Construction of the Morphological Structure Model of Overground Part of Naturally-Colored Cotton in Alaer Reclamation Area in Xinjiang

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Abstract: According to the main characteristics of naturally-colored cotton morphological structure, its topological structure is summed up into a combination of four kinds of metamer. The growth cycle is taken as the measure to use the automata and state transfer mechanisms to establish the order of occurrence of each metamer and the topology connection relationship between them, and the variation of the topological structure of the cotton plant at each discrete time point is shown. Studies have shown that the occurrence speed of the main stem metamer is 0.0225°$C^{-1}\cdot d^{-1}$, and the average growth cycle required for the emergence of the fruiting branch metamer is $i+2*j-3$ (i is the fruiting branch number, and j is the number of the fruiting branch metamer on the fruiting branch). At the same time, the growth of the internode organs in the metamer is expressed as a continuous function of the effective accumulated temperature after the occurrence of the metamer, and the geometric parameters of the leaf and cotton boll are correlated with its biomass, and a model combining the dispersion and the continuity is established to realize the continuous simulation of morphological structure of cotton plants. The root mean square errors (*RMSE*) of the simulation value and measured value of the length and diameter of the internodes of the main stem, the length of the internodes of the fruiting branches, the length and width of the leaves, and the diameter and length of the cotton bolls under the sample sizes of 40, 40, 40, 100, 100, 30, 30 are 1.16cm, 0.27cm, 1.05cm, 1.84cm, 3.06cm, 0.23cm, and 0.21cm, which can reflect the occurrence of the morphological structure of the cotton plants more accurately, laying the foundation for constructing the function-structure model of naturally-colored cotton.

Key words: Naturally-colored cotton, topological structure, geometric structure, morphological structure model.

1. Introduction

Naturally-colored cotton (hereinafter referred to as "Colored Cotton") is a general name for naturally grown, colored cotton, and is a new type of textile raw material. Its environmental protection and health characteristics can spare the bleaching and dyeing process of the cotton spinning industry with a very good energy-saving and emission-reduction effects, in line with the trend of protecting the ecological environment and pursuing low-carbon life [1]-[3]. The Alaer reclamation area of Xinjiang is located on the northern edge of the Taklimakan Desert, where the Aksu River and the Hetian River and the Yarkant River meet at the upper reaches of the Tarim River. The total area is 6,180 square kilometers. The effective accumulated temperature at or above 10°C is above 4000°C and the frost-free period is 220 days with an average daily sunshine of 9.5 hours from April to October and an annual sunshine of over 2900 hours. The unique natural conditions make Alaer Reclamation Area an important production base for China's colored cotton.

The plant structure of colored cotton has an important influence on the yield, but the traditional plant breeding method has a long experimental period and high cost, and is greatly affected by the natural environment. Generally, it takes a long time of cultivation to reach a more ideal form. With the continuous deepening of research on virtual crops, the plant of quantitative creation meeting specific requirements has become a possible way to solve the above problems. Alessia Perego *et al.* [4] designed a drought-tolerant ideal type of corn plant in the Lombardy plain region of northern Italy with a process-based ARMOSA model [5]; Suriharn [6] *et al.* used process-oriented CSM-CROPGRO-Peanut model [7], [8] to make a preliminary exploration of the ideal plant type of peanut; Sylvester-Bradley [9] *et al*. designed the ideal plant type for efficient use of resources for wheat in pluvial region in Southern Australia by integrating genetic and agronomic constraints. However, descriptions of Alessia Perego, Suriharn, and Sylvester-Bradley of plant is qualitative, but the crop's life activities are to some extent characterized by the interactions between crop morphology, physiological and ecological processes, and the environment. By realizing the parallel simulations of structures and functions, the growth process of crops can be more objectively and truly reflected. [10], [11] Therefore, establishing the function-structure model of crops is the key to using virtual crop technology to construct high-yield plant, and the morphological and structural model of crops is also a fundamental problem of researches on function-structure model. Therefore, the purpose of this study is to establish a discrete colored cotton topology in time, to analyze the continuous growth process of colored cotton organs in time, and to simulate the morphological characteristics of stems, branches, leaves and bud bolls of colored cotton plants, to establish a colored cotton morphological structure model combining the dispersion and the continuity, laying the foundation for constructing a colored cotton model based on function-structure mutual feedback.

