Monte Carlo Simulation of Solar Radiation in Maize Canopies and its Visualization

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Abstract: - The spatial distribution of solar radiation casts important influences on eco-physiological functions of plant canopies. A simulation model of the three-dimensional of direct and indirect solar radiation in real maize canopies is developed from measured 3D canopy structure meshes. The model includes two procedures: parallel direct light pass and diffusive indirect radiation pass. The former one is based on Monte Carlo ray tracing algorithm. After enough ray casting, the radiation is obtained. Then, the diffusive indirect radiation pass uses a modified Monte Carlo Radiosity model to evaluate the diffusion distribution. Results indicate that simulated sun fleck ratio is significantly consistent with measured date set.

Key-Words: - plant canopy, three-dimensional distribution, ray tracing, radiosity, Monte Carlo algorithm

1 Introduction

The solar radiation is the basic energy input of the plant to carry on each physiological activity. Its distribution in the plant canopies has important influence to the photosynthesis product production and the accumulation of the plant, the moisture content transpiration, as well as the growth process. Therefore, it becomes one of the most basic and important contents of the plant physiology ecology process, the crops optimization and the crops growth mode to study the model of the spatial distribution and dissemination of the solar radiation in the plant canopies[1-5]

Along with the thorough research of the plant structure and the physiological function,more and more request about the spatial distribution condition of the solar radiation in the plant canopies has been brought forward. The traditional plant canopies mostly model bases on the one-dimensional or two-dimensional spatial distribution. The corresponding solar radiation algorithm is the simpler statistical model. Its computation result has already could not satisfied the need of the simulate model of the three dimensional plant and the three dimensional radiation transmission model of remote sensing.

In recent years, the ray tracing algorithm[11-13] based on the geometric optics and the radiosity algorithm[14-16] based on the energy balance equation which have made important progress. In these algorithms, the object surface is divided into a mass of triangle elements. The radiant energy which comes from the radiant point, achieves the stable state of the three dimensional distribution after several diffusion. Using both the Monte Carlo and the Binary Space Partition algorithm, it can solve the stable state distribution within the complexity of $O(n \log n)$ on condition that the variance is smaller than the random assigned error boundary.

This article which is on the foundation of the three-dimensional structure in real maize canopies model, based on the principle of the ray transmits in straight line, has realized in the solution of the direct solar radiation intensity model in the 3D space of the plant canopies through tracking the solar parallel ray from the canopies. Then it regards the direct radiation distribution as the initial condition to solve the indirect radiation distribution of the plant canopies in the three-dimensional space by the Monte Carlo radiosity algorithm. It has made visualization and the analysis to the direct and indirect radiation distribution of the simulative computation. And unified with the practical measured data, it has validated the direct radiation distribution obtained by simulation.

2 Methods and Material

2.1 The outline of the Ray Tracing algorithm

The massive parallel solar ray enters the plant canopies and their diffusion result will determine the spatial distribution of the direct solar radiation. After that, the ray carries on subsequent reflection/refraction between the leaves, which will decide the indirect solar radiation distribution. Therefore, the algorithm which can get the intersection of the straight ray diffuse and the canopy triangle element becomes the foundation of this model.

The model used to describe the data structure of the ray is similar to the ray definition in the geometric optics [6-8,11]. In fact it contains two 3D vectors – the initial point o and the emit direction d - as well as the three elements group data structure of the scatter energy p. When the ray hits the nearest triangle element, it then sends its energy p to the triangle element. The Fig-1 shows the incidence of the parallel ray in plant canopies in the 3D space.

