

Research Article

The Dynamic Simulation of Distribution Regularity of Solar Radiation in the Individual Tomato Plant inside the Chinese Solar Greenhouse

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Abstract: In order to study the radiation regularity of the individual plant inside the Chinese solar greenhouse, the model of plant projection which is based on the geometric structure of tomato is established. In this model, parameters such as, geographic locations, seasons, growing and temporal variations were considered. It has been found that the imitative effect from 10 o'clock to 14 o'clock is better which is based on the error analysis and root-mean-square error detection of different days. Observed values and simulation values in the experimental field from March 28th to April 29th are analyzed by root-Mean-Square Error detection and the RMSE value of azimuth is 1.58 and the RMSE value of plant projected length is 3.38. The model established by this experiment could directly response the distribution regularity of solar radiation in the individual plant inside the Chinese solar greenhouse tomato and the model could provide reference for the solar radiation within the plant population of tomato.

Keywords: Distribution regularity, dynamic simulation, greenhouse, tomato

INTRODUCTION

Solar radiation is one of the most important environmental factors for the yield of tomato inside the Chinese solar greenhouse which is received the energy mainly from the sun (Sun and Chen, 2003; Yang *et al.*, 2009). However, the solar radiation received by plants inside the greenhouse is affected by geographic location of the greenhouse, structure of the greenhouse, planting period, plant growth and plant configuration.

To find out the mechanism of the solar radiation distribution and the effect on some plants inside greenhouse, models were made by some researchers (Sarlikioti *et al.*, 2011; Yuan *et al.*, 2012). A three dimensional reconstruction of maize canopy was established by using ral quadratic equations (Guo and Li, 1999). Considering the direct solar radiation on the maize canopy, a maize canopy model was established. There are also some 3D visual models of canopy on rice by using the visualization of wheatear by L-system (Meng *et al.*, 2005). Models including the photosynthetic rate difference and leaf-age were also established (Li and Geng, 2009).

However, there are few models including parameters (Wu *et al.*, 2009; Shi *et al.*, 2005) such as, geographic location of greenhouse, seasons, growing and temporal variations together with the solar radiation of individual plant. In this study, the relevant parameter of the Sun's orbit visual motion was calculated first and a geometric model of the individual tomato plant was established. To validate the precision of the model, the

field measurement was also made. At last, the effect of factors in the model was also discussed.

MATERIALS AND METHODS

Field planting of tomato is taken in the 29th greenhouse of College of Horticulture of Shenyang Agricultural University on March 20, 2012 using pot cultivation. The variety of the tomato is a cold-sensitive type and the cultivation type is infinite growth. The type of greenhouse is the Chinese solar greenhouse. The geographic coordinate is 123.56° east longitude and 41.58° north latitude. The data are measured on March 28 to April 29, 2012. The interval is 1 h from 8 o'clock to 16 o'clock and 9 sets of data are acquired, every set is measured 3 times for averaging. The length and width of the individual plant of solar greenhouse tomato is measured by tape and white board and the projection azimuth is measured by geologic compass.

Methods:

- The calculation of relevant parameter of the Sun's orbit visual motion:
- The calculation of declination of sun:

$$\delta = 0.3723 + 23.2567\sin\theta + 0.1149\sin 2\theta - 0.1712\sin(1) \\ 3\theta - 0.758\cos\theta + 0.3656\cos 2\theta + 0.0201\cos 3\theta$$

$$\theta = 2\pi(N - N_0) / 365.2422 \quad (2)$$

N stands for day which is the order number in a year (N equal to 1 when the data is January 1):

$$N_0 = 79.6764 + 0.2422 \times (\text{year} - 1985) - INT[(\text{year} - 1985) / 4] \quad (3)$$

- The calculation of solar altitude (α):

$$\sin \alpha = \cos L \cos \delta \cos \tau + \sin L \sin \delta \quad (4)$$

L stands for northerly latitudes; τ stands for true solar hour angle:

$$\tau = (S_0 - 12) \times 15^\circ \quad (5)$$

S_0 stands for apparent solar time.