2. Materials and Methods

2.1. Experimental Design

A field test had been conducted in the Alaer Reclamation Area from 2015 to 2017. The test variety was Xincai 4 and the soil was sandy loam. The plant spacing and row spacing were 12 cm and 30 cm, respectively. No water and fertilizer stress occurred in the field management. Samples were taken at seedling stage, budding boll stage, and boll opening stage of the colored cotton, and organ morphology and biomass were determined according to positions of leaf and node positions. Meteorological data were provided by the local weather station.

2.2. Research Methods

① Qualitatively observe cotton plants at different stages of growth, discriminate their growth patterns, and determine the overall framework of the morphological structure.

② Quantitatively determine the topological structure and geometric characteristics of cotton plants, statistically analyze the measured data, and extract the rules for the growth of morphological structures of cotton plants. Use root mean square error (*RMSE*) to measure the difference between simulation and measurement. The smaller the root mean square error value is, the closer the simulated value is to the measured value, and the more reliable the model is.

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

In (1), *RMSE* is the root mean square error, n is the sample size, S_i is the analog value, and F_i is the measured value.

③ Adopt visualization technology to dynamically display the morphological structure of cotton plants according to growth rules.

3. Cotton Morphological Structure Model

3.1. Occurrence Pattern of Colored Cotton Plant Structure

The crop growth process will experience distinctly different physiological stages, with one-way irreversible characteristics between the various physiological stages. Therefore, the physiological stage of crops can be regarded as the physiological age or growth order of crops. Organs with larger physiological age can only occur from organs whose physiological age is the same or smaller.

In order to refine the description of crop structure, Room, Hanan *et al.* [12]-[14] proposed the concept of structural units, and used the internode as the minimum topology unit in the crop model. Based on this, Zhao Xing, de Reffye Phylippe, Xiong Fanlun *et al.* [15] research showed that taking the mitogenetic unit of crops (collection of node, internode, and lateral organs on node (leaves, axillary buds, flowers, and fruits)) i.e the metamer as the minimum topology structural unit for constructing crop morphological structure model is more effective than using internodes, so in this study metamer is adopted as the basic scale of the colored cotton plant topological structure.

The experimental observations showed that there were 4 states of metamer of the colored cotton plants: ① State 1: physiological age is 1, without buds and lateral branches. ② State 2: physiological age is 1, with an axillary bud of a physiological age of 1, and this axillary bud will develop into a leaf branch similar to structure of the main stem. ③ State 3: physiological age is 1, with an axillary bud of a physiological age of 2, the axillary bud will develop fruiting branches. ④State 4: physiological age is 2, with an axillary bud of a physiological age of 2, and the axillary bud will develop into a new fruiting metamer. The first three states correspond to the physiological stages of the development of the main stem and the leaf branch of the colored cotton plants, and the State 4 corresponds to the physiological stage of fruiting branch development. "▮" indicates physiological age of 1, and "▯" indicates physiological age of 2. The four states of metamer are shown in Fig. 1.

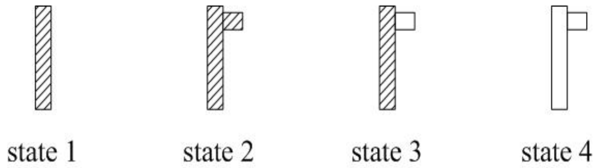

Fig. 1. Four metamer states of colored cotton plants.

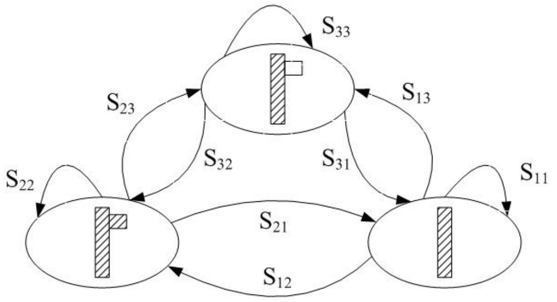

Fig. 2. The state transition of the metamer from the 5th to 7th node.

Through the observation of the fixed plants, the branches of the main stalks of the colored cotton are not branched from the first to fourth nodes, and the fruiting branches are generated from the eighth node and upper, there is no branch on the fruiting branch. The fruiting branches, leaf branches, or no branch may be generated at a certain probability from the fifth to the seventh node. The state transition of metamer from the 5th to 7th node is shown in Fig. 2.

