water

MDPI

Article

Optimizing Irrigation and Nitrogen Application for Greenhouse Tomato Using the DSSAT–CROPGRO–Tomato Model

Zhijie Shan [1,2], Junwei Chen [1,3], Xiping Zhang [4], Zhuanyun Si [5,*], Ruochen Yi [1,3] and Haiyan Fan [1,*]

1 Beijing Water Science and Technology Institute, Beijing 100048, China; shanzhj@iwhr.com (Z.S.); chenjunwei202204@163.com (J.C.); yiruochen1@163.com (R.Y.)
2 State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100048, China
3 College of Water Conservancy Engineering, Tianjin Agricultural University, Tianjin 300392, China
4 College of Urban and Rural Construction, Hebei Agricultural University, Baoding 071001, China; xpzhang1@hebau.edu.cn
5 Institute of Farmland Irrigation, Chinese Academy of Agricultural Sciences/Key Laboratory of Crop Water Use and Regulation, Ministry of Agriculture and Rural Affairs, Xinxiang 453002, China
* Correspondence: sizhuanyun@caas.cn (Z.S.); fanhaiyan0402@163.com (H.F.)

Abstract: The aim of this study was to optimize water-saving and high-efficiency irrigation and nitrogen application scheduling for greenhouse tomato cultivation in North China. Using experimental data on water and nitrogen inputs, the DSSAT-GLUE parameter adjustment tool was employed to calibrate the genetic parameters of the DSSAT–CROPGRO–Tomato model. Simulations were conducted to assess greenhouse tomato growth, water use, and yield under varying water and nitrogen conditions. After calibration, the model showed average relative errors of 3.19% for the phenological stages, 3.33% for plant height, and 4.52% for yield dry weight, meeting accuracy standards. The results from the calibrated model indicated that increasing irrigation or nitrogen levels initially enhanced yield but led to diminishing returns beyond optimal ranges. The maximum tomato yield and water–nitrogen use efficiency were achieved with irrigation quotas between 320 and 340 mm and nitrogen applications between 360 and 400 kg·ha^{-1}. These findings provide a guideline for efficient water and nitrogen management for greenhouse tomatoes under drip irrigation conditions.

Keywords: DSSAT–CROPGRO–Tomato model; greenhouse; tomato; water and nitrogen management; yield; scenario simulation

Academic Editors: Patrícia Palma and Alexandra Tomaz

Received: 13 November 2024
Revised: 16 January 2025
Accepted: 22 January 2025
Published: 3 February 2025

Citation: Shan, Z.; Chen, J.; Zhang, X.; Si, Z.; Yi, R.; Fan, H. Optimizing Irrigation and Nitrogen Application for Greenhouse Tomato Using the DSSAT–CROPGRO–Tomato Model. *Water* **2025**, *17*, 426. https://doi.org/10.3390/w17030426

1. Introduction

Tomato (*Solanum lycopersicum* L.) is among the most widely cultivated and popular vegetable crops globally [1], with China leading in terms of both the tomato planting area and total yield [2]. The manual adjustment of greenhouse environments to optimize tomato growth plays a crucial role in meeting the demands of climate variability and the increasing year-round need for high-quality produce. Water is essential to fertilizer efficiency, and fertilizer, in turn, is critical to enhancing water and soil productivity [3]. With modern agriculture advancing rapidly, irrigation and fertilizer application have become key strategies for ensuring high-quality and stable greenhouse crop yields. To maximize economic benefits, farmers often increase water and fertilizer application rates to boost yields. While this approach may provide short-term gains, excessive and unscientific inputs can increase production costs and reduce resource use efficiency. It can also increase the risk of greenhouse gas emissions, nitrate leaching, soil salinization, and pest and disease outbreaks. These issues hinder the sustainable and efficient development of controlled environment agriculture [4]. Thus, establishing precise irrigation and nitrogen application systems is essential for promoting sustainable agricultural practices.

Considerable research on water-saving, high-yield irrigation methods for greenhouse tomatoes has been conducted both domestically and internationally, producing substantial insights [5–10]. However, due to differences in experimental objectives and regional conditions, these findings have some limitations. In recent years, combining field experiments with crop growth models has become a valuable approach for optimizing cultivation management. The DSSAT model is one of the most popular crop growth models globally [11–14]. The model integrates climate, soil, crop, and field management modules to simulate crop growth dynamics on a daily scale, providing quantitative insights into the relationships between crop growth and environmental factors [15]. The model's accuracy has been significantly increased after extensive improvements and regional validations [16–19]. DSSAT has been used by many researchers to optimize irrigation schedules for crops like winter wheat [20], tomato [21], and corn [22]. For instance, Si et al. [23] optimized irrigation and nitrogen application rates for winter wheat under drip irrigation conditions in North China using the DSSAT–CERES–Wheat model.

Efficient water and nitrogen management is vital for high-quality greenhouse tomato production amid increasing land and water scarcity and ongoing environmental degradation [24]. Therefore, the DSSAT–CROPGRO–Tomato model was used in this study to simulate the growth dynamics and resource use efficiency of tomatoes in various water and nitrogen application scenarios. The findings will offer technical support for optimizing irrigation and nitrogen schedules to promote high-quality, efficient tomato production in greenhouse environments.

2. Materials and Methods

2.1. Field Experiment

The experiment was conducted in a solar greenhouse in the Yongledian Experimental Base (N 39°20′, E 116°20′, altitude 12 m) in 2022. The average annual rainfall and potential evaporation in the area was 565 mm and 1140 mm, the average annual temperature was 11.5 °C, and the frost-free period was 185 days. The daily temperatures in the greenhouse during the experiment are shown in Figure 1. The soil texture of the experimental field was loamy (sand/silt/clay: 12.44%/44.37%/43.19%). The soil bulk weight was 1.40 $g \cdot cm^{-1}$, the saturated water content was 34.44 $cm^3 \cdot cm^{-3}$, the field water holding capacity was 29.96 $cm^3 \cdot cm^{-3}$, the soil electric conductivity was 36.0 $mS \cdot cm^{-1}$, the cation exchange capacity (CEC) was 11.3 $cmol \cdot kg^{-1}$, and the groundwater mineralization was 802.3 $mg \cdot L^{-1}$. The depth of the groundwater was more than 8 m. The physicochemical properties of the soil in the 0~60 cm soil layer are shown in Table 1.

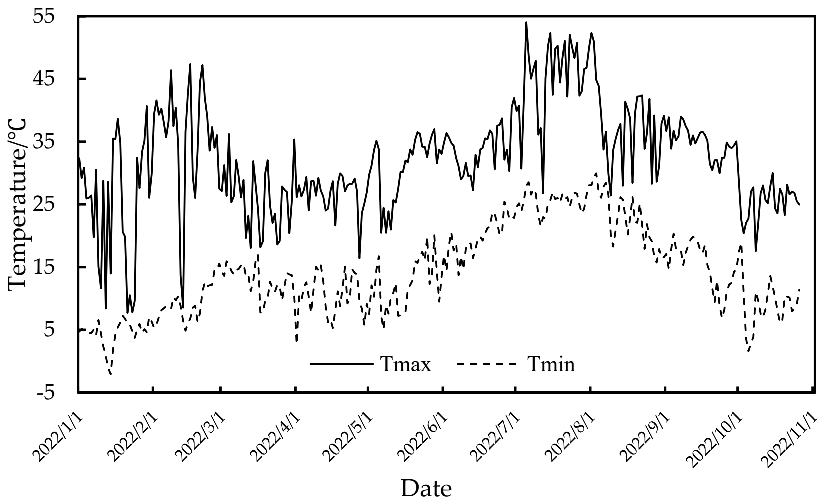


Figure 1. The air temperature in the greenhouse during the experiment.

