Optimization of Intercropping Planting Distance Using an Exhaustive Algorithm and Functional-Structural Plant Model

Wei-long Ding, Li-feng Xu, Yang Liu, Meng-jie Jin, Jun Dong

Abstract—Intercropping distance research, traditional field experiments are time-consuming and tedious, and cannot be applied to quantitative interspecific distance quickly. Therefore it has become a big concern for researchers in this field to further reduce manual operation, and more automatically and quickly get the optimal planting distance. In this paper, an optimization algorithm was applied to the intercropping distance of maize/soybean, which was based on a maize/soybean functional-structural model. We first built a maize and a soybean morphology model. Then based on the morphology models of the two crops, a functional-structural model of intercropping maize/soybean was established. We used an exhaustive search algorithm to change the plant positions by small increments and computed the corresponding light interception. Thus we can find the optimal distance combination that maximizes the light interception. Our method provides new ideas about intercropping for scholars who study intercropping models, and also gives users a reasonable suggestion for intercropping planting.

Index Terms—functional-structural model, interplant, plant spacing, optimal design.

I. INTRODUCTION

Intercropping between crops has been a hot topic in both domestic and international researches. The distance between crops is one of the main factors that affect land utilization and overall yield. Therefore, a high utilization rate with appropriate planting distance has been a target. Two different crops grow on the same land can not only increase the output, but also reduce the amount of fertilizers and pesticides applied [1]. Thus, intercropping has been a concern of the domestic and foreign agricultural experts. In crop intercropping practice, the inappropriate intercropping often leads to the low output of single crop in interplanting mode [2]. In the past, researchers studied the distance of intercropping planting, mainly through field experiment. They used the different combinations of planting distances by field grown plants, then analyzed output of crops with different intercropping distance, thereby obtaining optimal spacing for experimental planting [3]. The Optimum planting distance obtained with this method can provide direction and reference value for the optimization of intercropping distance, but it is time-consuming and more manpower and material resources are needed, and the worst thing is its tedious measurement.

At present, many researchers in the world study crop intercropping models. Sonohat et al. [4], through the application of 3D digital technology, realize the digitization of canopy structure of a tall fescue and white clover intercropping system, and analyze the photos of intercropping canopy to estimate the light illumination distribution and light interception, to determine the dominant species of intercropping system with optical radiation competition. Barillot et al. [1] used analyzing and comparing a Gramineae/Leguminosae intercropping crop canopy in the horizontal and vertical directions of light illumination distribution, use the SIRASCA model to layer the light distribution in the vertical direction of the intercropping canopy, and compare it with 3D digital projection model, and then analyze the advantages and disadvantages of a turbid medium analogy. Tsubo et al. [5] based on the turbid medium analogy, according to the canopy’s geometry scale and angle, use a statistical methods in a radiative transfer model of maize/soybean intercropping system’s light interception, and validate by data. Cici et al. [6] earliest study the chickpea/Sonchus oleraceus inter-plantation using the plant functional structural model. This study can provide reference for the breeding of the chickpea. For the maize/soybean virtual modeling, Xu et al. [7] use a field test and studied maize and soybean growth developmental differences in different maize/soybean planting patterns, and accordingly constructed a production and distribution model for the biomass of the intercropping system. But this model does not construct a three-dimensional visualization model of interplanting crops. In the optimization of maize and soybean intercropping spacing, Zhu Xingtang et al. [3] through field experiment, optimize the planting distance of maize and soybean in a 1:2 interplanting mode, but this optimization process is very cumbersome, because it takes more than three months, and also uses 36 plots of land for the planting experiment. An optimization of maize/soybean intercropping spacing based on a plant functional-structural model is not found in relevant literature at present.

