Abstract: The canopy structure of colored cotton is comparative complex. In this study, the vertical distribution of canopy leaf area was simulated by using the leaf area density ($LAD(z)$) and the cumulative leaf area index ($LAI(z)$) as index based on the probability density function of Beta distribution, and the distribution density for canopy leaf inclination was simulated based on ellipsoidal distribution function through layering the canopy of colored cotton following the Gaussian five-point method. After sprouting when the cumulative daily relative thermal effects ($T_{*}$) was 42, results revealed that the root mean square error ($RMSE$) of $LAD(z)$ and $LAI(z)$ were 0.273 and 0.307, respectively, and the $RMSE$ of the leaf inclination angle distribution frequency for each layer was 3.1%, 3.1%, 4.2%, 4.3%, and 5.8%, respectively. The model developed in this study is rationally sound and has validity, to a certain extent, when simulating the parameters of the colored cotton canopy. Moreover, the findings of this study have established a foundation for accurately and effectively studying the transmission of optical radiation and biomass production in future studies on the colored cotton canopy.

Key words: Cumulative daily relative thermal effect, leaf area vertical distribution, leaf inclination angle distribution, naturally colored cotton.

1. Introduction

Naturally colored cotton (hereinafter referred to as “colored cotton”) is a general term for naturally grown, colored cotton and is a new type of textile raw material that has been recently developed. Its environmentally friendly and robust characteristics can spare the bleaching and dyeing process utilized by the cotton spinning industry, which has an energy-saving and emission-reducing effect in order to protect the environment and pursue low-carbon processes [1]-[3]. The Alaer Reclamation Area in Xinjiang is located on the northern edge of the Taklimakan Desert and the upper reaches of the Tarim River where the Aksu, Hetian, and Yarkant Rivers meet, covering a total area of 6,180 km$^2$. The annual effective cumulated temperature above 10°C exceeds 4000°C. The frost-free period lasts 220 d with average daily sunshine of 9.5 h from April to October; annual sunshine lasts over 2,900 h. The natural conditions make the Alaer Reclamation Area an advantageous and important location as the production base for China’s colored cotton.

Crop canopy structure directly affects the interception of sunlight by plants, affects the photosynthetic efficiency and biological yield of plants, and has been one of the focus of cotton plant research [4]-[9]. Previous studies demonstrated that describing the canopy structure with the vertical distribution of leaf
area and the geometric distribution of leaf spatial dispersion can effectively link the canopy's sunlight acceptance state with the direction of sunlight projection, thus, facilitating the analysis of canopy photosynthesis [10]-[12]. Therefore, the leaf area index, the vertical distribution of leaf area, and the geometric distribution of leaf space dispersion are important parameters for studying the canopy structure of crops. These parameters of canopy structure in colored cotton especially impacts the biomass production of colored cotton plants under unique natural ecological conditions in the Alaer Reclamation Area. Traditional crop models that have simulated the leaf area index rarely considered the vertical distribution of leaf area [13]-[15]. This is unfortunate as the vertical distribution of canopy leaf area affects the interception of sunlight and ultimately affects the photosynthetic efficiency of the canopy.

The biomass yield of colored cotton plants is directly affected by the vertical distribution state of the canopy leaf area under sufficient sunshine conditions, therefore, studying the vertical distribution of the canopy leaf area is of great importance for improving the yield of this crop. In dynamic vertical distribution simulations of leaf area, the daily structure parameters of the canopy were obtained using the statistical interpolation method, which is strongly empirical but weak in mechanism analysis [16], [17]. Moreover, the vertical distributions of canopy leaf area of rice and wheat have been investigated at a single stage of crop growth and developmental period, but lacking continuous simulation of the whole growth and developmental period [18], [19].