Table 1. Physicochemical properties of the soil in the 0~60 cm soil layer.

Soil Layer (cm)	Ammonium N ($mg \cdot kg^{-1}$)	Nitrate-N ($mg \cdot kg^{-1}$)	Total Organic Carbon ($g \cdot kg^{-1}$)	Total Carbon ($g \cdot kg^{-1}$)	Total Nitrogen ($g \cdot kg^{-1}$)	pH	Soil Texture (%)		
							Sand <0.002 mm	Silt 0.002–0.02 mm	Clay 0.02–2 mm
0~10	86.043 ± 0.07	39.031 ± 0.09	14.19 ± 0.08	22.85 ± 0.16	1.72 ± 0.02	7.33 ± 0.02	11.64 ± 0.08	44.08 ± 0.07	44.28 ± 0.09
10~20	83.952 ± 0.08	15.497 ± 0.08	12.89 ± 0.07	17.66 ± 0.12	1.38 ± 0.03	7.99 ± 0.03	12.06 ± 0.07	43.39 ± 0.09	44.55 ± 0.11
20~30	31.413 ± 0.43	5.953 ± 0.10	5.03 ± 0.05	16.81 ± 0.08	1.00 ± 0.03	8.05 ± 0.05	13.33 ± 0.07	47.92 ± 0.07	38.75 ± 0.12
30~40	46.513 ± 0.02	13.34 ± 0.08	7.47 ± 0.08	16.94 ± 0.09	1.12 ± 0.02	7.99 ± 0.02	12.77 ± 0.08	43.5 ± 0.07	43.74 ± 0.08
40~60	22.559 ± 0.13	6.133 ± 0.07	3.56 ± 0.07	21.13 ± 0.06	0.76 ± 0.01	8.1 ± 0.03	12.38 ± 0.05	42.98 ± 0.06	44.64 ± 0.07

The tomato variety "Caomei 3" was used in the experiment, and the supplier was the Beijing Academy of Agriculture and Forestry Sciences. This variety is an infinite-growth, flavorful tomato. The plant is vigorous, with good comprehensive disease resistance. The fruit is a beautiful, deep pink color, and it has good properties of hardness, storage, and transportation resistance. Controlled water cultivation is favorable to enhance the sugar level and taste. The tomatoes were planted on 20 January 2022 and transplanted on 18 February 2022, with row spacing of 45 cm and plant spacing of 35 cm. The experiment was a two-factor split-plot design. The main block was the irrigation water treatment, and the irrigation water quota was set to the following three levels based on crop evapotranspiration (ET_C): 100% ET_C, 20 mm (I1); 85% ET_C, 17 mm (I2); and 70% ET_C, 14 mm (I3). Groundwater was used for irrigation, and each irrigation cycle lasted 7 days. In the secondary area, four levels of nitrogen fertilizer were applied: 220, 180, 160, and 140 $kg \cdot ha^{-1}$ (N1, N2, N3 and N4, respectively), and urea was used for fertilizer. The two factors were completely combined for a total of 12 treatments (Table 2). Each treatment was repeated 3 times for a total of 36 plots, with 0.5 m wide protective rows between each plot (Figure 2).

Table 2. Irrigation levels and nitrogen rates during tomato growth periods.

Treatment	Irrigation (mm)	Nitrogen Application ($kg \cdot ha^{-1}$)
I1N1	100% ET_C, 20	220
I1N2	100% ET_C, 20	180
I1N3	100% ET_C, 20	160
I1N4	100% ET_C, 20	140
I2N1	85% ET_C, 17	220
I2N2	85% ET_C, 17	180
I2N3	85% ET_C, 17	160
I2N4	85% ET_C, 17	140
I3N1	70% ET_C, 14	220
I3N2	70% ET_C, 14	180
I3N3	70% ET_C, 14	160
I3N4	70% ET_C, 14	140

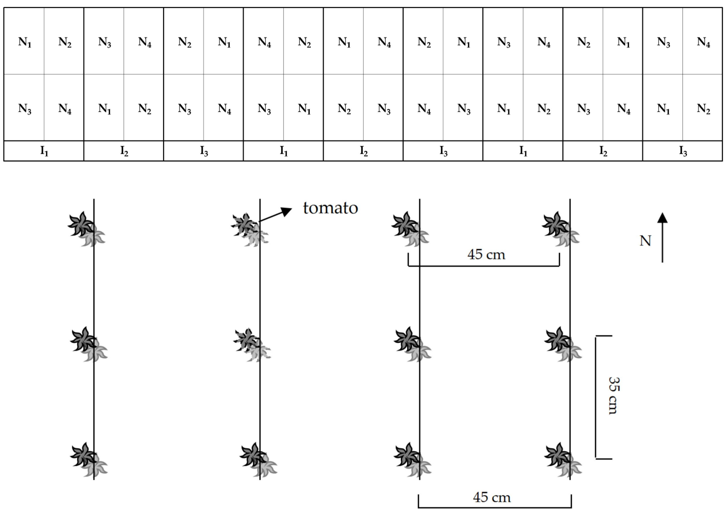


Figure 2. Layout of the experimental area.

2.2. DSSAT–CROPGRO–Tomato Model

The DSSAT model mainly includes soil water balance, nitrogen balance, phenological development, soil–plant atmosphere (SPAM), and growth development modules. The main function is to provide help with decision-making and support for the rational utilization of all types of resources in agricultural production [15,25]. The nitrogen balance module simulates nitrogen accumulation based on available nitrogen in the soil and nitrogen requirements of crops. The effective absorption of nitrogen from soil by crops depends on the concentration of available nitrogen in soil, the status of root development and the water table. Crop nitrogen requirements affect plant growth, nitrogen concentration in organs and critical nitrogen concentration [26,27]. The model incorporates atmospheric, plant, and soil data to calculate potential evapotranspiration, plant transpiration, soil evaporation, and root water uptake. There are two methods for calculating evapotranspiration in the model, the Penman–FAO method or the Priestley–Teller method, where the Priestley–Teller method only requires daily solar radiation and temperature. In this study, evapotranspiration was calculated using the Priestley–Teller method. Actual soil evaporation and plant transpiration were calculated by evapotranspiration [15,23]. The CROPGRO–Tomato model in the DSSAT system is used to simulate the physiological and growth dynamics of the tomato, such as leaf photosynthesis, plant respiration, dry matter accumulation and transformation, and plant response to environmental factors. The CROPGRO–Tomato model mainly includes data, simulation, analysis, and tool modules [15,28].

2.3. Model Parameters Rates

Crop variety parameters are often obtained using different parameter estimation methods. Among them, the Generalized Likelihood Uncertainty Estimation (GLUE) method has been made into a built-in parameter estimation program of the DSSAT model which can be used directly by users [29,30]. The measured indexes (phenological period, aboveground dry mass, dried fruit yield, and fresh fruit yield) in adequate water and nitrogen treatment (I1N1 and I1N2) from a field experiment in 2022 were used to determine the tomato genetic parameters required in the model in this study. First, a set of initial values required for model operation is set, and then a reliable set of genetic parameter combinations was obtained after 20,000 iterations by using the DSSAT-GLUE method (Table 3).

Table 3. Range and calibration value of genetic parameters in the model.