A function and structure model of plants can not only help us understand and study the operation of the plant system accurately, but can also deeply study the interaction between the...
three-dimensional morphological structure and physiological functions of plants based on specific plant morphology. Therefore using this model to study crop intercropping, we can further study crop growth under different environment or internal factors, and provide an intuitive basis for the effects of crop growth and development depending on changes in the external environment and on internal factors. Through combination with an effective optimization algorithm and a plant functional and structural model, we can simplify the design of planting distance, and obtain ideal distances automatically and rapidly. This study can provide some new design ideas for the spacing optimization in an interplanting mode, and can also provide the support to improve the intercropping yield and the land utilization rate, so it has practical and theoretical significance.

II. MODELING SHAPES OF MAIZE AND SOYBEAN

A. Morphological modeling of maize

The software called GroIMP [8,9] (Grammar-related Interactive Modeling Platform Growth) was used in this study. It is a modeling platform, based on Java and the tailored modeling language XL (eXtended L-system). The main functions of this platform are model building, 3D visualization of plant morphology and users interaction.

The morphological structure of maize is composed of stems without branches and alternating leaves. Since the stem is cylindrical, an internode was used as a unit in the model, and the stem consists of multiple connective internodes. The cylinder function provided by GroIMP was used to simulate the internodes. Maize leaves are bar-type, but obvious folds appear at their edges. So simulation of the leaves in this paper was achieved by controlling of feature points and forming triangle meshes using GroIMP polygon Mesh functions.

During the growth period of maize, the male tassels will appear at the top, and the female tassels will appear at the location of the 8th-11th internodes. In this paper, functions provided by GroIMP are also used to simulate the male tassels and the female tassels.

The shape of the female tassels is similar to a cylinder, but it is not regular. In this paper, a instantiation function Instance of GroIMP was used to simulate a female tassel by a curved surface. The male tassel is composed of tassel-stalk and grains. The simulation of the tassel-stalk was similar to that of the stem axis. And the simulation of grains was similar to the female tassels, using the instantiation function Instance from GroIMP to provide a curved surface for a grain. Finally, the grains were generated on the top of each internode of tassel-stalk, and grains are along the direction of tassel-stalks, thus we realize the simulation of the tassel.

By the analysis of the topology structure of maize, the initial graph structure topological of maize ω and rule set \{R1, R2, R3, R4, R5\} are determined, briefly described as:

\[ \omega: B(I) \]

\[ R1: B(i) (i<=maxRank) \rightarrow #(0) B(i+1) M(i, 1) \]

\[ R2: M(i, j) (i<=maxRank, j<=maxOrder) \rightarrow P(i, j) M(i, j+1) \]

\[ R3: P(i,j) (i<=maxRank, j<maxOrder) \rightarrow I(i, j) \& (180) L(i, j) \]

\[ R4: P(i, j) (i<=maxRank, j=maxOrder) \rightarrow P(i, j) \& \{ (i<=14 && i>=8) \rightarrow \text{probability}(\alpha) \text{Ec}(i, j) \} \]

\[ R5: P(i, j) (i<=maxRank, j=maxOrder) \rightarrow I(i, j) \text{E}(i) \]

where B is the base, M is the meristem, P is the growth unit, I is the internode, and J is the blade, e is the male tassel, Ec is the female tassel and the position of female tassel is considered by the condition, probability(α) is used to control the probability of the occurrence, \& (180) is used to control the alternate relation among maize leaves, #(0) is used to control the space angle of the branch, the parameters i and j represent respectively the stem number and the internode number, maxRank is the maximum number of single stem, and maxOrder is the maximum number of internodes. E is the male tassel. In the Windows 7 system, using the GroIMP platform and using Java language and XL language to realize the above methods, this paper establish the maize's morphological model, as shown in Fig.1.

Fig.1. A single maize’s morphology.

B. Morphological modeling of soybean

Soybean belongs to Fabales and Leguminos. Its morphology includes four main parts: stems, petioles, leaves, flowers (not considered in this study) and pods. The whole soybean plant is similar to a tree structure. Its height is commonly about 0.6 ~ 1 meters; its stems are stout and erect; its leaves are trifoliolate leaves, meaning that they are generally composed of 3 leaves circular or elliptic lanceolate shape; the flower is a bisexual butterfly type; the pod shape has oblong, pendulous, and slightly bend characteristics, with 2 to 5 seeds.

