate. By noon, the light intensity increased, but the CO_2 concentration decreased significantly and became the main factor limiting the rate of assimilation. Therefore, increasing light intensity in the morning or supplementing CO_2 at noon can increase photosynthetic output. In the results of leaf light interception and photosynthesis rate analysis (Figures 8 and 10), the light interception and photosynthetic rate of the lower leaves in the 20-leaf canopy were significantly lower than those in the other two canopies. The main reason is that, in the parametric modeling process,

FIGURE 10: Net assimilation per day of leaves in the three canopies.

the blade azimuth model (ϕ_L) we choose will make the blade distribution ratio in each azimuth range change with the LAI. As the LAI increases, more leaves will turn orientation towards rows with better lighting conditions to intercept more light. It can be seen that when the light conditions in winter are weak, maintaining a reasonable LAI is more conducive to canopy photosynthesis. From the results of this study, the 25-leaf canopy is the best canopy structure for light interception and photosynthesis. However, considering that the light interception of leaves under 20 leaves is weak and the leaf function is weak due to the effects of leaf senescence, the number of leaves in the canopy during winter should be controlled within 25 leaves.

5. Conclusions

Low temperature and low light energy in the winter of east China are important reasons for the decline in cucumber yield, especially in greenhouses without supplementary light. This study provides an important management basis for the optimal use of light in the greenhouse in winter. Using 3D modeling technology, the virtual structure model of cucumber canopy was established, and combined light interception modeling and photosynthesis modeling, the light environment in the canopy and the photosynthetic performance of leaves were quantitatively studied to obtain cucumber management strategies in winter. By using the FvCB model, Rubisco-limited (A_c) and RuBP regeneration-limited (A_j) assimilation rate of each leaf in three canopies with different leaves per plant were simulated, respectively. Based on the simulated result, we analyzed the effects of light and CO_2 changes on the photosynthesis at different time periods and different leaf positions. Through a comparative analysis of photosynthetic characteristics in the virtual canopy, we have come up with strategies to improve the canopy photosynthetic capacity, and a suitable canopy structure that is conducive to winter canopy photosynthetic yields.

Data Availability

All data used during the study are available from the corresponding author by request (e-mail: qiantingting@saas.sh.cn).

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

Tingting Qian and Xiuguo Zheng contributed equally to this work.

Acknowledgments

The authors would like to thank Dr. Feng Lu for her support during the preparation of this manuscript. This work was supported by Shanghai Agriculture Applied Technology Development Program of China (no. G2015060402), National Natural Science Foundation of China (no. 61762013), and Shanghai Science and Technology Commission Project of China (no. 19DZ2281300).

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