Parameters	Define	Realm	Calibration Value
EM-FL	Time between plant emergence and flower appearance (°C·d^{-1})	7~35	30.42
FL-SH	Time between first flower and first pod (°C·d^{-1})	1~9	3.833
FL-SD	Time between first flower and first seed (°C·d^{-1})	15~20	19.50
SD-PM	Time between first seed and physiological maturity (°C·d^{-1})	45~55	45.16
LFMAX	Maximum leaf photosynthesis rate at 30 C, 350 vpm CO_2, and high light (mg·m^{-2}·s^{-1}, in CO_2)	1~1.4	1.10
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2·g^{-1})	300~380	380
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	0.65~0.85	0.744
SFDUR	Seed filling duration for pod cohort at standard growth conditions (°C·d^{-1})	23~27	26.03
PODUR	Time required for cultivar to reach final pod load under optimal conditions (°C·d^{-1})	40~65	57.12
THRSH	Threshing percentage. The maximum ratio of (seed/(seed + shell)) at maturity. Causes seed to stop growing as their dry weight increases until the shells are filled in a cohort.	7~10	8.50

Using the calibration parameters in Table 3, the model was evaluated under different water and nitrogen conditions (I1N3 treatment ~ I3N4 treatment in 2022), including the phenological period, average stem and leaf number, canopy height, and dry matter mass in the ground and tomato yield. The simulated and measured values based on the calibrated CROPGRO–Tomato model are shown in Table 4.

Table 4. Calibration and validation results of the CROPGRO–Tomato model.

	Treatment	Anthesis Date (d)			Maturity Date (d)			Fruit Yield (kg·ha^{-1})			Aboveground Biomass (kg·ha^{-1})			Plant Height (m)		
		Sim	Mea	ARE	Sim	Mea	ARE	Sim	Mea	ARE	Sim	Mea	ARE	Sim	Mea	ARE
Model validation	I1N3	24	25	4	118	116	1.7	5532	5548	0.3	10,510	10,298	2.1	1.25	1.23	1.6
	I1N4	24	25	4	118	115	2.6	4979	4915	1.3	9710	9113	6.6	1.22	1.15	6.1
	I2N1	24	23	4.3	118	117	0.9	7083	7014	1	12,390	12,685	2.3	1.31	1.3	0.8
	I2N2	24	23	4.3	118	116	1.7	6025	6059	0.6	11,030	12,142	9.2	1.28	1.25	2.4
	I2N3	24	24	0	118	115	2.6	5399	5519	2.2	10,230	10,277	0.5	1.26	1.21	4.1
	I2N4	24	24	0	118	115	2.6	4931	4925	0.1	9540	9140	4.4	1.24	1.18	5.1
	I3N1	24	23	4.3	118	120	1.7	5685	6265	9.3	10,240	11,771	13	1.29	1.26	2.4
	I3N2	24	23	4.3	118	119	0.8	4888	5546	11.9	9230	10,334	10.7	1.26	1.22	3.3
	I3N3	24	22	9.1	118	121	2.5	4600	5046	8.8	8710	9313	6.5	1.25	1.21	3.3
	I3N4	24	22	9.1	118	122	3.3	4151	4598	9.7	8060	8664	7	1.24	1.19	4.2
	averages			4.34			2.04			4.52			6.23			3.33
	RMSE		1.18			2.57			345.37			786.02			0.04	
	nRMSE		5.06			2.18			6.23			7.58			3.57	

Notes: Sim, simulated value; Mea, measured value; ARE, absolute relative error, %. RMSE, root mean square error, %. nRMSE, normalized root mean square error, %.

In this study, a variety of statistical methods were selected as validation and evaluation indicators to evaluate the reliability of the model calibration and validation results, including absolute relative error (ARE), root mean square error (RMSE), and normalized root mean square error (nRMSE).

The absolute relative error (ARE) refers to the ratio of the absolute error caused by the simulation to the true value multiplied by 100%. The smaller the value of ARE, the higher the simulation accuracy of the model [31]. The calculation formula is as follows:

$$ARE = \frac{|S_i - O_i|}{O_i} \times 100\% \quad (1)$$

The root mean square error (RMSE) refers to the average difference between the simulated and actual values of a model. The calculation formula is as follows:

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

The normalized root mean square error (nRMSE) measures the accuracy of a model by comparing simulated and observed values normalized to the mean of the observed data. The equation is as follows:

$$nRMSE = \frac{\sqrt{\sum_{i=1}^{n} \frac{(S_i - O_i)^2}{n}}}{\overline{O}} \times 100 \quad (3)$$

where O_i is the observed value at different growth stages; S_i is the simulated value; and $\overline{O}$ is the observed average value. When nRMSE < 10%, the analog value accuracy is very good; when 10% ≤ nRMSE ≤ 20%, the analog value accuracy is good; when 20% ≤ nRMSE ≤ 30%, the analog value accuracy is fair; and when nRMSE > 30%, the analog value accuracy is poor [20].

2.4. Irrigation and Nitrogen Management Scenario Setting

After calibration and validation, different levels of irrigation and nitrogen application were set up based on the CROPGRO–Tomato model to simulate the growth characteristics, yield, and water- and nitrogen-use efficiency of tomato. In this study, the total irrigation amount were set to 260, 280, 300, 320, 340, 360, 380, and 400 mm, a total of 8 levels.

Eight nitrogen application levels were set to 200, 240, 280, 320, 360, 400, 440, and 480 kg·ha^{-1}, and the two factors were completely combined to form 64 treatments (Table 5). According to the results of the field experiment, 20 irrigation periods and 4 nitrogen applications were set during the growth period, and the irrigation cycle was 7 days. The first nitrogen application was carried out at the time of tomato transplanting, the second nitrogen application was carried out when the diameter of the first tomato crop reached 1.5~2.5 cm, the third was performed when the diameter of the second fruit grew to 3 cm in size, and the fourth was conducted when the diameter of the third fruit grew to 3 cm in size.

Table 5. Different water and nitrogen application scenarios.

Scenario No.	Irrigation Amount (mm)	Nitrogen Application (kg·ha^{-1})	Scenario No.	Irrigation Amount (mm)	Nitrogen Application (kg·ha^{-1})
1	260	200	33	340	200
2	260	240	34	340	240
3	260	280	35	340	280
4	260	320	36	340	320
5	260	360	37	340	360
6	260	400	38	340	400
7	260	440	39	340	440
8	260	480	40	340	480
9	280	200	41	360	200
10	280	240	42	360	240
11	280	280	43	360	280
12	280	320	44	360	320
13	280	360	45	360	360
14	280	400	46	360	400
15	280	440	47	360	440
16	280	480	48	360	480
17	300	200	49	380	200
18	300	240	50	380	240
19	300	280	51	380	280
20	300	320	52	380	320
21	300	360	53	380	360
22	300	400	54	380	400
23	300	440	55	380	440
24	300	480	56	380	480
25	320	200	57	400	200
26	320	240	58	400	240
27	320	280	59	400	280
28	320	320	60	400	320
29	320	360	61	400	360
30	320	400	62	400	400
31	320	440	63	400	440
32	320	480	64	400	480

2.5. Measurement Items and Methods

2.5.1. Soil Moisture Content

The soil moisture content was measured using the soil drying method in layers (0–20, 20–40, 40–60, 60–80, and 80–100 cm) before planting, before and after irrigation, and after harvesting.

2.5.2. Dry Matter Accumulation

Tomato plants were sampled at harvest, and the plants were classified according to organs such as stems, leaves, and fruits. All organs were dried in an oven at 105 °C for 0.5 h, and then in an oven at 75 °C to constant weight. The dry weight of each organ was weighed separately.

