Research on the inversion analysis method based on crop growth model parameters in greenhouse

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Abstract. Inversion analysis is conducted to ascertain crop growth model parameters of temperature, moisture stress index and dry matter conversion factor. The objective function of the inversion analysis is to minimize the error sum squares which simulated calculation of dry matter weight and measured value with coordinate alternation method. Based on the model, the economical irrigation system and irrigation low limit of the cucumber in greenhouse were calculated. Results show that the irrigation low limit of 85.3% is very close to the measured value of 85%. It shows that the model and its parameters are reasonable and feasible.

1 Introduction

Under the current situation, the irrigation cost is only a small proportion in the vegetable crops growing. Farmers pay more attention to production and often excessive irrigation and fertilization. This causes a series of problems those excessive accumulation of nitrate in soil, soil salinization, groundwater nitrate content exceeded, low utilization rate of fertilizer, decreased vegetable quality[1-4]. Therefore, it has been widely carried out the research on the water demand of greenhouse vegetables and the irrigation low limit [5-7]. But at present the research on the irrigation low limit is mainly through the field experiment, and the maximum yield is the goal [8]. The research on the economic irrigation system with the maximum benefit as the goal and the irrigation low limit has not been reported. In this study under the greenhouse drip irrigation under mulch cucumber as the material，the theoretical calculation method is used to calculate the economic irrigation system of greenhouse vegetables and irrigation low limit. This study is significant for the development of water saving and high efficiency of greenhouse vegetables.

2 MATERIALS AND METHODS

2.1 Field Experiment

The experiment was tested in Beiguo Zhichun agricultural demonstration zone (E116°54'，N39°36') of Wuqing district, Tianjin city. The area was warm in the day and cold in the night in autumn, more north wind, less sunshine, sparse precipitation. The annual average temperature was 11.6℃ in the area. Average annual sunshine hours were 2705h in the area. The average frost-free period was 212d in the area. Average annual rainfall was 606.8mm in the area. Test area was plastic film arched steel tube greenhouse that is 8m wide and 85 m long, roof top for 3m. The soil of the test area was medium loam, the soil bulk density (0-100cm) was 1.45g/cm^3, and the basic character of the soil was shown in Table 1. During the experiment, the planting of cucumber in the greenhouse was “The Big Dipper”, and the planting date was September 9, 2014. By wide/narrow row planting, each ridge planting two rows of cucumber, wide row spacing 1.0m, narrow row spacing 0.5m, spacing 0.5m, length of ridge 5.0m, were planted 56 ridge crops. According to the actual growth situation, the irrigation was done every 6d to 15d and the length of irrigation was about 240min. The irrigation water source was well water and the well depth was 80m. In the greenhouse at the top of the layout of air vents and install WS-II type greenhouse automatic temperature control equipment, could realize manual opening and closing device, the opening scope was 0-50cm. The thickness of 0.8 mm in the greenhouse was laid by the plastic film, and the thermal insulation of the outer covering with the electric roller shutter was used. Autumn and winter heat insulation was set off 9:30 am and 5:00 pm down everyday. At night, the heating equipment was automatically opened every half hour to ensure that the temperature in the greenhouse was not less than 8℃, so as to avoid affecting the growth of crops.

TABLE I Basic Properties of Soil

Sampling Depth	**pH**	**Salinity/g/kg**	**Organic Content. /%**	**Available Phosphorus /mg/Kg**	**Available Nitrogen /mg/Kg**
0-20cm	7.15	2.71	1.89	133.3	100.8
20-40cm	7.66	1.63	1.46	99.3	84.42
40-60cm	7.88	1.17	1.32	51.1	45.43
60-80cm	7.91	1.27	0.94	37.8	27.65
80-100cm	7.85	1.24	1.00	36.3	22.4

2.2Testing Items and Methods

(1) Testing of Soil Moisture Content

In the study, the characteristics of soil moisture content of drip irrigation under mulch were measured every 7 days, and the method was drying and weighing, controlling temperature of 105 ℃ and drying to constant weight. Each test was measured two points, one was under the film, is located in the middle of the two drip tape; one is outside the film, is located in the wide line. Test depth was 0-100cm per 20cm layer.