Soybean stems and petioles are similar to cylinders, so an internode was considered as an unit and the cylinder function provided by GroIMP was used to model the stems and petioles. The soybean leaf’s contour is oval or similar to a circular, so the simulation of the three-dimensional structure of the soybean uses the fitting function to generate the control points, and then utilize the Polygon Mesh function to draw the leaves. Pods are irregular surfaces, and the convex extent of the curved surface is determined by the number and size of the grains. In this paper we use pods with two gains to construct the pod model. The basic steps of drawing soybean pods are as follows:

Step 1: Extract the characteristic data of the soybean, analyze them with MATLAB, and build the trajectory equation for the soybean contour.

Step 2: Calculate the control points according to the trajectory equation of the pod.
Step 3: According to the contour length, the contour is divided into four parts, and the four 3D coordinates of the contour are extracted and used as the feature points of the section.

Step 4: Generate the control points according to the feature points and the height function of the contour section.

Step 5: The 3D coordinates of the section control points are put into the Bezier Curve function, and then draw the contour curve of the section.

Step 6: The contour curve of the boundary contour is combined with the contour curve of the section by using the NURBS curve, to draw the three-dimensional structure of pods.

Analyzing of the topological structure of soybean, the initial graphics structure $\omega$ of soybean generating structure and rule set \{R1, R2, R3, R4\} are as follows:

$\omega$: $B(l)$

R1: $B(i) (i<=maxRank) \rightarrow \#(0) B(i+1) M(i, 1)$

R2: $M(i, j) (i<=maxRank, j<=maxOrder) \rightarrow P(i, j) M(i, j+1)$

R3: $P(i, j) (i<=maxRank, j<=maxOrder) \rightarrow I(i, j) &\{180\} G(i, j)$

R4: $P(i, j) (i<=maxRank, j<=maxOrder) \rightarrow RL(i, j) &\{60\} \phi(60)$

$L_{ij}(i, j) \phi(180)_{ij} \phi(-60)_{ij} L_{ij}(i, j)$

where B is the base, m is the meristem, P is the growth unit, I is the internode, $L_{ij}$ is the leaf, G is the pod, &\{180\} is used to control the angle between soybean pod and stem, RL(a) is used to control the angle of stem and branches, $\phi(60)$ controls the 3 trifoliolate leaves, parameters i and j presents the tiller number and internode number, maxRank is the maximum number of single stem, and maxOrder is the maximum number of internodes. On the GroIMP platform, the model of soybean is established, as shown in Fig. 2.

Fig.2 A single soybean morphology.

In this section, according to the respective maize and soybean visualization simulations in the previous two sections, we consider the visualization of each maize or soybean plant as a thread, take advantage of the GroIMP parallel multi thread technology, to distribute the threads number of maize or soybean plants, and then start the threads of maize and soybean modeling at the same time, to construct the maize/soybean intercropping visualization model, as shown in Fig 6.

III. CONSTRUCTION OF MAIZE/SOYBEAN INTERCROPPING MODEL

The light interception of the plant leaves and other organs is an important factor of the photosynthesis of plants. In order to simulate the plant growth and describe the 3D morphology of a plant, calculation the light distribution in the plant canopy precisely is required. The light interceptions of single plant canopy can be obtained by the radiation model GroIMP platform \[8,9\]. The radiation model provided by the GroIMP platform can be used to calculate the light interception amount of each organ in the scene, and the light distribution in the plant is obtained. Because the characteristics of the plant’s canopy also influence the interception in the canopy, and based on algorithms within the GroIMP platform, the calculation of the interception in the radiation model is redesigned. The maize canopy is divided into two parts, the upper part which is the parts above the soybean plant, and the lower part with the rest. With the leaf area index of the upper and lower parts of the maize canopy, together with the unit area of the soybean calculated, radiation intensity of the upper and lower parts of the maize and the soybean canopies is calculated using the radiation. According to canopy radiation intensity, we can calculate the crops’ extinction coefficients \[10\] respectively. Then the light interception amount of the intercropping soybean and maize can also be calculated \[11\].