2.5.3. Yield and Economic Benefit

Yield is calculated by multiplying the average yield per plant by planting density. Net income is obtained by subtracting total input from total income. The calculation formula is as follows:

$$Net\ income = (Y \times P) - (W \times C_1 + N \times C_2) - V \quad (4)$$

where Y (kg·ha^{-1}) is the simulated fruit yield, P is the fruit yield price (4.0 CNY·kg^{-1}), W is the irrigation water amount (m^3·ha^{-1}), C_1 and C_2 are the water and urea prices (5.0 CNY·m^{-3} and 2.5 CNY·kg^{-1}). V is the fixed inputs in production, including seeds, machinery, herbicides, pesticides, harvesting, and labor costs.

2.5.4. Assessment Criteria

The tomato water consumption (ET_C, mm), water-use efficiency (WUE, kg·m^{-3}), nitrogen partial factor productivity ($NPFP$, kg·kg^{-1}), harvest index (HI, kg·kg^{-1}), yield, and economics were used to assess the optimal water and nitrogen application schedule.

Based on the water balance equation, the water consumption for each treatment was calculated using Equation (5) [32]. The contribution of groundwater recharge to tomato water consumption was negligible (K = 0), given that the groundwater depth in the experimental area exceeded 8 m. Additionally, as the experiment was conducted in a greenhouse, there was no effective precipitation throughout the tomato growth period; thus, P_0 = 0. Field observations of soil moisture indicated that for irrigation levels below 20 mm, irrigation had minimal impact on soil moisture content below 60 cm depth, and there was no deep leakage (D = 0) [33]. Consequently, Equation (5) was simplified to Equation (6).

$$ET_C = P_0 + K + M - D + (W_0 - W_t) \quad (5)$$

$$ET_C = M + (W_0 - W_t) \quad (6)$$

where ET_C is tomato water consumption (mm); P_0 is precipitation (mm); K is the amount of groundwater recharge (mm); M is the irrigation depth (mm); D is the amount of water that seeps into the soil below 100 cm (mm); W_0 and W_t are the soil water storage (mm) at the beginning and end of the season, respectively.

The water-use efficiency was calculated using Equation (7):

$$WUE = Y/ET_C \quad (7)$$

where WUE denotes water-use efficiency (kg·m^{-3}) and Y denotes the fresh weight of the tomato yield (kg·ha^{-1}).

The nitrogen partial factor productivity was calculated using Equation (8):

$$NPFP = Y/N \quad (8)$$

where $NPFP$ represents the partial productivity of the nitrogen fertilizer (kg·kg^{-1}), and N is the total nitrogen application (kg·ha^{-1}) in the whole growth period of the greenhouse tomato.

The harvest index is the ratio of economic yield (seeds, fruits, etc.) to the aboveground biomass of a crop at harvest. It reflects the proportion of the crop's assimilated products distributed among the seeds and nutrient organs and the ability of a crop population to convert photosynthetically assimilated substances into economic products. The harvest index is an important indicator for evaluating the yield level of crop varieties and the effectiveness of cultivation. It was calculated using Formula (9):

$$HI = Y/BY \tag{9}$$

where HI represents the harvest index (kg·kg^{-1}), and BY is the aboveground biomass (kg·ha^{-1}).

3. Results

3.1. Calibration and Validation of CROPGRO–Tomato Model

3.1.1. Phenology

As can be seen from Table 4, water stress, nitrogen fertilizer stress, or their interaction can affect the flowering and maturity stages. Further analysis showed that the simulated values of the flowering and maturity stages subjected to the water and nitrogen stress treatment were different from the measured values. The ARE values for water and nitrogen stress treatment I3N4 were 9.1% and 3.3% at flowering and maturity, respectively. This treatment had higher ARE values than all other treatments. The absolute relative error (ARE) of simulated values and measured values at the flowering and maturity stages for different treatments ranged from 0 to 9.1% and 0.8% to 3.3%, respectively. The ARE of simulated values and measured values at the flowering stage was less than 5% in all treatments except for the I3N3 and I3N4 treatments, and the ARE of simulated values and measured values at the maturity stage was less than 3% in all treatments. The normalized root mean square error (nRMSE) values were 5.06% and 2.18% at anthesis and maturity, respectively, both less than 10%. This shows that the phenological period of greenhouse tomato can be simulated by using the fixed parameters.

3.1.2. Yield and Aboveground Biomass

The ARE values of tomato yield dry weight ranged from 0.10% to 11.9%, with an average value of 4.52%. The ARE values of aboveground dry matter mass ranged from 0.5% to 10.7%, with an average of 6.23%. By comparing the ARE values of each treatment, it was found that the ARE values of tomato yield dry weight with the I3N1, I3N2, I3N3, and I3N4 treatments were 9.3%, 11.9%, 8.8%, and 9.7%, respectively. The ARE values of the aboveground dry matter mass of the I1N4, I2N2, I3N1, I3N2, I3N3, and I3N4 treatments were 6.6%, 9.2%, 13%, 10.7%, 6.5%, and 7.0%, respectively. The simulated values of these treatments differed greatly from the measured values, mainly due to the effect of moisture. The yield simulation was better in the treatments with adequate water supply, while the ARE values of the yield of the water-stressed treatments were large, and the simulation was slightly poorer. The I3N4 treatment exhibited an especially severe water and nitrogen deficit. The unnatural deficit of water and nitrogen prevented the tomatoes from growing normally. This resulted in abnormal yield formation, which led to a large simulation error. The nRMSE values for tomato yield dry weight and aboveground dry matter mass were 6.23% and 7.58%, respectively, which were less than 10%. This indicates that the rate-set parameters simulated greenhouse tomato yield and aboveground biomass well.

3.1.3. Plant Height

As can be seen from Table 4, the ARE values of the plant height of each treatment ranged from 0.8% to 6.1%. The absolute value of relative error for most of the treatments was less than 5%. The nRMSE value of plant height was 3.57%, which was less than 10%. This indicates that the model can better simulate the plant height growth of greenhouse tomato under different water and nitrogen supply conditions. It is shown based on the comparison of the ARE and nRMSE values of the indicators that the calibrated CROPGRO–Tomato model has a high simulation accuracy, and can be used to simulate the effects of different water and nitrogen treatments on tomato growth and yield formation indicators.

3.2. Optimization of Water and Nitrogen Schedule Based on the DSSAT–CROPGRO–Tomato Model

3.2.1. Influence of Water and Nitrogen Coupling on Water Consumption of Tomato in Greenhouse

The improved CROPGRO–Tomato model was used to simulate the water consumption of greenhouse tomatoes under varying water and nitrogen supply conditions. The simulation results (Figure 3) indicated that water consumption increased at higher irrigation levels. Specifically, when irrigation exceeded 320 mm, the nitrogen input did not significantly impact water consumption with the same irrigation quota. Conversely, when irrigation was below 340 mm, variations in nitrogen application rates substantially affected water consumption, with the differences becoming more pronounced as irrigation decreased. At an irrigation level of 400 mm, water consumption across all nitrogen treatments remained consistent at 371 mm. At an irrigation level of 320 mm, water consumption across nitrogen treatments ranged from 347 to 352 mm, and at 260 mm, it varied between 303 and 314 mm. Notably, under the same irrigation conditions, nitrogen supply changes had minimal impact on water consumption. Under the same nitrogen application rate, water consumption increased with the increase in irrigation levels. Further analysis revealed that with nitrogen rates between 200 and 480 kg·ha^{-1}, water consumption followed an upward trend as irrigation increased, ranging from 310 to 371 mm, with no significant differences across nitrogen groups.