(2) Testing of Environmental Factors

The temperature and humidity in the greenhouse were measured by the WatchDog2450 small weather station, and once every 30min automatically recorded the data. Leaf temperature, transpiration rate, and photosynthetic active radiation PAR were tested by CI-340 hand-held photosynthetic apparatus. The soil temperature was tested by three parameter meter (WET-2-K1), and the average value of the test results was 0-5cm depth. Leaf temperature, transpiration rate and photosynthetic active radiation were tested once per 7d and and the leaves were selected at the top 3 to 5 leaves with three replications.

(3) Testing of Crop Growth Rate

The leaf area and leaf dry weight were calculated by the area method, and the fruit and stem dry weight were calculated by the volume method. The area method was to take the blade as a rectangle with the maximum longitudinal and transverse length of the leaf as the calculation length and width, and the calculation leaf area was equal to the product of the length and width. Through a series of ascending leafs, using leaf area meter to get the actual leaf area, so as to find out the relationship between actual leaf area and calculating leaf area. Volume method is the fruit as a cylinder, to calculate the diameter as a fruit of the largest diameter, the biggest fruit length as calculated length, according to the volume of a cylinder formula calculated fruit volume calculation, and find out the relationship between the fruit dry weight and the calculation volume. The relationship between fresh weight and dry weight of fruit can be found out. For the stem, it was also considered as a cylinder, and the ratio coefficient (stem weight/stem volume) was 0.0886. In this study, these coefficients were known for the conversion factor, through the field fixed strains tested leaf area, fruit and stem calculation volume. The growth of stem, leaf and fruit dry weight can be obtained by using the conversion coefficient.

(4) Simulation Method of Crop Growth Process

In this study, the change of dry matter weight was used to describe the process of crop growth. The total dry matter weight was calculated by the American CERES series model, the empirical calculation method was used to establish the empirical relationship between the daily light volume and the photosynthetic active radiation. The model suggests that the production of dry matter （PCARD，g/m^2） is an exponential function of the photosynthetic effective radiation（IPAR，$MJ/m^2/d$），

$$PCARD=7.5\times IPAR^{0.6} \qquad (1)$$

The photosynthetic active radiation(IPAR) intercepted by crop canopy is a function of the photosynthetic active radiation(PAR,MJ/m^2/d), leaf area index(LAI) and extinction coefficient(K=0.85).

$$IPAR/PAR=1-e^{-K\times LAI} \quad (2)$$

Temperature and water stress can reduce the amount of dry matter accumulation, under the condition of considering water stress and temperature stress. Actual dry matter production (CARBO, t/hm^2) is,

$$CARBO=PCARD\times PRFT\times SWDF \quad (3)$$

In the formula, PRFT is the temperature coefficient and SWDF is water stress coefficient, the formulas are,

$$PRFT= (1-0.0025(T-T_P)^2)^{\sigma_T} \quad (4)$$

$$SWDF= (ET/ET_m)^{\sigma_w} \quad (5)$$

T_P is the most suitable temperature for the growth of the crop,℃; T is the daytime temperature, $T=0.25T_{min}+0.75T_{max}$, T_{min} is the daily minimum temperature and T_{max} is the daily maximum temperature, ℃; σ_T is temperature stress index; ET is the evaporation and transpiration of crops under water deficit, mm/d; ET_m is the maximum evapotranspiration of crops under sufficient water supply, mm/d, $ET_m = K_C ET_0$; K_C is the crop coefficient; ET_0 is the reference crop water requirement calculated by Penman-Monteith formula[9]. σ_W is the water stress index.

If PRFT<0, then PRFT=0.

The actual amount of dry matter production is the weight of all dry matter, including the root, which can be obtained through calculation. Because the number of root in the total dry matter proportion is very small, especially in the greenhouse conditions, less than 4%[10], so this study uses the following formula to calculate the weight of dry matter on the ground,

$$W=CARBO\times 30/40\times CVF \quad (6)$$

In the formula, CVF is the dry matter conversion factor, including the ground dry matter weight proportion of dry matter production.