The leaf space dispersion state can be divided into the leaf inclination angle and the leaf azimuth angle. Botanical studies have shown that the leaf azimuth angle of the crop canopy is basically symmetrical [20], and the leaf azimuth angle has less effect on the canopy’s photosynthetic productivity, while the distribution of the leaf inclination angle has a great effect [21], [22], the distribution of leaf inclination at different canopy heights of colored cotton directly determines the interception efficiency of canopy to solar radiation, which thereby affects plant biomass production. Related scholars have conducted extensive studies simulating crop leaf inclination angle distribution. For example, Campbell [23] used the ellipsoidal distribution function to simulate the leaf inclination angle distribution in soybeans, corn, and sunflowers and proved the applicability of the ellipsoidal distribution function in simulating crop leaf inclination angle distribution. In a separate study, Li et al. [24] investigated the rice canopy, which has almost no hanging leaf area or standing plant types, to continuously simulate the canopy's leaf inclination angle distribution using the dual-parameter ellipsoidal distribution function combined with the Powell method. Liu et al. [25] layered the corn canopy according to the depth of the leaf area, divided the leaf inclination angle of each layer into six levels in intervals of 15°, and obtained the leaf inclination angle distribution of each layer level by statistical investigation and achieved good results.

Based on the findings of previous studies on the characteristic parameters of crop canopy structure, this study aims to build a dynamic model simulating the vertical distribution of leaf area and leaf inclination angle distribution of the colored cotton canopy in the Alaer Reclamation Area. These findings will establish a foundation for investigating the transmission of optical radiation and biomass production of the colored cotton canopy.

2. **Materials and Methods**

2.1. **Experimental Design**

The field experiment was conducted in the Alaer Reclamation Area from 2017–2018. The model was established by using experimental data with the seeding date April 15, 2017. The model was tested by using experimental data with the seeding date May 3rd, 2018. The tested variety was “Xincai No. 4,” the soil was sandy loam, and the planting density was 0.12 m plant spacing and 0.30 m row spacing. Water or fertilizer stress was not observed during field management. Meteorological data was retrieved from the local
meteoroological station.

2.2. Research Methods

2.2.1. Thermal effect as the growth factor

Daily temperature is one important environmental factor that affects cotton growth, and plays the most crucial role in the development of cotton plants under conditions lacking water or fertilizer stress. It is known that the growth of colored cotton tends to stagnate when the temperature is greater than 35°C or less than 12°C. The traditional effective accumulative temperature method does not consider the hysteresis effect of high temperatures on the development of colored cotton, thus, the thermal effect was used to quantify the growth and development of colored cotton, such that:

\[
RTE(T) = \begin{cases} 
0 & (T < T_b) \\
\left(\frac{T - T_b}{T_o - T_b}\right) & (T_o \geq T \geq T_b) \\
\left(\frac{T_o - T}{T_o - T_a}\right) & (T_o \geq T \geq T_a) \\
0 & (T > T_a)
\end{cases}
\]  

(1)

where \(RTE(T)\) represents the relative thermal effect at temperature \(T\) \([26]\), and \(T_o (30^\circ C), T_b (12^\circ C),\) and \(T_a (35^\circ C)\) are the optimum, lowest, and highest temperatures required for colored cotton development, respectively. It should be noted that the temperature is not fixed and fluctuates throughout the day. Goudriaan and Van Laar \([27]\) and Cao and Luo \([28]\) proposed that the comprehensive effect of temperature changes in a given day is comprised of 50% average temperature \((T_{av})\), 25% maximum temperature \((T_{max})\), and 25% minimum temperature \((T_{min})\). Thus, the daily \(RTE\) can be expressed as:

\[
RTE = 0.25 \times (2.0 \times RTE(T_{av}) + RTE(T_{max}) + RTE(T_{min}))
\]  

(2)

where \(T_*\) is the cumulative daily relative thermal effect after the sprouting of colored cotton. \(T_*\) is used as a scale for describing the growth and development process of colored cotton and is defined as follows:

\[
T_* = \sum_{i=1}^{n} RTE_i
\]  

(3)

where \(i\) represents the number of days after the sprouting of colored cotton.