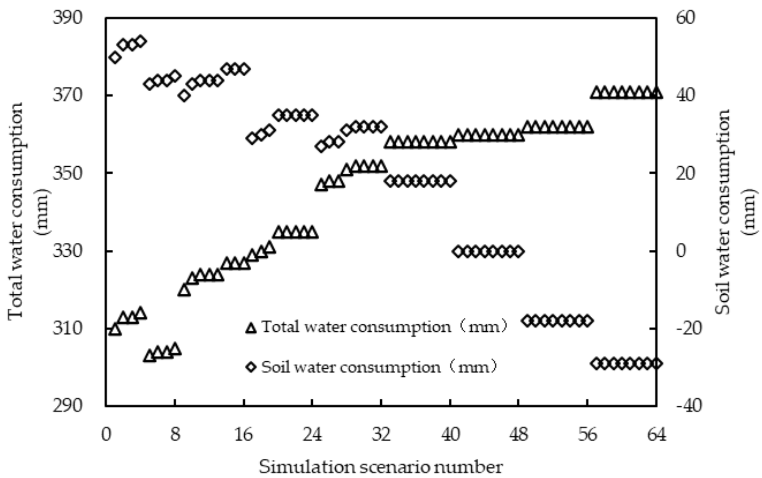
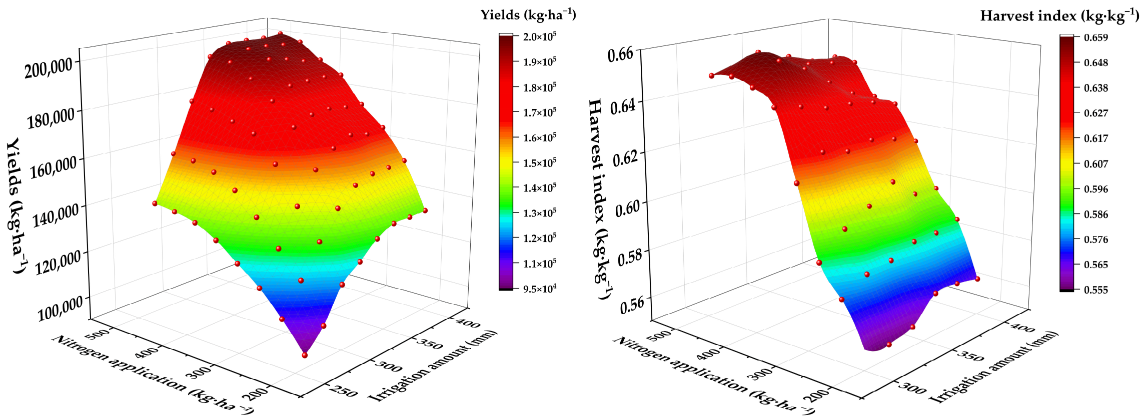


Figure 3. Effect of water–nitrogen coupling on water consumption of greenhouse tomatoes.

Soil water consumption, on the other hand, decreased as irrigation increased. When irrigation exceeded 340 mm, water consumption was predominantly from irrigation, and soil water storage remained consistent. When irrigation was below 320 mm, the proportion of soil water consumption relative to total water consumption increased as irrigation decreased. At an irrigation level of 260 mm, the proportion of soil water consumption across nitrogen treatments ranged from 14.75% to 17.20%, with an increasing trend in soil water consumption observed as nitrogen application rates rose, though differences among treatments were minimal. These findings underscore that irrigation levels are the primary factor influencing water consumption. Both total water consumption and soil water consumption increased with the amount of nitrogen applied when irrigation was between 280 and 320 mm, but no deep leakage was observed.

3.2.2. Effect of Water–Nitrogen Coupling on Greenhouse Tomato Yield

The simulation results for greenhouse tomato yield under varying water and nitrogen supply conditions (Figure 4) showed an increasing trend with increasing irrigation levels. However, when irrigation exceeded 320 mm, the yield response to further irrigation began to plateau. Within the irrigation range of 260~400 mm, the tomato yield increased consistently with an increase in nitrogen application at the same irrigation level. In particular, when irrigation ranged from 320 to 340 mm, yields across nitrogen treatments were high and demonstrated a positive trend with additional nitrogen input. However, when nitrogen application exceeded 360 kg·ha^{-1}, further increases in nitrogen yielded only marginal gains in yield, indicating a diminishing response to nitrogen fertilization. Furthermore, as nitrogen application increased, the harvest index within the same irrigation treatments either stabilized or slightly declined once nitrogen levels surpassed 360 kg·ha^{-1}, even while maintaining high yield levels.



(**a**) (**b**)

Figure 4. Effect of different water–nitrogen coupling schemes on yield (**a**) and harvest index (**b**) of greenhouse tomatoes.

3.2.3. Effect of Water–Nitrogen Coupling on Water- and Nitrogen-Use Efficiency of Greenhouse Tomatoes

Water-use efficiency (WUE) (Figure 5) and nitrogen partial factor productivity (NPFP) (Figure 6) were calculated based on the simulation results for greenhouse tomato yield and water consumption in various water–nitrogen coupling scenarios, using Equations (7) and (8). As shown in Figures 5 and 6, under the same irrigation conditions, WUE exhibited an increasing trend with an increase in nitrogen fertilizer input. However, when nitrogen input exceeded 360 kg·ha^{-1}, the rate of increase in WUE began to slow due to the synergistic effects of nitrogen fertilization. At a given nitrogen application level, when irrigation exceeded 320 mm, the positive effect of additional irrigation on WUE diminished. NPFP initially increased at higher irrigation levels under the same nitrogen conditions, then stabilized and eventually declined. Conversely, under a fixed irrigation level, NPFP decreased as nitrogen input increased.

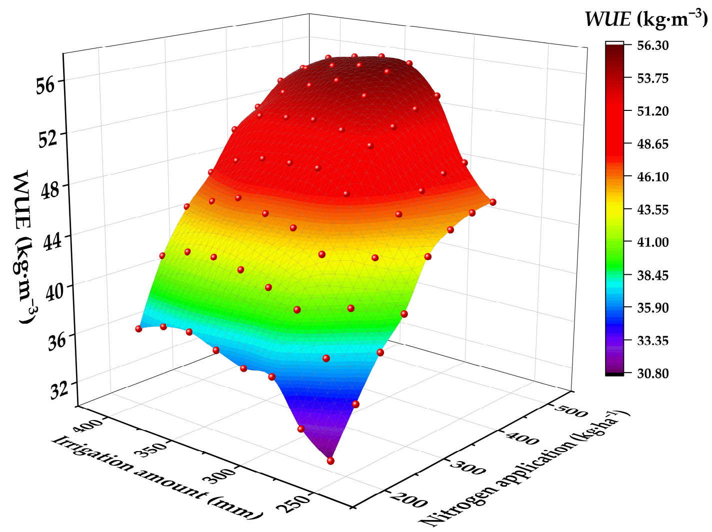


Figure 5. WUE of tomato in different water–nitrogen coupling scenarios.