The above formula can calculate the weight of dry matter on the ground (W).The distribution of dry matter on the ground can be calculated by the distribution coefficient. Distribution coefficient of dry matter in the ground is the dry matter weight of various organs take up the proportion of the dry matter total weight in the ground The weight of dry matter on the ground is the product of the distribution coefficient and the dry matter of the ground,

$$DM_l = DM_S\times CP_l \quad (7)$$

$$DM_{st} = DM_S\times CP_{st} \quad (8)$$

$$DM_f = DM_S\times CP_f \quad (9)$$

In the formula, DM_l, DM_{st}, DM_f are the cumulative values of dry matter weight of leaves, stems and fruits at time t, t/hm^2; DM_S is the total dry matter weight of the upper part of the t time, t/hm^2; CP_l, CP_{st}, CP_f are the distribution coefficient of the leaves, stems and fruits of aboveground dry matter of plant.

(5) Method of Economic Irrigation System

Confirming the economic irrigation system under the condition of a certain water supply by optimization method, the target function of the optimization which appropriate temperature for the constraint conditions is the largest pure income per unit area, including pure income is only considering the cost of irrigation equipment, electricity charges, artificial management fees, etc. In order to facilitate the calculation, electricity, irrigation equipment cost and artificial management expenses in conjunction with conversion and all of these are calculated with the cost of water. In order to make the calculation convenient, the costs of electricity, irrigation equipment and labor management are calculated with water cost. Within the scope of the irrigation system optimization, it can be considered constant of management cost as fertilizer, spraying pesticide, greenhouse skylight opening and closing, temperature control, seeds and cultivation.

Thus the objective function can be written as follows,

$$B=\max(P_C\times y-P_W/1.5/\eta) \quad (10)$$

B is net income of only considering the irrigation cost, yuan/hm^2; Y is crop yield, t/hm^2; W is irrigation quota, mm; η is water efficiency of irrigation, η= 0.9; P_C is the unit price of crop products, yuan/t; P_W is the water price, yuan/m^3. According to Optimization process, irrigation quota is 30 mm. The price of cucumber products is 3000 yuan/t, water price is 1.5 yuan/m^3.

The crop yield of different irrigation amount and different irrigation time was calculated by daily simulation of crop water requirement and crop growth model, and then the yield increase efficiency of drip irrigation in greenhouse was calculated by the formula (10).

3 Result Analysis

3.1 Correction of the Conversion Factor in the Determination of Dry Matter

The relationship between the actual value and the calculated value is found to have a good linear relationship, which is determined by the formula (11), and the results are shown in table 2. From table 2 we can see that the correlation coefficient is above 0.97, and the correlation is very high. The determination of dry matter weight with the conversion coefficient is accurate enough.

$$y=ax+b \tag{11}$$

In the formula, y is the actual leaf area, leaf dry weight, stem weight, fruit dry weight and fresh weight of the fruit, g; x is the calculated leaf area(cm^2), actual leaf area (cm^2), calculated stem volume (cm^3), fruit volume (cm^3) and fruit dry weight (g); a, b are the conversion coefficient.

TABLE II Calibration Results of Conversion Coefficient

Coefficients	**Transform Coefficient**		**Correlation Coefficient R**
	a	**b**	
Calculated from the leaf length and width to the leaf area	0.8801	-26.686	0.9781
Calculated from the leaf area to leaf dry weight	0.0036	-0.1814	0.9275
Calculated from the stem volume to stem weight	0.0886	—	—
Calculated from the fruit volume to fruit dry weight	0.048	-0.0047	0.9973
Calculated from the fruit dry weight to fruit fresh weight	19.315	-0.6754	0.9927

3.2 Cucumber Photosynthesis and Distribution Coefficient Change Process

According to the change of dry matter weight (Fig. 1), the distribution coefficient of the photosynthetic products of cucumber can be obtained. Fig. 2 shows the change process of cucumber leaf and stem, fruit distribution coefficient with quadratic parabolic equation. The results are: y_L = 2E-05X^2 –0.0083X + 1.1427, y_s= 2E-05 X^2 - 0.0063 X + 0.7943, y_F = -6E-05 X^2 + 0.0231X – 1.5965. y_L is distribution coefficient of leaf, y_s is distribution coefficient of stem, y_F is distribution coefficient of fruit. X is the number of days to be counted in planting date. The corresponding correlation coefficients are 0.9332, 0.8206 and 0.9371.