Mean solar time which is local time can be figured up by true solar time:

$$S_0 = S_d + E_t / 60 \quad (6)$$

S_d stands for local time, its unit is hour; E_t stands for time difference, its unit is minute:

$$S_d = S + \{F - [120^\circ - (JD + JF / 60)] \times 4\} / 60 \quad (7)$$

S = Beijing time, its unit is hour

F = Beijing time, its unit is minute

JD = Longitude

JF = Latitude

The movement of true sun contributes to the variation of time difference and has no relationship with the location. The expression of time difference is:

$$E_t = 0.0028 - 1.9857 \sin \theta + 9.9059 \sin 2\theta - 7.0924 \cos \theta - 0.6882 \cos 2\theta \quad (8)$$

- The calculation of solar azimuth (A°):

$$\cos A_0 = (\sin \alpha \sin L - \sin \delta) / \cos \alpha \cos L \quad (9)$$

There is no difference between the three expressions quoted by this experiment and the expressions quoted by ordinary books. Its advantage is that it makes a distinction between the common year and the leap year and eliminates the cumulative effect of calculated value grown progressively due to the leap year. These expressions differentiate different geographic locations and different time. And they have year correction, longitude correction time correction.

- The calculation of projected length (h):

$$h = M / \tan \alpha \quad (10)$$

h = The projected length of individual plant of tomato

M = The plant height of individual plant of tomato

ANALYSIS METHODS

- **The establishment of plant morphology:** The establishment of the model of plant projection is based on the geometric structure of tomato. The type of this experimental material is vigorous growth. The lignified stem height at the base of tomato is 0.5 to 1.5 m. The flower of the vigorous growth is produced terminally at the 7 to 9th lamina of main stem and the main stem is being replaced by the adjacent lateral bud. Then inflorescences inserted on every 2 to 3 laminae. The lateral bud under the inflorescence keeps on growing and forms lamina and inflorescence alternately. The morphology of tomato is fit to the geometrical coin feature. So the cone is chosen to imitate the plant morphology of tomato (Fig. 1).
- **The establishment of the plant projection coordinates system:**
 - The horizontal projection of plant is drawn and all physical quantities are marked

α stands for solar altitude, A_0 stands for the projection azimuth of plant, M stands for plant height, F stands for plant width, c_1 stands for the vertical distance between the growing tip of the plant and the largest plant width, c_2 stands for the vertical distance between the largest plant width and the first leaf, c_3 stands for

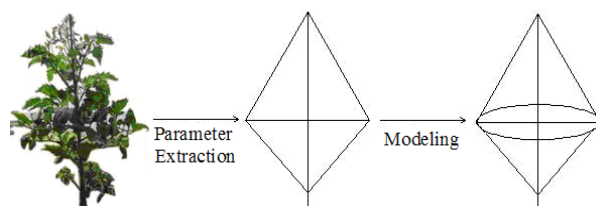


Fig. 1: The establishment of plant morphology of tomato

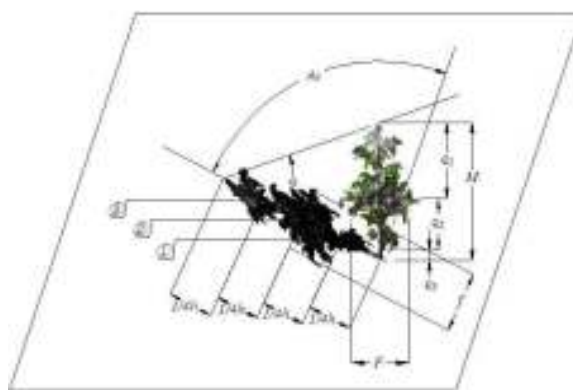


Fig. 2: The diagram of the physical quantities of tomato plant the plant is modeled and rectangular coordinate system is established

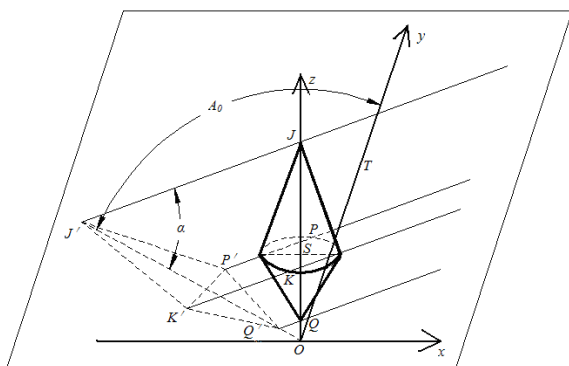


Fig. 3: The establishment of the plant rectangular coordinates system

the vertical distance between the stem base and the first leaf, h stands for the projected length of plant, f stands for projection breadth and (1) (2) (3) points are in the 4 equal-part points (Fig. 2).

The rectangular coordinate is built that due east is going to be along the x-axis, due south is going to be along the y-axis (Fig. 3) and the points of plant is labeled. Point J stands for the highest growing point, point K and point P stand for the positions of the maximum plant width. Point Q stands for the position of the first leaf, point J', point K', point P' and point Q' are the projective point of J, K, P and Q. Point S is located in the axis of plant and point S, point K and point Pare in one plan. Point T is on the positive axis of y.