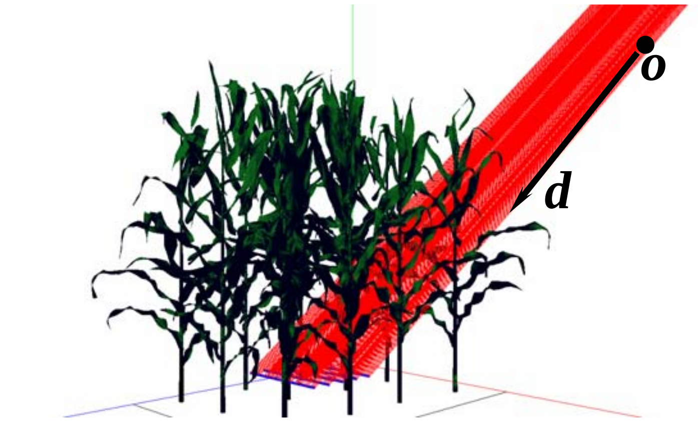


Fig-1 1 the map of the incidence of the parallel ray in 3D maize canopies

This research uses the Binary Space Partition Tree with the recursion structure to organize all the triangle elements[11,12].The basic idea of the Binary Space Partition Tree is to divide the father space into two sub cuboid spaces which are not intersect each other by each administrative level unceasingly, until each sub space contains no more than 1 triangle element. So it can reduce times which should be used to solute the intersection of the triangle and the ray. Because when the cuboid surrounding box of some sub space does not intersect with the ray, there is no need to solve the intersection of any triangle element in the space and the ray. Both theoretical analysis and the experience indicate that the complexity is O(log n) to trace one ray in this way, and it's an important way to accelerate the simulate computation[7,8,10,14].

2.2 The Monte Carlo radiosity model of direct radiation

The direction of the parallel solar ray which is incidence in the top of the canopy is determined by the solar Altitudinal angle and the azimuth Angle. If a base plane is set on the top of the canopies which is parallel to the ground, the solar ray will evenly penetrate this plane. In reverse, it may also extract the even distribution point from this base plane as the beginning point of the ray, and take the direction of the sunlight as the diffuse direction to transmit the ray. All the rays from the base plane will become the incidence ray of the canopies. By tracking these rays and transferring their energy to the triangle elements which have been hit, it can solve the direct solar radiation distribution in the canopies. In practice, it produces the solar ray in each grid by dividing the base plane into even grids according to the even distribution. The number of the grid will be obtained by the gradually auto-adapted of the error control. when the given relative error boundary is 0.001, the grid size can make 0.15 cm×0.15 cm to carry on the projection. In order to maintain the energy conservation in the simulation as well as the simulate ray enters the actual territory from the other neighboring canopy units, it adopts the duplicate territory algorithm which duplicates the same structure of the canopies around the actual measured Regional [7,13].

2.3 The Monte Carlo radiosity model of indirect radiation

After the radiant energy of the parallel solar ray enters the canopies, it will carries through many reflection and refraction. And this process is called the indirect radiation[13,15]. The indirect radiation will redistribute a part of the energy in the canopies. Concretely speaking, part of the energy will shift between the different lamina or/and the different plant, but some others will possibly be reflected out of the canopies. If the energy of each bin is considered as an unknown vector, then all the energy of the triangle elements will constitute a system of linear equations. Suppose that the optics attribute of each bin i is the Lambert system with each item of the same nature, then we will obtain the following linear fundamental equation[9-11]:

$$B_i = E_i + (\rho_i + \sigma_j)\sum_{j=1}^{n} B_j F_{ji} \qquad (1)$$

B_i is the radiation of bin i, E_i is the out intensity of bin i, F_{ji} is the shape factor between the bin j and i, namely the ratio of the energy which leaves bin j to bin i, ρ_i is the reflectivity of bin i, σ_i is the transmission/refractive index of bin i, n is the total number of the bin. the E_i here is the direct solar radiation which the triangle element receives. The formula (1) of all the bins will composes the following system of linear equations[9-11]:

$$\begin{bmatrix} 1 & -\rho_1 F_{12} - \sigma_1 F_{12} & \cdots & -\rho_1 F_{1n} - \sigma_1 F_{1n} \\ -\rho_2 F_{21} - \sigma_2 F_{21} & 1 & \cdots & -\rho_2 F_{2n} - \sigma_2 F_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ -\rho_n F_{2n} - \sigma_n F_{n1} & -\rho_n F_{n2} - \sigma_n F_{n2} & \cdots & 1 \end{bmatrix} \qquad (2)$$

In order to overcome the above difficulties, the model uses the Monte Carlo Ray Tracing method to simulate the indirect radiation physical process directly, instead of the definite iteration method. Its basic process is: Scatter the energy of the bin, and emit the ray by the cosine distribution to the spatial direction randomly; the bin which has been hit will obtain the energy which the ray carries on; the energy of the bins which are not hit by the ray will escapes the system; Circulates this process until the surplus radiant energy left little enough.

according to the physics significance, the algorithm has reappeared the radiate transmission process by the stochastic testing way: The incidence energy repeated the reflection and refraction between the triangle elements according to the Lambertian system. And because of the $\rho_i + \sigma_i < 1.0$, the total energy in the transmission weakens unceasingly until nothing left, which makes sure the convergence to the iteration solution.