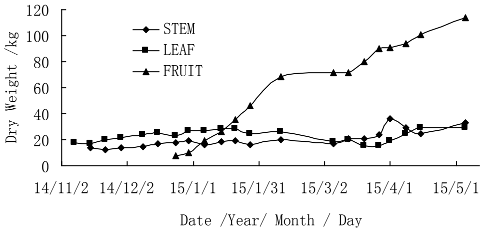

Fig. 1 The Growth Process of Stems, Leaves and Fruits of Cucumber

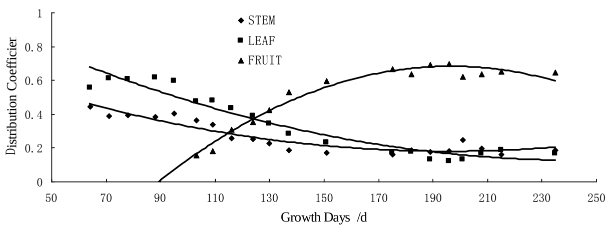

Fig. 2 The Change of Photosynthate Allocation Coefficient of Cucumber

From Fig. 2, dry matter mainly allocated to the leaves and stems, the distribution coefficient leaves is higher than that of the stems in the initial testing period. Leaves and stems of the partition coefficient decreases gradually with the growth of the crops, to the end of the testing period to uprooting, distribution coefficient of stems is slightly higher than that of leaves; distribution coefficient of fruit increases gradually, increased from 0.18 to 0.67, then gradually decreased.

Calibration and Test of Crop Growth Model Parameter

Temperature, water stress index and dry matter conversion factor of three crop growth model parameters were calibrated. The objective of minimum error sum of squares between the simulated and measured values of dry matter weight (the total value of stem, leaf and fruit) in the rate setting process is determined by the calibration process and the results are shown in TABLE Ⅲ.

Calibration process to shoot dry matter weight (stem, leaf and fruit of total value) of simulated values and measured values of error square and minimum as the goal, through the optimization analysis, the results are shown in Table 3. The measured values and simulated values with time change process and scatter diagram shown in picture 3 and picture 4. From the Fig. 3 and Fig. 4 can be seen, the model calculated value and measured value is close which the correlation coefficient is above 0.98. It shows that the crop growth model and its parameters can be used to describe the greenhouse crop growth process and temperature and effects of water stress on crop growth and yield

TABLE III The Calibration Results of Growth Model Parameters

Item	Initial parameters	Optimized Parameters
Optimum Temperature T_p/℃	30	30
Temperature Stress Index σ_T	1.0	1.0
Water Stress Index σ_W	1.0	2.0
Dry Matter Conversion Factor CVF	0.72	0.36
SS		0.2348
Standard Error		0.2167
Correlation coefficient between simulated and measured values R^2		0.9819

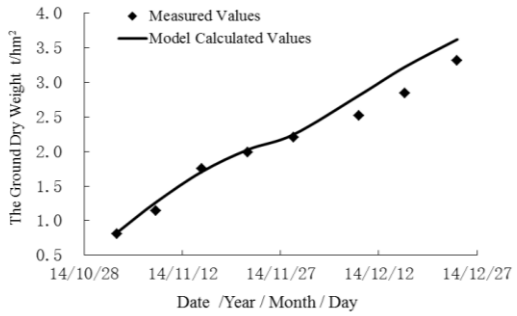

Fig. 3 Modeling Values and Measured Values of Ground Dry Weight

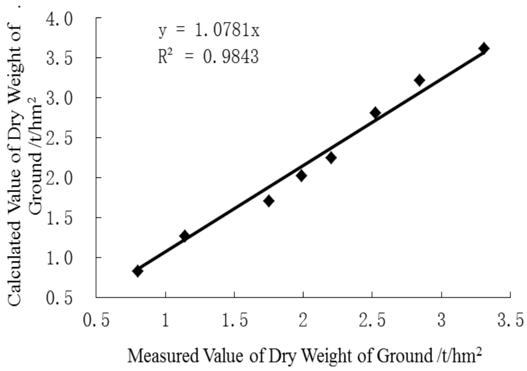

Fig. 4 Scatter Plot of Modeling and Measured Values

Economic Irrigation System and Its Effect on Water-Saving and Increasing Production

In the optimization process of irrigation system, the irrigation quota is constant, and the optimal irrigation time is optimized. So the optimization calculation is a nonlinear programming problem with the irrigation time as the decision variable. Coordinate rotation method is adopted here, and the results are shown in TABLE Ⅳ.