The coordinates of every point coordinate:

$JO = M, J'O = m, KP = F, K'P' = f, JS = c_1, SQ = c_2, QO = c_3, \angle JJ'O = \alpha, \angle J'OT = A_0, h = M \cdot \cot \alpha$
Point J:

$$x_J = 0, y_J = 0, z_J = M$$

Point J':

$$x_{J'} = -M \cot \alpha \sin A_0, y_{J'} = -M \cot \alpha \cos A_0, z_{J'} = 0$$

Point Q:

$$x_Q = 0, y_Q = 0, z_Q = c_3$$

Point Q':

$$x_{Q'} = -c_3 \cot \alpha \sin A_0, y_{Q'} = c_3 \cot \alpha \cos A_0, z_{Q'} = 0$$

Point K':

$$x_{K'} = -(c_2 + c_3) \cot \alpha \sin A_0 - \frac{f}{2} \cos A_0, y_{K'} = (c_2 + c_3) \cot \alpha \sin A_0 - \frac{f}{2} \cos A_0, z_{K'} = 0$$

Point P':

$$x_{P'} = -(c_2 + c_3) \cot \alpha \sin A_0 + \frac{f}{2} \cos A_0, y_{P'} = (c_2 + c_3) \cot \alpha \sin A_0 + \frac{f}{2} \cos A_0, z_{P'} = 0$$

RESULTS AND DISCUSSION

- The projection rule of plant whose plant height and plant width are the same is simulated in different dates. The projection azimuth and plant projection area are affected by solar altitude and solar azimuth. The simulations of the plants whose plant height is 0.409 m and plant width is 0.403 m in March 28th, April 13th and April 29th are shown in Fig. 4.
- The projection rules of plant whose plant height are different are simulated in the same date. The projected length, projection breadth and projection azimuth are different as for the different plant heights and plant widths with the same solar altitude and solar azimuth at a given time. The simulations of the plants whose plant heights are 0.409, 0.684 and 0.927 and plant widths are 0.403, 0.562 and 0.592 m, respectively in March 28th are shown in Fig. 5.

The projected shape and projected area of the individual tomato plant are decided by itself plant morphology and solar altitude. The higher the plant height is and the wider the plant width is, the larger the projected area is. The wider solar altitude is, the closer projection of the growing point is to the base of the plant, the smaller the projected area is and the longer the sun path through plant canopy is. The movement path of plant projection shapes length limited change rules of a butterfly arc belt with the change of solar altitude. And it moved southward from March 28th to April 29th.

- **The comparison between the actual measurement and the model simulation rule of the plant projection:** The actual measurement and the model simulation rule of the plant projection are compared. The imitative effect from 10 o'clock to 14 o'clock is better than that from 8 o'clock to 10 o'clock and 14 o'clock to 16 o'clock based on the error analysis and root-mean-square error detection of different time (Fig. 6).
- **The model test of the individual tomato plant:** The conformity between the value of simulation and observed value is analyzed by root-mean-square error detection which is the common statistical method when the model is tested. The smaller the RMSE is, the consistency of the value of simulation and measured value is and the more precise the simulated result is. So, the predictability of model simulation value is better mirrored by RMSE, the equation is:

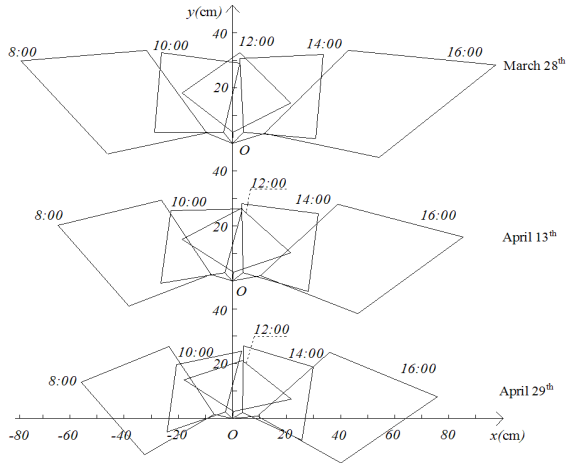


Fig. 4: The simulations of the plants whose plant height is 0.409 m and plant width is 0.403 m in different dates