2.2.2. Root mean square error

Using the root mean square error value (RMSE) to evaluate the difference between the measured values and simulated values, the smaller the root mean square error value is, the closer the measured values are to the simulated values and the more reliable the model is. RMSE is defined as:

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (F_i - S_i)^2}
\]  

(4)

where \(n\) is the sample size, \(F_i\) is the measured value, and \(S_i\) is the simulated value.

3. Model Description

3.1. Vertical Distribution of the Leaf Area

Canopy leaf area density (LAD\((z) (m^2/m^3)\)) refers to the amount of leaf area per unit volume of the canopy
at a certain height \( (z) \). The cumulative leaf area index (LAI(z) \( (m^2/m^2) \)) refers to the cumulative value of the leaf area index in leaf layer from the top surface of the crop canopy to a certain height \( (z) \). LAD(z) and LAI(z) are important parameters describing the vertical distribution of leaf area for the crop canopy. Because colored cotton is a field crop, the leaf area vertical distribution of a single plant hardly represents the whole field. Therefore, based on a single colored cotton plant, the leaf area vertical distribution of the canopy for the whole field was studied.

3.1.1. Distribution of plant height

There were some differences in individual growth of cotton plants observed in the field. Colored cotton planting experiments have shown that the plant height \( (z_{top}) \) in the field has a normal distribution, and its probability density function is as follows:

\[
f(z_{top}) = \frac{1}{\sqrt{2\pi\sigma_{z_{top}}}} e^{-\frac{(z_{top}-z)^2}{2\sigma_{z_{top}}^2}}
\]

where \( z \) \( (m) \) is the mean value and \( \sigma_{z_{top}} \) \( (m) \) is the standard deviation; \( \sigma_{z_{top}} \) and \( z \) vary with \( T^* \) during the growth process. These results are obtained by experimental fitting:

\[
z(T^*) = 0.38 \times 10^{-4} T^*^2 + 1.82 \times 10^{-3} T^* + 3.40 \times 10^{-3} \left( R^2 = 0.946 \right)
\]

\[
\sigma_{z_{top}}(T^*) = 1.71 \times 10^{-3} T^* - 0.98 \times 10^{-2} \left( R^2 = 0.921 \right)
\]

After topping colored cotton plants during the field management process, plant height will no longer change and, correspondingly, the \( z \) and \( \sigma_{z_{top}} \) values will also be fixed.

3.1.2. Vertical distribution of a single plant’s leaf area

Zhang et al. [29] previously reported that the total leaf area of a single plant’s (\( AREA_{sp}(z_{top}) \)) has an exponential relationship with the plant height \( (z_{top}) \), such that:

\[
AREA_{sp}(z_{top}) = c_1 z_{top}^{c_2}
\]

where \( c_1 \) and \( c_2 \) change with the growth of colored cotton. The relationship between \( c_1 \), \( c_2 \), and \( T^* \) is obtained by experimental fitting:

\[
c_1(T^*) = -4.16 \times 10^{-3} T^* + 0.593 \left( R^2 = 0.94 \right)
\]

\[
c_2(T^*) = 1.49 \times 10^{-3} T^*^2 - 0.183 T^* + 5.521 \left( R^2 = 0.92 \right)
\]

where \( T^* \) is the cumulative daily relative thermal effect, \( AREA_{sp}(z_{top}) \), at plant height, \( z_{top} \) on a given day during the growth and development period of colored cotton, can be calculated by (8)–(10).

Ross et al. [16] defined the vertical distribution function for leaf area of a single plant \( (V_{sp}(z)) \ (m^2/m) \), indicating the contribution to the total leaf area of a single plant at a certain height \( (z) \), such that:

\[
V_{sp}(z,T^*) = \frac{AREA_{sp}(z_{top},T^*)}{z_{top}} S(z^*) \left( \frac{z}{z_{top}}, z^* \in [0,1] \right)
\]
where \( S(z) \) is a vertical distribution shape function for the leaf area of a single plant. The probability density function of the \( \beta \) distribution can have different shapes under the control of \( \alpha \) and \( \beta \). Thus, \( S(z) \) can be represented by the probability density function of the \( \beta \) distribution as follows:

\[
S(z) = \frac{1}{B(\alpha, \beta)} z^{\alpha-1} (1-z)^{\beta-1}
\]