In summary, regarding to the randomly given error boundaryε, the algorithm only needs a time complexity of $O(n \log n)$ to be constringency [16,20], and its spatial complexity is only $O(n)$. Because the time and spatial complexity are higher than the traditional definite solution, they specially suit to solve the complex indirect radiation question of the canopies.

2.4 Field testing and The data pretreatment

2.4.1 The testing field and actual measured region

In order to get the 3D data of the maize canopies and validate the veracity of the algorithm, it has used the 3D structure data of the maize canopies and the vertical distribution data of the perpendicular incidence illumination facula which have been collected. This experiment was carried on the experiment fields of the science park belonged to the China Agricultural University. There are two kinds of density processing methods to deal with the maize, the row spacing of the sparse density plant condition is 60 cm×60 cm, and of the conventional density plant condition is 30 cm×60 cm, but both row directions are north and south. In the metaphase of the maize grouting, it has successively carried on the intensity mensuration of the Photosynthesis Active Radiation (PAR) and the 3D coordinates mensuration to the canopies. At this time, the form and the spatial distribution of each organic in the plant are never changed.

Choose the representative plots in the experiment fields as the actual measured field. The sparse density plant condition includes 12 (3 ×4 lines) maize, and the routine density plant condition includes 20 (5 ×4 lines) maize. Partition the triangle elements and collect the 3D coordinates of all the plant organs on the actual measured territory, and make them as the space model of the simulate computation to carry on in this article.

In order to obtain the 3D structure data of all the plants in the actual measured field, it used the Fastrak three dimensional digitization meter (American Polhemus Corporation) to measure the 3D coordinates of the outline of the leaf and other organs. Measure at the bottom of the plant to make sure where is the plant position in the actual measured field. The world coordinate system uses the right-handed coordinate system, the positive direction of X is south, Y axial is zenith ward, and Z axial is west. The zero point is in the northeast corner of the actual measured field.

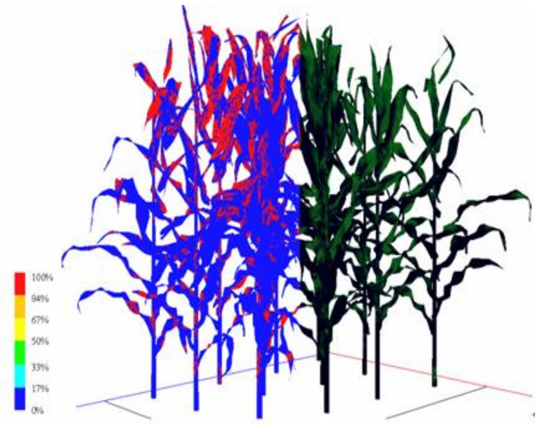
2.4.2 The division of the triangle elements in the canopies

The surface of the plant is divided into a lot of consecutive triangle elements by using the measured 3D space coordinates of the maize organ. The maize canopies model obtained under the sparse density plant condition contains about 200,000 triangle elements, but about 300,000 under the routine density plant condition. Thereupon, the question of how to get the direct solar radiation 3D distribution in the plant canopies, transforms to solve the distribution of the solar radiation in the triangle elements. For the concrete rule of the triangle elements production, please refer to [14, 16].

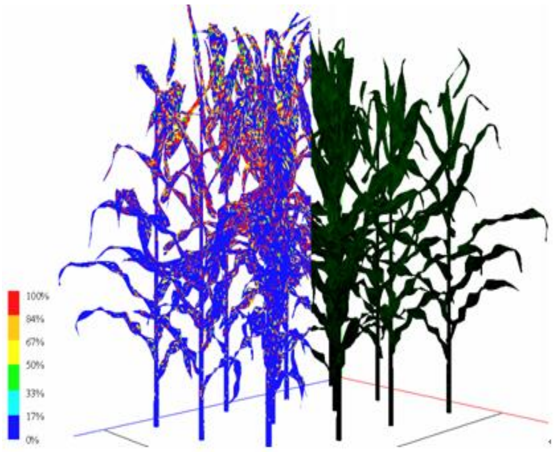
3 The results of the simulation and Its Visualization