Through the calculation of light distribution in the canopy and single leaf photosynthesis efficiency, the available photosynthetic products from all leaves are collected to the CAP (Common Assimilate Pool) \[12\]. Photosynthetic product $P(t)$, which is produced by the current growth stage of soybeans or leaves, is dynamically added to CAP, and the assimilation substance CAP(t) in day t is:

$$\text{CAP}(t) = \text{CAP}(t-1) + P(t)$$  \hspace{1cm} (1)

Growth is based on the source-sink hypothesis and organ sink forcing the current assimilates distributed to various organs for growth and development. During growth cell cycle t, the sum of sink strength of each organ is added up. In the case of no material transport resistance, each growing organ obtains the assimilation product $G_c(t)$ from the pool through competition, according to their percentage of its own sink strength to the total sink strength \[15\]. Thus, the biomass amount $D_c(t)$ of organ O in growth cycle t is:

$$D_c(t) = D_c(t-1) + G_c(t)$$  \hspace{1cm} (2)

According to allometric relationships between the biomass increment of organ O in growth cycle t and plant’s 3D size, the diameter variation $M_o(t)$ of organ O is:

$$M_o(t) = G_c(t) \times \mu_o$$  \hspace{1cm} (3)

$\mu_o$ is the conversion factor between biomass and organ size \[13\].

The Fig.3 shows how to establish the growth process of maize/soybean intercropping patterns, and generate the virtual model of the maize/soybean intercropping. In this paper, one day was considered as the basic time unit for growth cycle. Maize/soybean plants grow once in each simulation step, and their intrinsic function and three-dimensional shape structure changes once. Therefore, the growth dynamics of the maize/soybean plant before the termination of the plant growth are simulated. The simulation steps are as follows:

Step 1: Based on the previous 3D morphology and structure of maize/soybean plant, the light interception amount of the leaves is calculated.

Step 2: All the leaves within the canopy produce photosynthesis using the intercepted light, photosynthetic products are added to their pool C.

Step 3: Calculate the sink strength of each organ, and obtain the biomass increment of each organ according to the calculation results.
Step 4: According to allometric relationships between the biomass increment of organ, calculate the size variation of each organ.
Step 5: According to the change of organ size, the morphology and structure of maize/soybean are updated.

**Fig.3. Flow chart of maize/soybean plant growth algorithm**

**IV. OPTIMIZATION PROCESS OF INTERCROSSING PLANTING DISTANCE**

Intercropping means that in the same period and the same field, two or even more crops are planted according to branch or alternated with zoning pattern. The interplanting mode is a mode that intercropping crops are planted in a certain proportion by branch or zoning model. There has been a great deal of maize and soybean intercropping pattern research in field trials. Based on the establishment of a maize/soybean intercropping function and structure model, the focus in this study is the interplanting pattern with ratio 2:3, to study the intercropping and compact planting, as shown in Fig.4. The vertical distance between maize and soybeans, soybean and soybean is defined as inter distance $D_{\text{inter}}$, the horizontal distance between maize and maize, soybean and soybean is defined as space distance $D_{\text{space}}$.

**Fig.4 The 2:3 maize/soybean intercropping pattern (● represents the maize, the other one represents the soybean, inside the dotted line is the calculation region).**

In our algorithms, more light interception is the optimization target. Through continuous iteration of interplanting distance, corn population spacing and soybean population spacing, the best distance combination which maximum light interception would be obtained from the specific threshold range. The description of the algorithm is as follows:

Step 1: Construct the maize/soybean intercropping population function-structure model;
Step 2: in the specified intercropping ratio, initialize population $P$, inter distance $D_{\text{inter}}$ and space distance $D_{\text{space}}$;
Step 3: Determine the inter and space distance’s threshold, and calculate the maximum iteration number;
Step 4: Change the inter distance $D_{\text{inter}-i}$, determine whether the changed inter distance $D_{\text{inter}-i}$ is in the intra-domain of the inter distance. If it is true, execute Step 5, otherwise jump to step 6;
Step 5: Change the space distance $D_{\text{space}-i}$, determine whether the changed space distance $D_{\text{space}-i}$ is in the intra-domain of the inter distance. If it is true, store the $D_{\text{space}-i}$ and the light interception $par_i$ at $D_{\text{space}-i}$ into the register, otherwise execute step 4;
Step 6: Sort all the $par_i$ in the register and receive the maximum $par_{max}$, the output the corresponding $D_{\text{inter}}$ and $D_{\text{space}}$, the distance combination is regarded as the best distance.

**V. EXPERIMENT RESULTS AND DISCUSSION**

In Windows 7 operation system, we used GroIMP as the modelling platform and XL together with Java as the programming languages to establish the maize/soybean intercropping function-structure model and realize the methodology. The hardware configurations for the experiments are Intel(R) Core(TM) 2 Duo i5 2.66 GHz CPU, 2 GB memory, NVIDIA GeForce 610 graphics card.

In the experiments, the ratio 2:3 was used as maize/soybean intercropping mode for planting distance optimization. Furthermore, the interplanting space distances, the inter distance of maize and soybean population is within the range [50cm, 60cm], and the simulated intercropping population was with 10 columns. After 3240 minutes running for growth, within the domain of $D_{\text{inter}}$ and $D_{\text{space}}$, the optimal planting distance combination for optimized light interception can be calculated simulating unit land area, shown in Table 1. The change of light interception quantity in 120 days’ growth process of initial plants and optimal plants are shown in Fig.5. After 110 days, the light interception is basically stable. The light interception before optimization was 7416 mol$m^{-2}$d$^{-1}$, while after...
optimization is $9424 \text{ mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, which is about 1.27 times more. Fig. 6 shows the visualization simulation results of the soybean/maize population.

**Table 1: The optimal planting distance of maize/soybean intercropping in the ratio 2:3**

<table>
<thead>
<tr>
<th>planting distance</th>
<th>optimal distance (cm)</th>
<th>initial distance (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{\text{int}}$</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>$D_{\text{maize space}}$</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>$D_{\text{soybean space}}$</td>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>

Based on the constructed maize/soybean functional-structural model, the planting distance in a specified maize/soybean interplanting mode was optimized, and the optimum planting distance combination was obtained. Compared with the field tests, we can quickly get the optimum planting distance combination in the specified domain and intercropping pattern. The field test data in the paper for interplanting functional-structural model is from Xu et al. [7], and Qiu et al [13]. From Xu’s work, the biomass within the 2:3 maize/soybean intercropping mode is basically the same with the biomass output by our maize/soybean intercropping model. However, in this paper, the light interception amount in the unit land is considered as the only optimization target, and in practice, even when the amount light interception is maximum, the output of crops is not necessarily the largest, because the amount of output is not only influenced by the intercepted light, but also by the climate condition, the content of the soil nutrient element and the carbon dioxide concentration etc.

However, the output of crops and the amount of light interception have a positive correlation [14]. Therefore, in this paper the canopy light interception amount is considered as the optimization target with certain theoretical support and evidence.

**VI. CONCLUSIONS**

In this paper, by improving the calculation method of the light interception, and using the calculation method for assimilation product and change of organ size, we constructed the maize/soybean intercropping function-structure model, and realized the optimization of intercropping planting distance using an exhaustive search algorithm based on the maize/soybean intercropping function-structure model. Experiment results show that the distance optimization based on the maize/soybean intercropping function-structure model can automatically and quickly calculate the distance combination of maximum light interception in a specified domain. In view of the fact that the optimization algorithm of planting distance specifies the pattern and the planting distance change domain, we still need to explore more suitable optimization algorithm for intercropping planting distance, especially the optimization algorithm without a specified domain.

**REFERENCES**