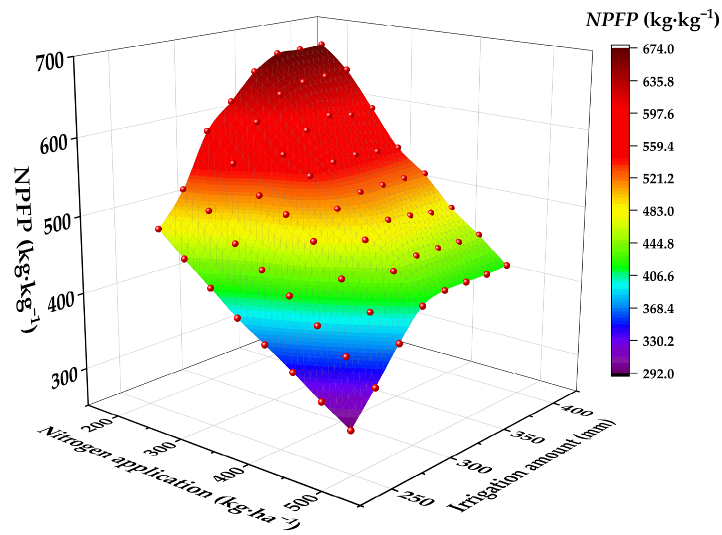


Figure 6. NPFP of tomato in different water–nitrogen coupling scenarios.

Scenarios 28~30 and 36~37 emerged as optimal water–nitrogen treatments under the experimental conditions considering economic yield, water-use efficiency, and nitrogen partial factor productivity, comprehensively. The recommended irrigation quota for greenhouse tomatoes is 320~340 mm, with a corresponding nitrogen application rate of 360~400 kg·ha^{-1}. These findings provide a robust theoretical basis for agricultural practices in this region, supporting high-yield, high-efficiency, and sustainable greenhouse tomato production.

3.3. Economic Benefit

Figure 7 shows the response of net income to irrigation and nitrogen fertilizer application. Net income increased with the increase in irrigation and nitrogen application, ranging from 352,833 CNY·ha^{-1} to 677,946.1 CNY·ha^{-1} across the 64 scenarios. The highest net income was obtained by the application with irrigation of 340 mm and nitrogen application of 400 kg·ha^{-1}. It should also be noted that excessive irrigation and nitrogen application can reduce water-use efficiency and nitrogen partial factor productivity of tomato. Therefore, the irrigation quota of 320~340 mm and the nitrogen fertilizer application rate of 360~400 kg·ha^{-1} are good choices for setting water levels and growing greenhouse tomatoes.

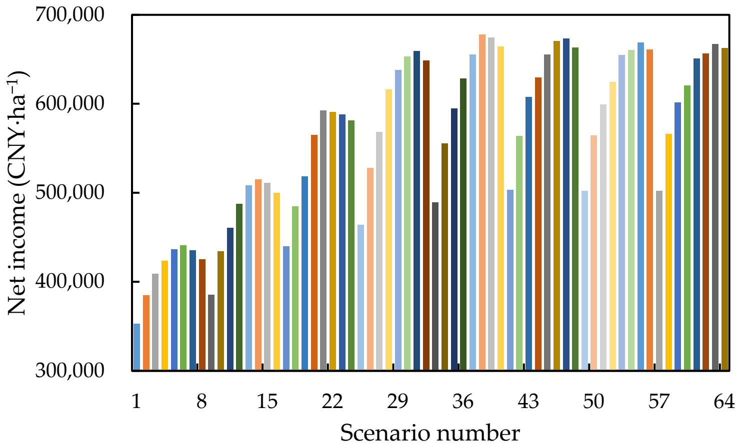


Figure 7. Economic analysis (net income) of tomato in different irrigation and nitrogen fertilizer application scenarios.

4. Discussion

4.1. Calibration and Validation of the CROPGRO–Tomato Model

Previous studies have shown that the DSSAT model can meet the needs of the various environmental and management interactions of different crops such as wheat [20], rice [31], corn [34], and cotton [35], such as the variety, climate impact, and the management of water and nitrogen coupling. Zhao et al. [21] used the DSSAT–CROPGRO–Tomato model simulation to determine a high-precision parameter estimation scheme for a greenhouse tomato trial, and the results showed that genetic parameter estimation using observations with adequate irrigation treatments could improve the simulation accuracy of the model. Through sensitivity analysis and uncertainty analysis of the genetic parameters of the DSSAT–CROPGRO–Tomato model, Li et al. concluded that the simulation accuracy of the high-irrigation treatment was higher than that of the low-irrigation treatment [29]. In this study, the DSSAT-GLUE method was used to calibrate the parameters of the CROPGRO–Tomato model to simulate the growth and yield of greenhouse tomato. The results showed that the model showed high accuracy in the simulation of tomato phenology. However, under water and nitrogen stress, especially with severe water stress, the simulation error of the model increases significantly, indicating that the application of the model under extreme conditions still needs further improvement. Li et al. [29] found that the simulation accuracy of the CROPGRO–Tomato model for simulating tomato growth and development in the higher soil moisture treatment was higher than that in the lower soil moisture treatment. Yao et al. [20] simulated the growth and development of winter wheat in water stress conditions using the DSSAT model, and the results showed that water stress would reduce the model simulation's accuracy. Similarly to the results of this study, the CROPGRO–Tomato model was used to simulate the flowering stage and ripening stage of tomato under different water and nitrogen supply conditions. The ARE values of plant height, tomato yield, and other indicators are mostly within 10% of the measured values, which is similar to the research results of Zhao [21] and Li [36]. It is further shown that the DSSAT–CROPGRO–Tomato model has good applicability, and the crop variety parameters determined in this study are scientifically reasonable and can be used to simulate the effects of different water and nitrogen supplies on the phenology, growth process, yield, and other indicators of greenhouse tomato.

The DSSAT model is widely used in water–nitrogen interaction analysis and crop growth simulation, but existing studies have shown that the model has certain limitations [14,20,37]. In the simulation of water–nitrogen interactions, the DSSAT model relies on a simplified nitrogen transformation equation, which fails to take into account microbial activity and soil heterogeneity, resulting in a low simulation accuracy of nitrogen dynamics under complex soil and climate conditions [38]. In addition, the water–nitrogen interaction itself has significant nonlinear characteristics, especially under extreme moisture conditions. It is also difficult for the model to accurately capture the combined effects of water stress on crop growth and nitrogen uptake, which limits the applicability of DSSAT in the face of extreme climatic events, such as drought or floods. In addition, DSSAT often relies on more generalized crop variety parameters in crop growth simulation, failing to fully consider the variability of different varieties and agricultural management practices, resulting in insufficient accuracy of the model in practical applications. In regional-scale applications, the model's ability to handle spatial heterogeneity is weak, making it difficult to accurately reflect soil conditions and water and fertilizer management strategies in different plots [39]. To overcome these deficiencies, future research should be devoted to improving the model's simulation of nitrogen dynamics, strengthening the nonlinear description of the water–nitrogen coupling effect, and combining remote sensing technology and big data analysis to improve the model's applicability at the regional scale and under extreme climatic conditions. Meanwhile, the modeling of crop variety differences and diversity of agricultural management practices should be strengthened to improve the accuracy and reliability of DSSAT application in precision agriculture.

4.2. DSSAT–CROPGRO–Tomato Model Scenario Simulation

The application of crop models offers predictive insights and scientific guidance for agricultural production. Developing water-saving irrigation systems is a crucial strategy for maximizing water resource efficiency and reducing agricultural water demand [17]. In this study, calibrated DSSAT–CROPGRO–Tomato model was used to simulate the growth and yield indices of greenhouse tomato under different combinations of water and nitrogen. This allowed for analysis of the effects of differing water and nitrogen supplies on the tomato growth, yield, water consumption, water-use efficiency (WUE), and nitrogen partial factor productivity (NPFP). The results indicated that with an adequate water supply, optimal nitrogen input enhanced tomato growth and yield. However, under water stress or excessive nitrogen conditions, yield and water–nitrogen efficiency declined.