After the statistics on the experimental data, the transition probability between states is:

$$S = \begin{vmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{vmatrix} = \begin{vmatrix} 0.22 & 0.39 & 0.39 \\ 0 & 0.34 & 0.66 \\ 0 & 0 & 1 \end{vmatrix} \tag{2}$$

By setting the number of self-loops of each state and the transition probability between the states, a random automaton model was established to achieve random changes in the topological structure during the growth of cotton plants, as shown in Fig. 3, which reflects the schematic diagrams of the topological structure of the cotton plant automatically generated in the 4th, 9th, and 13th growth periods, respectively(the interval between two adjacent metamers).

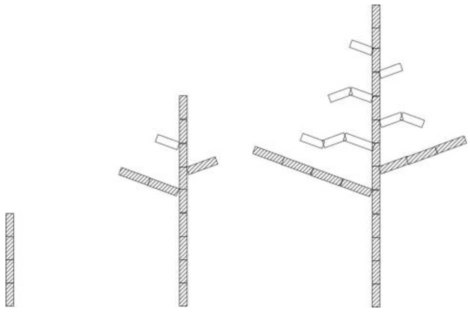

Fig. 3. Randomly generated topological structure of cotton plants at 4, 9 and 13 growth cycles.

3.2. Dynamic Growth Process of Colored Cotton Plants

In order to accurately describe the dynamic process of colored cotton growth, the production speed of metamers and the geometric expansion rules of each organ on the metamer should be determined on the basis of the occurrence pattern of cotton plant structure.

Temperature is one of the most important environmental factors affecting the growth of cotton. Under the condition without water and fertilizer stresses, it plays a key role in the development of cotton plants. During the day, the temperature changes, and experience shows that the growth of cotton plants is nearly stagnant below 12°C. Therefore, the SUM_{GDD}, the daily effective accumulative temperature GDD (Growing Degree Day in °C·d) is used to measure the dynamic growth of colored cotton plants.

$$GDD = \frac{T_1 + T_2}{2} - 12 \tag{3}$$

In (3), T_1 and T_2 are the highest temperature and the lowest temperature in a day, respectively.

$$SUM_{GDD} = \sum_{i=1}^{n} GDD_i \tag{4}$$

In (4), n is the number of days after emergence of colored cotton plants.

①The Speed of the Generation of Main Stem Metamers

The number of metamers was set to be 1 when the cotton plant just emerged. Analysis of the experimental data showed that the number of main stem metamers had a strong linear correlation with cumulative temperature SUM_{GDD} after seedlings' emergence, as shown in Fig. 4. The speed of the main stem metamer is 0.0225°$C^{-1}\cdot d^{-1}$ (the reciprocal 44.44°C·d is the accumulated temperature required for one growth cycle, i.e. the interval between two adjacent metamers). From this, it is possible to predict the number of $STEM_{metamer}$ (i.e. the number of growth cycles) of the main stem metamers at any accumulated temperature.

$$STEM_{metamer} = \lfloor 0.0225 * SUM_{GDD} + 1 \rfloor \tag{5}$$

"$\lfloor\ \rfloor$" in (5) means rounding down.

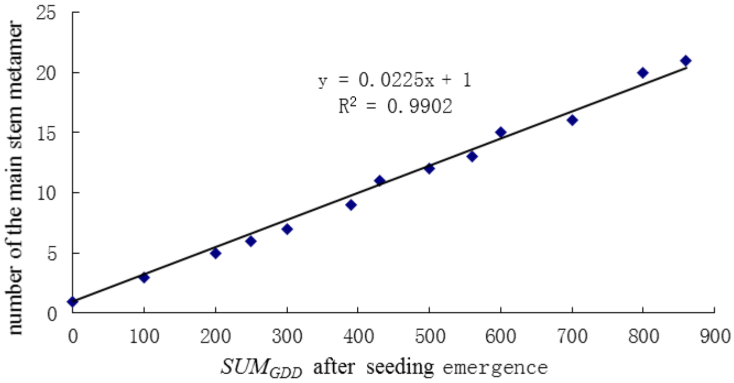

Fig. 4. Relationship between the number of main stem metamer and accumulated temperature.