(12)

\[
B(\alpha, \beta) = \int_0^1 u^{\alpha-1} (1-u)^{\beta-1} \, du
\]

(13)

The relationship between \( \alpha, \beta \), and \( T \), can be measured by experimentation, such that:

\[
\alpha(T_*) = 6.68 \times 10^{-2} T_* - 5.3 \times 10^{-2} \left( R^2 = 0.95 \right)
\]

(14)

\[
\beta(T_*) = 0.3802 T_*^{0.3466} \left( R^2 = 0.92 \right)
\]

(15)

where \( V_{sp}(z, T_*) \) is the vertical distribution function for the leaf area of a single plant any day during the growth and development period and can be obtained by (11)–(15).

### 3.1.3. Vertical distribution of the leaf area in the field

On the basis of the vertical distribution of a single plant leaf area of colored cotton, the overall vertical distribution of leaf area \( (V(z)) \) in the field can be obtained by introducing plant density \( (\rho \, \text{plant/m}^2) \), and \( LAD(z) \, (\text{m}^2/\text{m}^3) \), the canopy leaf area density in the field can be obtained by the integral of \( V(z) \):

\[
V(z, T_*) = V_{sp}(z, T_*) \rho f(z_{\text{top}}, T_*)
\]

(16)

\[
LAD(z, T_*) = \int_z^{z_{\text{top}}} V(z, T_*) \, dz_{\text{top}}
\]

(17)

where \( z_{\text{a}} \) is the height of the top of the canopy and conforms to normal distribution. Thus, it is represented as follows:

\[
z_{\text{a}} = z(T_*) + 1.96 \sigma_{z_{\text{top}}}(T_*)
\]

(18)

Due to the aging and death of leaves at the bottom of the canopy, the height at the bottom of the canopy \( (z_b) \) will increase over time; the result is obtained by experimental fitting:

\[
z_b = 5.87 \times 10^{-5} T_*^2 + 7.8 \times 10^{-4} T_* - 0.98 \times 10^{-2} \left( R^2 = 0.95 \right)
\]

(19)

\( LAI(z) \) is the cumulative leaf area index of the canopy and can be obtained by the integral of \( LAD(z, T_*) \), the leaf area density of the canopy, at height \( z \). At \( T_*=42 \) after sprouting in 2018, after the simulated and measured values of the leaf area density in the field population at different canopy heights were recorded and \( RMSE \) was 0.273 (Fig. 1). After the simulated and measured values of the cumulative leaf area index in the field population at different canopy heights were recorded and \( RMSE \) was 0.307 (Fig. 2), when \( z \) was 0–0.13 m, the cumulative leaf area index reached the maximum value recorded (i.e. the leaf area index).
3.2. Leaf Inclination Angle Distribution

The leaf inclination angle is the angle between the normal vector of the leaf center and the vertical direction of the ground surface, such that the angle between the tangent line of the leaf center and the horizontal plane ranged between 0 and $\pi/2$. The larger the leaf inclination angle, the more the leaf extends vertically, the smaller the leaf angle is, and the more the leaf extends horizontally. The distribution of the crop canopy leaf inclination angle is closely related to the amount of solar radiation captured by the canopy, which is an important parameter of the crop canopy structure.