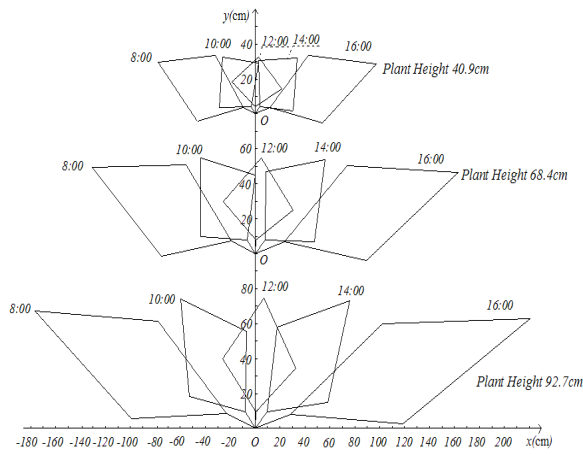


Fig. 5: The simulations of the plants with different plant heights and different plant widths in March 28th

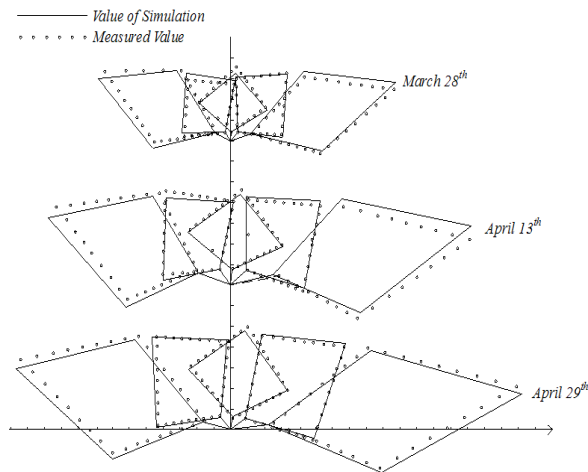


Fig. 6: The comparison between the actual measurement and the model simulation rule of the plant projection in March 2nd, April 13th and April 29th

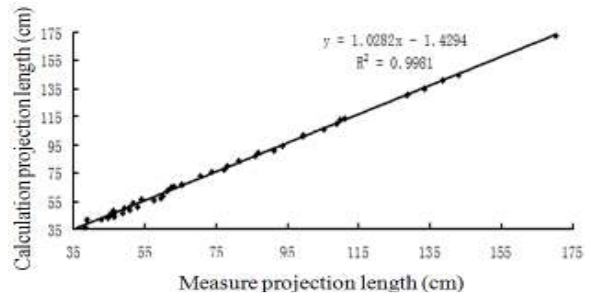


Fig. 7: The linear relation for measured projection length and calculation projection length

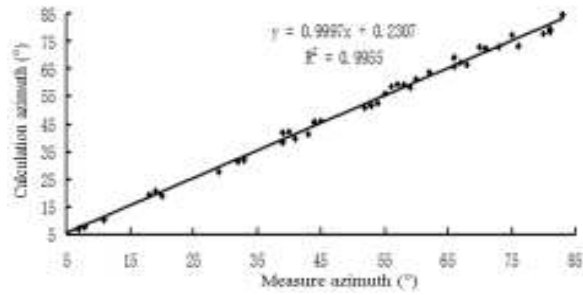


Fig. 8: The linear relation for measured azimuth and calculational azimuth

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (OBS_i - SIM_i)^2}{n}} \quad (11)$$

OBS_i stands for actual observed value, SIM_i stands for model simulation value and n stands for sample size. The actual observed value and model simulation value of experimental field from March 28th to April 29th are analyzed by root-mean-square error detection and the RMSE value of azimuth is 1.58 and the RMSE value of plant projected length is 3.38 (Fig. 7 and 8).

CONCLUSION

The individual tomato plant model was established to simulate the distribution regularity of solar radiation and it has achieved this well. The simulation of the plant whose plant height is 0.409 m and plant width is 0.403 m in different dates was calculated by this model. The actual observed value and model simulation value of experimental field from March 28th to April 29th are analyzed by Root-Mean-Square Error detection and the RMSE value of azimuth is 1.58 and the RMSE value of plant projected length is 3.38.

The geometric model of plant morphology can reflect the relation between the plant morphology and solar radiation distribution better than the statistical model in the individual plant of solar greenhouse tomato. By the dynamic simulation model of solar radiation, the distribution regularity of solar radiation

under condition of different azimuth angles and different solar altitudes can be accurately calculated easily. Through the analysis of projection simulation, the plant projection azimuth is decided by solar azimuth, the plant projection length is mostly decided by solar altitude. So, the projection area of tomato plant is mainly decided by solar altitude. The dynamic simulation of distribution regularity of solar radiation in the individual plant of solar greenhouse tomato shows that the shape of plant projection is affected by plant morphology and the movement path of plant projection arc a butterfly belt.

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