②The Speed of the Generation of Fruiting Branch Metamers

Since no branch occurs from the first to fourth node of the main stem, and fruiting branches, leaf branches or no branch may occur from the 5th to 7th nodes. Therefore, the accumulated temperatures required for different cotton plants to produce the first fruit-bearing metamer are not the same. After the observation of the fixed plant, when the first fruiting metamer appears, the consequent generation of the metamers of fruiting branches has a stronger regularity: the interval between two adjacent metamers of the same fruiting branch is roughly 2 times the interval between two adjacent metamers on the main stem. The interval between the metamers of the same node of the two adjacent fruiting branches is approximately the same as the interval between the two adjacent metamers on the main stem, which can be described by (6).

$$F_{metamer}(i,j) = F_{metamer}(1,1) + 44.44 * (i + 2 * j - 3) \tag{6}$$

In (6), i is the fruiting branch number, j is the serial number of the metamer on the fruiting branch, and $F_{metamer}(i,j)$ is the accumulated temperature required for the appearance of the metamer of the j-th fruiting node on the i-th fruiting branch. $F_{metamer}(1,1)$ is the average accumulated temperature required for the first metamer of the first fruiting branch, and $F_{metamer}(1,1)$ is calculated as 269.19℃·d from the transition probabilities of the metamer state of (2) and the accumulated temperature required for a growth cycle as determined in Fig. 4. From (6), the number of average growth cycles $F_{GC}(i,j)$ required for the occurrence of the No.j metamer on No.i fruiting branch can be obtained.

$$F_{GC}(i,j) = i + 2 * j - 3 \tag{7}$$

③Geometrical Structure Parameters of Cotton Plant Organ

The length and diameter of the internodes of the main stem, the length of the internodes of the fruiting branches, the length and width of the leaves, and the diameter and length of the cotton boll are important geometric parameters of the cotton plant, and these parameters can be used to show the characteristics of geometric extension of the cotton plant.

The growth of the main stem consists of two parts. One is the differentiation of the node, i.e. the increase of the number of nodes, and the second is the elongation of the internode. According to field observations of fixed plants, the final internode length SNL_{maxi}(cm), final diameter SND_{maxi}(cm) and node order SNP_i at each node of the main stem obtained after data fitting conformed to the relationships of one variable quadratic curve, and every internode length of the main stem SNL_i(cm), the diameter SND_i(cm) and the effective accumulated temperature TA_i after the occurrence of the internode can be described by the logistic equation.

$$SNL_{\max i} = 1.98\times10^{-2} SNP_i^2 - 1.46\times10^{-1} SNP_i + 5.2136 \quad (R^2=0.9216) \tag{8}$$

$$SNL_i = SNL_{\max i}\frac{1}{1+e^{3.6581-0.0382TA_i}} \quad (R^2=0.9042) \tag{9}$$

$$SND_{\max i} = -5.19\times10^{-3} SNP_i^2 + 6.13\times10^{-2} SNP_i + 2.1373 \quad (R^2=0.8927) \tag{10}$$

$$SND_i = SND_{\max i}\frac{1}{1+e^{2.9014-0.0367TA_i}} \quad (R^2=0.8736) \tag{11}$$

The fruiting node length of each fruiting branch is greatly affected by the first fruiting node of the fruiting branch. The final length of the first fruiting node of each fruiting branch $FNL_{i,1max}$(cm) presents a relationship of one variable quadratic curve with the number i of the fruiting branch on the main stem. The final length of each fruiting node $FNL_{i,jmax}$ is linearly related to the fruiting node order j on the same fruiting branch, and the expansion pattern of fruiting node is the same as the internode of the main stem.

$$FNL_{i,1\max} = -0.568\times10^{-1} i^2 + 1.6813i + 3.5807 \quad (R^2=0.8915) \tag{12}$$

$$FNL_{i,j\max} = FNL_{i,1\max}(1.1302 - 0.1176j) \quad (R^2=0.8743) \tag{13}$$

After the fitting of the experimental data of the leaves, $Leaf\_L_{i,j}$(cm), the length of leaf at the i-th fruiting branch and the j-th fruiting branch node, has a power exponent relationship with $Leaf\_Q_{i,j}$(g), the biomass of the leaf, and the product of the leaf length and maximum width $Leaf\_W_{i,j}$(cm) is 1.54 times $Leaf\_A_{i,j}$(cm^2), the leaf area.