3.2.1. Layering of the canopy

Reynolds et al. [30] stated that if the simulation on the distribution of the canopy leaf inclination angle is not conducted hierarchically, it will lead to a large deviation when compared to the model for the light radiation transmission of the canopy. Ni et al. [31] adopted the Gaussian integral method to effectively calculate the photosynthesis rate of the canopy after layering the tomato canopy following the methods described by Goudriaan [32]. In a previous study conducted by Liu et al. [25], results revealed that the layer number does not significantly affect simulation accuracy when it is greater than 3 layers. Despite these findings, the complexity of the colored cotton canopy should be considered, as well as subsequent coupling with the canopy photosynthetic model. Thus, the distribution of the leaf inclination angle can be studied by dividing the colored cotton canopy into 5 layers, according to the $LAI$ values through the Gaussian five-point distance method, such that:

$$LGUSS_i = DIS_i \times LAI \ (i = 1, 2, 3, 4, 5)$$

(20)

where $LGUSS_i$ is the canopy leaf area depth of Gaussian layering, $DIS_i$ is the distance coefficient of the Gaussian integral method and $LAI$ is the leaf area index. The distance coefficients and weights of the five-point Gauss integral (Table 1), and the weighted values ($WT_i$) are usually used for the weighted calculation of the instantaneous photosynthesis rate of each canopy layer in the photosynthesis model.

Table 1. Weighted Values and Distance Coefficients Derived from the Gaussian Integral Five-Point Method

| $i$ | 1   | 2   | 3   | 4   | 5   |
|-----|-----|-----|-----|-----|-----|
| $WT_i$ | 0.11846 | 0.23931 | 0.28444 | 0.23931 | 0.11846 |
| $DIS_i$ | 0.04691 | 0.23077 | 0.50000 | 0.76924 | 0.95309 |
3.2.2. Numerical simulation of the leaf inclination angle distribution of each layer

Considering the simulation study of leaf inclination angle distribution of crop canopies, Lemeur [33] stated that the leaf inclination angle density function \( f(\alpha) \) of a layer in the canopy consists of the ratio of the leaf area, such that the leaf inclination angle is within a specific range \([\alpha, d\alpha]\), to the leaf area in the layer, given that the leaf inclination angle and leaf azimuth angle are independent of each other. The integral value of \( f(\alpha) \) in \([0, \pi/2]\) can be calculated as follows:

\[
\int_{0}^{\frac{\pi}{2}} f(\alpha) d\alpha = 1
\]

Campbell [34] proposed a universal ellipsoidal research method for the leaf inclination angle distribution and provided the leaf inclination angle density function \( f(\alpha) \), the spherical leaf inclination angle distribution, the cone leaf inclination angle distribution, and the horizontal or vertical leaf inclination angle distribution. These can be regarded as a special form of the ellipsoidal leaf inclination angle distribution, such that:

\[
f(\alpha) = \frac{2\chi^3 \sin\alpha}{\Lambda (\cos^2\alpha + \chi^3 \sin^2\alpha)^2}
\]

where \( \chi \) is the ratio of the horizontal half-axis length to the vertical half-axis length of the ellipsoid, and \( \Lambda \) is closely related to \( \chi \), which determines the shape of the leaf inclination angle distribution. When \( \chi > 1 \), the \( \Lambda \) value can be derived by (23), and when \( \chi \to \infty \), the leaf inclination angle approaches a horizontal distribution. When \( \chi < 1 \), the \( \Lambda \) value can be derived by (24), and when \( \chi \to 0 \), the leaf inclination angle approaches a vertical distribution. When \( \chi = 1 \), the \( \Lambda \) value approaches 2 and the ellipsoid distribution becomes spherical.

\[
\Lambda = \chi + \frac{\ln \left[ \frac{(1+\varepsilon)}{(1-\varepsilon)} \right]}{2\varepsilon \chi}, \quad \varepsilon = \sqrt{1-\chi^2}
\]

\[
\Lambda = \chi + \frac{\sin^{-1}(\varepsilon)}{\varepsilon}, \quad \varepsilon = \sqrt{1-\chi^2}
\]