TABLE IV Irrigation System, Yield and Benefit with Different Irrigation Amount

rrigation /mm	Yield /t/hm^2		Benefit /Million Yuan/hm^2	ET /mm	Irrigation time(Counting the number of days from planting date)/d
	dry weight	fresh weight			
2	1.7	33.8	10.018	236.2	49/61
108	1.8	35.6	10.501	245.6	49/61/68
144	1.9	36.9	10.823	252.1	49/61/68/78
180	1.9	37.7	11.018	256.9	49/61/68/78/87
216	2.0	38.2	11.096	258.7	49/61/68/78/87/95
252	2.0	38.3	11.083	259.5	49/61/68/78/87/95/101
288	2.0	38.3	11.023	259.5	49/61/68/78/87/95/101/104

TABLE V The Yield and Benefit of Actual Irrigation

Irrigation /mm	Yield /t/hm^2		Benefit /Million Yuan/hm^2	ET /mm	Irrigation time(Counting the number of days from planting date)/d
	dry weight	fresh weight			
510	1.9	35.66	8.736	258.9	49/61/68/78/87/95

Economic irrigation system is the optimal irrigation system with the maximum benefit, and the corresponding irrigation amount is the economic irrigation water consumption. The irrigation water is 216mm, the irrigation times is 6 times, corresponding to the irrigation time as shown in table 4. The corresponding yield was 38.2t/hm^2, the benefit was 110960 yuan/hm^2 and the evaporation and transpiration was 258.7mm. Compared with the economic irrigation and the actual irrigation (TABLEⅤ), the yield and efficiency increased by 4.25t/hm^2 and 13120 yuan/hm^2 and the irrigation water saving was 7.59% which had significant effect on increasing the water saving and increasing production.

3.3The Change Process of Irrigation Low Limit

According to the obtained economical irrigation system (TABLEⅣ), which check soil moisture content and the corresponding time before irrigation (Counting the number of days from planting date) of the economical irrigation system can be used to obtain several groups of data (data set is equal to the number of times of irrigation). With these numbers painted irrigation of soil moisture and irrigation time curve (Fig. 5), the curve is the change process line of economical irrigation low limit value. According to the Fig. 5, before irrigation of soil moisture content (0-60 cm), the variation of soil moisture content is much smaller with time variation of crop growth period. Therefore, it can be thought that soil moisture content low limit value of economical irrigation is a constant. Its value is equal to the average of soil moisture content before irrigation and the coefficient is 0.240%. According to the irrigation low limit value, the maximum irrigation benefit per unit area can be achieved. The result is consistent with the irrigation low limit (85%) obtained by experiments with Niu Yong et al[11].

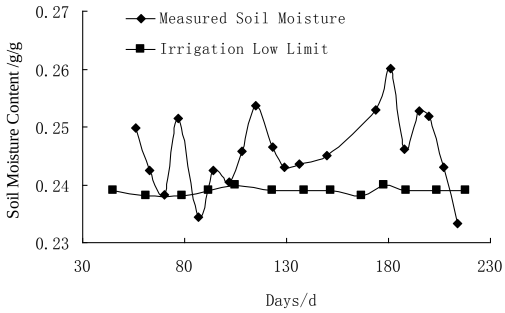

Fig. 5 Relationship between Soil Moisture Content (0-60cm) and Irrigation Time before Irrigation and Growth Period

4 Conclusions

(1) Dry matter determination in the conversion coefficient of calibration results show that the conversion coefficient to calculate crop growth process of high precision, reasonable and feasible.

(2) The parameters of crop growth model are optimized which temperature of 30℃, the water stress index σ_T of 1, σ_W of 2 and the dry matter conversion factor is 0.36.

(3) Economic irrigation system has a good effect of increasing water saving and increasing yield, which can increase the yield of 2.54t/hm^2, increase the efficiency of 23600 yuan/hm^2, and save the irrigation water by about 7.59%.

(4) Economic irrigation low limit value is a constant of 0.240, accounting for 85.8% of the field capacity.

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