The study showed that tomato water consumption in greenhouses increased with irrigation volume. When irrigation exceeded 320 mm, nitrogen input had minimal effect on water consumption at the same irrigation level, consistent with findings by Lei et al. [40]. Under deficit irrigation conditions, tomato yield, WUE, and NPFP values increased with the increase in irrigation amount. When the amount of irrigation reaches a certain level, the growth of yield tends to flatten out or decline. Nitrogen application significantly improved tomato yield and WUE; an appropriate nitrogen level facilitated nutrient uptake, promoted root water absorption, increased net photosynthesis, and ultimately enhanced yield [41]. Li et al. [42] also observed that while increases in both irrigation and fertilizer levels significantly raised yield, excessive water or nitrogen application led to diminished yield, indicating that over- or under-application was suboptimal for tomato production. Other studies have shown that, at a given irrigation level, moderate fertilizer application enhances irrigation WUE, whereas excessive fertilizer lowers it [43]. Additionally, research has demonstrated that within a certain irrigation range, tomato yield rises significantly with irrigation, while WUE decreases markedly [44].

We also analyzed the economic benefits of greenhouse tomato considering the water consumption, yield, and water- and nitrogen-use efficiency. Ultimately, the DSSAT–CROPGRO–Tomato model simulations determined that the optimal irrigation level for greenhouse tomatoes in this region is 320~340 mm, and the corresponding nitrogen fertilizer application rate is 360~400 kg·ha^{-1}. These findings provide valuable technical support for the development of high-quality and efficient irrigation and nitrogen application strategies for greenhouse tomato production. In future studies, we will explore the complex interactions of water and nitrogen in plant growth more deeply, in particular the effects on soil microbial activity, root growth, and plant nutrient uptake. This will help to better elucidate the growth mechanism of plants under different soil, water, and nitrogen conditions, and provide more reliable theoretical basis and technical support for agricultural production.

5. Conclusions

(1) The genetic parameters of greenhouse tomato in the experimental area in the CROPGRO–Tomato model according to DSSAT-GLUE are as follows: 30.42, 3.833, 19.50, 45.16, 1.10, 380, 0.744, 26.03, 57.12, and 8.50 for EM-FL, FL-SH, FL-SD, SD-PM, LFMAX, SLAVE, XFRT, SFDUR, PODUR, and THRSH, respectively.

(2) The CROPGRO–Tomato model performs well when simulating various growth indicators of greenhouse tomato, except the average stem and leaf number. The stem and leaf number are affected by field management measures, resulting in an average ARE of 13.84%. The ARE values of other growth indicators are less than 10%.

(3) Considering the economic yield of tomato, water, and nitrogen utilization efficiency, and other indicators, the optimal irrigation rate for greenhouse tomato in this region is 320~340 mm, and the nitrogen application rate is 360~400 kg·ha^{-1}.

Author Contributions: Conceptualization, Z.S. (Zhijie Shan); methodology, J.C. and Z.S. (Zhuanyun Si); investigation, J.C. and R.Y.; data curation, J.C., X.Z. and R.Y.; formal analysis, J.C. and X.Z.; writing—original draft preparation, J.C. and X.Z.; writing—editing, J.C. and Z.S. (Zhijie Shan); supervision, X.Z. and H.F.; project administration, X.Z. and H.F.; funding acquisition, Z.S. (Zhijie Shan) and Z.S. (Zhuanyun Si). All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Key Research and Development Program of China (2023YFD1900802-01), the Major Science and Technology Projects of Ministry of Water Resources of the People's Republic of China (No. SKS-2022044), the Central Water Conservancy Development Fund Funded Project (11000023T000002098219), and the Central Public Interest Scientific Institution Basal Research Fund (Y2024QC19).

Data Availability Statement: The data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Jin, N.; Zhang, D.; Jin, L.; Wang, S.Y.; Yang, X.T.; Lei, Y.Z.; Meng, X.; Xu, Z.Q.; Sun, J.H.; Lyu, J.; et al. Controlling water deficiency as an abiotic stress factor to improve tomato nutritional and flavour quality. *Food Chem. X* **2023**, *19*, 100756. [CrossRef] [PubMed]
2. National Bureau of Statistics of China. *China Statistical Yearbook*; China Statistics Press: Beijing, China, 2022.
3. Dong, J.S.; Xue, Z.; Shen, X.J.; Yi, R.C.; Chen, J.W.; Li, Q.; Hou, X.F.; Miao, H.C. Effects of different water and nitrogen supply modes on peanut growth and water and nitrogen use efficiency under mulched drip irrigation in Xinjiang. *Plants* **2023**, *12*, 3368. [CrossRef]
4. Cheng, G.T.; Wang, Y.F.; Jiang, W.T.; Lin, J.S.; Feng, X.D.; Chang, H.F.; Qiao, H.X.; Liang, Y. Research progress on comprehensive preventive and control measures for soil obstacle in facility tomato. *China Veg.* **2023**, 16–24. [CrossRef]
5. Abdelghany, A.E.; Dou, Z.; Alashram, M.G.; Eltohamy, K.M.; Elrys, A.S.; Liu, X.; Wu, Y.; Cheng, M.; Fan, J.; Zhang, F. The joint application of biochar and nitrogen enhances fruit yield, quality and water-nitrogen productivity of water-stressed greenhouse tomato under drip fertigation. *Agric. Water Manag.* **2023**, *290*, 108605. [CrossRef]
6. Sun, Y.N.; Duan, L.B.; Zhong, H.Y.; Cai, H.J.; Xu, J.T.; Li, Z.J. Effects of irrigation-fertilization-aeration coupling on yield and quality of greenhouse tomatoes. *Agric. Water Manag.* **2024**, *299*, 108893. [CrossRef]
7. Wang, H.D.; Qu, Y.; Wen, Z.J.; Cheng, M.H.; Zhang, F.C.; Fan, J.L.; Yang, Q.L.; Liu, X.G.; Wang, X.K. Interactive effects of irrigation and N fertilization management on fruit yield, quality and water-N productivity of greenhouse cherry tomato. *Sci. Hortic.* **2024**, *328*, 112895. [CrossRef]