The density function \( f(\alpha) \) of the leaf inclination angle distribution can be determined as long as \( \chi \) is determined. After layering the canopy following the Gaussian method, and considering the difference of the leaf inclination angle distribution at the different heights of the canopy, and the leaf inclination density function with different \( \chi \) values was determined for each layer. The leaf inclination angle of each layer was divided into six sections at intervals of 15°, and the frequencies of the leaf inclination angles were measured for each section of each layer. Generally, \( 0.1 \leq \chi \leq 10 \) sufficiently describes the leaf inclination angle density function of any canopy with a unimodal state, and \( \chi \) is fitted by using the exhaustive search method for each layer. Setting 0.1 as the initial value of \( \chi \) and 0.01 as the step size, the \( \chi \) value of each layer was fitted, such that:

\[
S = \sum_{i=1}^{6} \left| F(\alpha_i) - F^*(\alpha_i) \right| \rightarrow \text{min}
\]

where \( F(\alpha) \) is the integral of \( f(\alpha) \) on each interval of the layer under a given \( \chi \) value, \( F^*(\alpha) \) is the measured frequency of the leaf inclination angle distribution for each interval in a given layer, and \( \text{min} \) is the minimum value of \( S \) after searching 1,100 rounds, whose corresponding \( \chi \) value was the optimal \( \chi \) value for
that layer. In 2017 when $T^*=42$, layering colored cotton by the Gaussian method provided the optimal $\chi$ values of each layer (Table 2). Additionally, the density function curve for the leaf inclination angle of each layer in the canopy was also derived (Fig. 3). The density of the leaf inclination angle distribution in the interval of $0-30^\circ$ was larger and decayed rapidly after $30^\circ$.

**Table 2. The Optimal $\chi$ Values of Each Layer at $T^*=42$**

| Canopy depth | Min  | $\chi$ |
|--------------|------|--------|
| Layer 0–1    | 0.0003 | 1.56 |
| Layer 0–2    | 0.0007 | 1.98 |
| Layer 0–3    | 0.0005 | 2.34 |
| Layer 0–4    | 0.0007 | 2.72 |
| Layer 0–5    | 0.0003 | 3.64 |

**Fig. 3. Leaf inclination angle density based on Gaussian layering when $T^*=42$.**

For each layer, $f(\alpha)$ was integrated for the 6 sections at intervals of $15^\circ$, and simulated values of leaf inclination angle frequencies for the different sections of each layer were obtained (Table 3). As the depth of the canopy leaf area increased from top to bottom, the leaf inclination angle became smaller and the leaves flattened, which was consistent with field observations.

**Table 3. Simulation Values of the Leaf Inclination Angle Distribution Frequency at $T^*=42$**

| Canopy depth | Leaf inclination interval (°) | 0–15 | 15–30 | 30–45 | 45–60 | 60–75 | 75–90 |
|--------------|-------------------------------|------|-------|-------|-------|-------|-------|
| Layer 0–1    |                               | 0.0980 | 0.2108 | 0.2133 | 0.1814 | 0.1549 | 0.1416 |
| Layer 0–2    |                               | 0.1611 | 0.2714 | 0.2088 | 0.1471 | 0.1130 | 0.0986 |
| Layer 0–3    |                               | 0.2202 | 0.3025 | 0.1921 | 0.1215 | 0.0884 | 0.0754 |
| Layer 0–4    |                               | 0.2838 | 0.3173 | 0.1708 | 0.0996 | 0.0698 | 0.0587 |
| Layer 0–5    |                               | 0.4282 | 0.3057 | 0.1237 | 0.0642 | 0.0428 | 0.0353 |

By conducting linear regression using the measured data from 2018 and the simulated leaf inclination angle frequency distributions for each section of each layer at $T^*=42$, the results indicate that the Campbell ellipsoidal distribution function effectively simulates the leaf inclination angle distribution of colored cotton.
canopy (Fig. 4).

(a) Comparison of layer 0–1 ($\chi = 1.56$) data.  (b) Comparison of layer 0–2 ($\chi = 1.98$) data.

(c) Comparison of layer 0–3 ($\chi = 2.34$) data.  (d) Comparison of layer 0–4 ($\chi = 2.72$) data.

(e) Comparison of layer 0–5 ($\chi = 3.64$) data.  (f) Overall comparison of all hierarchical data.

Fig. 4. A 1:1 regression analysis of the simulated and measured values of the leaf inclination angle frequency when $T_*=42$.