With a solar position which is given at random, it can calculate the spatial distribution of the direct and indirect ray radiation in the actual measured territory of the entire canopy using the model above. Concretely speaking, it can calculate the facula and shadow distribution as well as the precise radiation intensity of all the plant surfaces and the triangle elements of any height according to the optical quality of the plant leaf and the 3D space model. The computational procedure will export it as the data file or as an image romanced by the OpenGL. The simulate result can be adjusted through the hue - energy adjustment[7], and directly realize the 3D visualization. The visualized result of the direct and indirect solar ray and the radiation intensity in the sparsely plant maize canopies on 2002-8-8 10:10 is given below by the radiant intensity – color rank chart and the radiation intensity - hue mapping chart. Set the size of the direct radiation ray grid 0.15 cm×0.15cm, and the error boundary of the indirect radiation computation 0.003. When the PAR wave band simulation is carried on, unified set the ρ=0.12, σ=0.06 of the leaf, and the ρ=0.15[22, 23] of the soil surface layer.

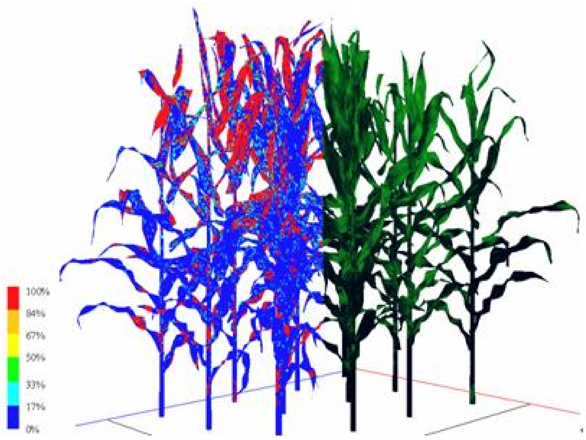
In the radiation intensity - color rank chart, according to the relative illumination strength rank which received by the triangle surface, it used 5 kinds of discrete colors to draw the 3D canopies. But in the radiation intensity - hue mapping chart, it used the logarithmic mean hue mapping method commonly used the in the computer graphics for drawing[8]. The logarithmic mean hue mapping method is based on the ratio of the illumination intensity of the triangle elements and the logarithmic mean value of all the triangle elements, as well as the reflection ratio of the triangle elements on the red, green and blue bands to display the color value. The color rank chart is advantageous for the direct-viewing demonstration of the energy intensity distribution in the space. But the hue mapping chart approaches to the camera's imaging process, and the pictures formed even more conform to the people's visual custom. The following color graph 2-1, 2-2 and the left side of 2-3 is the color rank chart, and the hue mapping chart is on the right. In the graph, it used red, green and blue color to draw the X axis, Y axis and Z axis in the coordinate system. The black line at the bottom of the canopies represents the boundary of the actual measured field.



Graph 2-1 The color rank chart and the hue mapping chart of the direct solar ray radiation intensity in the sparsely plant maize canopies



Graph 2-2 The color rank chart and the hue mapping chart of the indirect solar ray radiation intensity in the sparsely plant maize canopies



Graph 2-3 The color rank chart and the hue mapping chart of the total solar ray radiation intensity in the sparsely plant maize canopies

4 Discussion

The application of this model shows that all of the canopy structures which have been measured and established the triangle grid data, can carry on the radiate simulation and be visualized. The model can provide the accurate basis for the radiation distribution rule of any kind of plant canopies in each layer apiece, thus provides the quantitative data support for the plant shape of the plant production and the optimized design of the community structure. As use of the Binary Space Partition and the Monte Carlo algorithm, its computation complexity is remarkably lower than the corresponding definite algorithm[17-19].

Because of the shortcoming of the 3D accurate mensuration technology, the model is confined to be validated. But the model is based on the geometrics optics law, the probability statistics principle and the computational mathematics theory. All its computation precision, controllability and the repeatability surpass the actual measuring technique [20].Therefore, the simulate result may make up the insufficiency of the actual measure, and it is an effective method for the research of the ray radiation of the plant canopies in the 3D space.

Except the solar ray, the outside radiation which enters the plant canopy, also include the scattered radiation from the entire sky hemisphere. If regards the sky hemisphere as a spherical lamp-house of big radius, then the radiation intensity obtained by the CIE formula can separate it into a series of triangles surface lamp-house. Then combined with the emission of the Monte Carlo ray and the ray tracing, and used the similar randomization radiation computation model, it will be allowed to solve the sky scatter and radiation distribution in the canopies question.

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