$$Leaf\_L_{i,j} = 12.601 Leaf\_Q_{i,j}{}^{0.2838} (R^2=0.8802) \tag{14}$$

$$Leaf\_W_{i,j} = \frac{1.54 Leaf\_A_{i,j}}{Leaf\_L_{i,j}} \quad (R^2=0.8617) \tag{15}$$

The shape of the cotton boll is approximately a cone, and $Boll\_D_{i,j}$ *(cm)* , the diameter of cotton boll at the i-th fruiting branch and the *j-th* fruiting branch internode, has a power exponent relationship with

$Boll\_Q_{i,j}$(g), the biomass of the cotton boll, and $Boll\_L_{i,j}$(cm), the length of cotton boll, has a linear relationship with $Boll\_D_{i,j}$.

$$Boll\_D_{i,j} = 2.268 Boll\_Q_{i,j}^{0.2621} \quad (R^2=0.8913) \tag{16}$$

$$Boll\_L_{i,j} = 1.385 Boll\_D_{i,j} + 0.0711 \quad (R^2=0.8926) \tag{17}$$

3.3. Visualization of Colored Cotton Morphological Structure Model

Based on the topological structure generation, combined with the geometric structure parameters, the size and position of each organ of cotton plants in different growth cycles can be calculated. The petioles of the leaves are approximately a cylinder, the leaves are represented as triadius leaves, and the cotton bolls are represented by cones. The shape, size, spatial coordinates, rotation transformation, lighting and material settings of the cotton plant organs are all achieved by calling OpenGL functions. The simulated display of colored cotton plants at different growth stages is shown in Fig. 5.

(a) Seedling Stage 1 (b) Seedling Stage 2

(c) Bud and Boll Period 1 (d) Bud and Boll Period 2

(e) Boll Opening Period 1 (f) Boll Opening Period 2

Fig. 5. Morphological structure of different growth stages of colored cotton.

4. Model Inspection and Discussion

The test data of 2016-2017 were used to test the structure and morphology of the constructed color cotton plants. The Root Mean Square Error (*RMSE*) between the measured value and the simulated value of the internode length and diameter of the main stem, internode length of fruiting branches, length and width of leaves, and length and diameter of cotton bolls were 1.16cm, 0.27cm, 1.05cm, 1.84cm, 3.06cm, 0.23cm, and 0.21cm respectively under this circumstances of sample size of 40, 40, 40, 100, 100, 30, and 30 respectively. The results showed that the simulation effect of the model on the morphological structure of colored cotton plants was generally good.

Temperature is one of the key factors affecting the growth and development of cotton. This model establishes the morphogenesis process of colored cotton plant organs by effective cumulative temperature accumulation, establishes the order of occurrence of each metamer and the topological connection between them by the growth cycle through automata and state transfer mechanisms, with a certain mechanism, and meanwhile the relationship between the biomass and the morphology of individual organs (leaves, bolls) are taken into account. The accuracy of the model compared to the previous cotton morphological structure model [16]-[19] is improved to some extent, because the accuracy of the morphological structure model determines the reliability of the function-structure model [20]-[23], the basis of this model will be beneficial to in-depth study of the function-structure model of colored cotton.

Colored cotton is a complex biosome whose internal growth and development mechanism is very complex. This model assumes that other environmental factors are in an ideal state. Only the effect of single environmental factor temperature on the growth and development of colored cotton was studied, i.e. the comprehensive effect of environmental factors on the growth of colored cotton was ignored, and the difference of color cotton varieties was not considered, so the applicability of the model in a wider context needs to be further tested and corrected.

5. Conclusion

The growth cycle was used as a measure to show the changes in the topological structure of colored cotton plants at various discrete time points, at the same time, through introduction of the cumulative daily effective accumulated temperature and association the geometrical dimension of the leaves and cotton bolls with their biomasses, the continuous growth simulation of the length and diameter of the main stem internodes, the length of the fruiting branch internodes, the length and width of the leaves, and the diameter and length of the cotton bolls were achieved. The experiments showed that the root mean square errors (RMSE) were 1.16cm(n=40), 0.27cm(n=40), 1.05cm(n=40), 1.84cm(n=100), 3.06cm(n=100), 0.23cm(n=30) and 0.21cm(n=30) respectively, effectively reflecting the morphological structure development of colored cotton.

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