4. Results and Discussion

The cumulative daily relative thermal effect at $T_*=42$ is an important parameter between the budding and flowering periods, and the flowering and multi-boll periods. This is one of the key time periods for the growth and development of colored cotton. Thus, at $T_*=42$, the main parameters of colored cotton canopy (i.e., leaf area density, cumulative leaf area index, and leaf inclination angle distribution) were successfully simulated in this study.

When considering the difference in the growth and development of colored cotton plants, plant height was normally distributed, which correlates better with field observations than using average plant height to
simulate population parameters. In the simulation, when the planting density was 0.12 m for plant spacing and 0.30 m for row spacing, and when comparing the vertical distribution of the leaf area at canopy heights of 0.13, 0.24, 0.32, 0.41, 0.5, 0.6, 0.75, 0.86, and 0.96 m, the RMSE of leaf area density was 0.273 and 0.307 for the cumulative leaf area index. Overall, the simulated values correlated well with the observed values; however, the measured values were smaller than the simulated values, which may be due to environmental stress was not considered in the model. Additionally, due to competition among plants in the field, the vertical distribution shape function of leaf area per plant may be affected by different planting densities, and leaf area density may vary greatly in different planting densities.

The χ values of leaf inclination distribution for the 0−1, 0−2, 0−3, 0−4, and 0−5 layers were 1.56, 1.98, 2.34, 2.72, and 3.64, respectively, after fitting and had a transverse ellipsoid shape. Comparing the experimental data to simulation values, the RMSE values for each layer were 3.1, 3.1, 4.2, 4.3, and 5.8%, respectively; the overall RMSE was 4.2%. These results prove that using the Gaussian five-point method for hierarchical division of the canopy according to the depth of leaf area is feasible. Moreover, using the Campbell ellipsoidal distribution function to fit the leaf inclination distribution of colored cotton is more accurate.

The simulation results derived from the model can be used as canopy structure parameters for canopy radiation transmission and photosynthesis models. These findings are helpful for possible future investigations on the functional-structural model of colored cotton. However, there are too many parameters in this model that could lead to error magnification, thereby affecting the accuracy of the model. Moreover, the colored cotton canopy structure is extremely complicated, and is affected and restricted by many factors. In this study, only the relationship between the main structure parameters of the colored cotton canopy and the cumulative daily thermal effects was studied with the assumption that other environmental factors were ideal. Thus, the comprehensive effects of other environmental factors were ignored, as well as differences in colored cotton varieties. Therefore, the applicability of this study’s model in a wider context requires further investigation and correction.

5. Conclusion

The cumulative daily relative thermal effect as the scale for the growth and development process in colored cotton excluded the effect of unsuitable temperatures. Plant height in the population was normally distributed, which reflects the uneven growth and development of plants in the field. In this study’s model, the vertical distribution shape function of the leaf area illustrated the heterogeneity of the vertical distribution of the leaf area space. Additionally, the leaf area density and cumulative leaf area index at different heights of the canopy were simulated more accurately during the growth and development period when on the scale of cumulative daily relative thermal effects. Moreover, the leaf inclination angle distribution of the colored cotton plant was comprehensively reflected by dividing the canopy into five layers following the Gaussian five-point method. In doing so, the leaf inclination angle distribution density of each layer using the ellipsoidal distribution function was simulated, and the leaf inclination angle distribution frequency using the integral leaf inclination angle distribution density function was also simulated with the ranges 0–15°, 15–30, 30–45°, 45–60°, 60–75°, and 75–90°. Results revealed that the simulated values correlated well with the measured values, verifying that the model has sound rationality and validity for use in the numerical simulation of colored cotton canopy parameters with great accuracy and practicability.

Conflict of Interest

The authors declare no conflict of interest.
Author Contributions

Zhenqi Fan conducted the research and wrote the paper; Lixin Zhang analyzed the data; Jingchao Fan gave comprehensive guidance; all authors had approved the final version.

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