8. Wu, Y.; Si, W.; Yan, S.; Wu, L.; Zhao, W.; Zhang, J.; Zhang, F.; Fan, J. Water consumption, soil nitrate-nitrogen residue and fruit yield of drip-irrigated greenhouse tomato under various irrigation levels and fertilization practices. *Agric. Water Manag.* **2023**, *277*, 108092. [CrossRef]
9. Yu, H.Y.; Zhao, W.J.; Ding, L.; Zhou, C.Q.; Ma, H. Effects of coordinated regulation of water, nitrogen, and biochar on the yield and soil greenhouse gas emission intensity of greenhouse tomatoes. *J. Environ. Manag.* **2024**, *370*, 122801. [CrossRef] [PubMed]
10. Zhang, J.W.; Xiang, L.X.; Liu, Y.X.; Jing, D.; Zhang, L.L.; Liu, Y.; Li, W.Q.; Wang, X.Y.; Li, T.L.; Li, J.M. Optimizing irrigation schedules of greenhouse tomato based on a comprehensive evaluation model. *Agric. Water Manag.* **2024**, *295*, 108741. [CrossRef]
11. Ma, W.W.; Shi, J.C.; Jin, X.X.; Ning, S.R.; Li, S.; Tao, Y.Y.; Zhang, Y.N.; Liu, Y.; Lin, S.; Hu, P.C.; et al. Improved CERES-Rice model to simulate the growth of mulched dry rice. *Trans. China Soc. Agric. Eng.* **2017**, *33*, 115–123.
12. Corbeels, M.; Chirat, G.; Messad, S.; Thierfelder, C. Performance and sensitivity of the DSSAT crop growth model in simulating maize yield under conservation agriculture. *Eur. J. Agron.* **2016**, *76*, 41–53. [CrossRef]
13. Xu, N.; Dang, T.H. Prediction of nitrogen fertilizer effect of winter wheat based on DSSAT model: A case study of Weibei dry plateau in the gully area of the Loess Plateau. *J. Irrig. Drain.* **2017**, *36*, 147–154. [CrossRef]
14. Du, J.T.; Zhang, N.; Gong, K.N.; Du, M.Z.; Yang, Y.P.; Wang, X.P. Optimization of drip irrigation system of cotton under membrane in southern Xinjiang based on DSSAT model. *China J. Ecol.* **2021**, *40*, 3760–3768. [CrossRef]
15. Jones, J.W.; Hoogenboom, G.; Porter, C.H.; Boote, K.J.; Batchelor, W.D.; Hunt, L.A.; Wilkens, P.W.; Singh, U.; Gijsman, A.J.; Ritchie, J.T. The DSSAT cropping system model. *Eur. J. Agron.* **2003**, *18*, 235–265. [CrossRef]
16. Bhatia, V.S.; Singh, P.; Wani, S.P.; Chauhan, G.S.; Rao, A.V.R.K.; Mishra, A.K.; Srinivas, K. Analysis of potential yields and yield gaps of rainfed soybean in India using CROPGRO-Soybean model. *Agric. For. Meteorol.* **2008**, *148*, 1252–1265. [CrossRef]
17. Wang, P.Y.; Liu, J.R.; Zhang, T.Q.; Liu, X. Optimization of sugarcane deficit irrigation in Guangxi based on DSSAT model. *J. Irrig. Drain.* **2021**, *40*, 133–139. [CrossRef]
18. Li, Y.; Zhang, S.Y.; Liu, Q.Z.; Ji, Y.D.; Yao, N.; Song, X.Y. Effects of droughts and meteorology on spring wheat in western Loess Plateau based on DSSAT-CERES-Wheat model. *Trans. China Soc. Agric. Mach.* **2022**, *53*, 338–348.
19. Maldonado-Ibarra, I.; Rodríguez, G.R.; Castillo-Rosales, D. Determination of genetic coefficients of three springwheat varieties under a Mediterranean environment applying the DSSAT model. *Chil. J. Agric. Res.* **2015**, *75*, 418–424. [CrossRef]
20. Yao, N.; Zhou, Y.G.; Song, L.B.; Liu, J.; Li, Y.; Wu, S.F.; Feng, H.; He, J.Q. Parameter estimation and verification of DSSAT-CERES-Wheat model for simulation of growth and development of winter wheat under water stresses at different growth stages. *Trans. China Soc. Agric. Eng.* **2015**, *31*, 138–150.
21. Zhao, Z.L.; Li, B.; Feng, X.; Yao, M.Z.; Xie, Y.; Xing, J.W.; Li, C.X. Parameter estimation and verification of DSSAT-CROPGRO-Tomato model under different irrigation levels in greenhouse. *China J. Appl. Ecol.* **2018**, *29*, 2017–2027. [CrossRef]
22. Li, Z. The response of spring maize-soil system to different water-nitrogen management regimes and applicability research of DSSAT-CERES-Maize model in hetao irrigation district. Ph.D. Thesis, Inner Mongolia Agricultural University, Hohhot, China, 2017.
23. Si, Z.Y.; Zain, M.; Li, S.; Liu, J.M.; Liang, Y.P.; Gao, Y.; Duan, A.W. Optimizing nitrogen application for drip-irrigated winter wheat using the DSSAT-CERES-Wheat model. *Agric. Water Manag.* **2021**, *244*, 106592. [CrossRef]
24. Han, Y.J.; Han, T.H. China's wheat yield increase potential and realization path during the 14th five-year plan period. *Issues Agric. Econ.* **2021**, 38–46. [CrossRef]
25. Ritchie, J.T. International consortium for agricultural systems applications (ICASA): Establishment and purpose. *Agric. Syst.* **1995**, *49*, 329–335. [CrossRef]
26. Liu, H.; Yang, J.; Drury, C.F.; Reynolds, D.; Tan, C.S.; Bai, Y.; He, P.; Jin, J.; Hoogenboom, G. Using the DSSAT-CERES-Maize model to simulate crop yield and nitrogen cycling in fields under long-term continuous maize production. *Nutr. Cycl. Agroecosystems* **2011**, *89*, 313–328. [CrossRef]
27. DeJonge, K.C.; Ascough, J.C., II; Ahmadi, M.; Andales, A.A.; Arabi, M. Global sensitivity and uncertainty analysis of a dynamic agroecosystem model under different irrigation treatments. *Ecol. Model.* **2012**, *231*, 113–125. [CrossRef]
28. Rinaldi, M.; Ventrella, D.; Gagliano, C. Comparison of nitrogen and irrigation strategies in tomato using CROPGRO model. A case study from Southern Italy. *Agric. Water Manag.* **2007**, *87*, 91–105. [CrossRef]
29. Li, B.; Li, C.X.; Yao, M.Z.; Wei, X.G.; Bao, Z.R.; Sun, X.L. Sensitivity and uncertainty analysis for CROPGRO—Tomato model at different irrigation levels. *J. Shenyang Agric. Univ.* **2020**, *51*, 153–161.
30. He, J.; Jones, J.W.; Graham, W.D.; Dukes, M.D. Influence of likelihood function choice for estimating crop model parameters using the generalized likelihood uncertainty estimation method. *Agric. Syst.* **2010**, *103*, 256–264. [CrossRef]
31. Wang, B.; Yang, H.X.; Feng, J.; Guo, Z.Y.; Guo, Y.W. Rice genotype coefficient optimization of DSSAT based on PSO. *Trans. China Soc. Agric. Mach.* **2023**, *54*, 369–375.
32. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper 56*; FAO: Rome, Italy, 1998; p. 300.
33. Shen, X.J. Real-time irrigation forecasting technology for cotton with under-membrane drip irrigation. Master's Thesis, Shihezi University, Shihezi, China, 2008.

34. Liu, Y.; Guan, X.; Yang, M.; Ding, C.; Cui, J.; Huang, J.; Mei, F.; Wang, H.; Wang, T. Optimizing the summer maize irrigation schedule in North Henan Province based on the DSSAT model. *Acta Ecol. Sin.* **2019**, *39*, 5348–5358.
35. Wang, X.P.; Xin, L.; Du, J.T.; Li, M.F. Simulation of cotton growth and yield under film drip irrigation condition based on DSSAT model in Southern Xinjiang. *Trans. China Soc. Agric. Mach.* **2022**, *53*, 314–321.
36. Li, B.; Sun, X.L.; Yao, M.Z.; Bao, H.; Wang, J.H. Parameter estimation and verification of the DSSAT-CROPGRO-Tomato model under the condition of different amounts of straw returned to the field in the greenhouse. *China J. Ecol.* **2021**, *40*, 908–918. [CrossRef]
37. Mao, X.; Yang, J.L.; Zhu, X.H.; He, C.; Feng, H.; He, J.Q. Simulation accuracy of growth and development of winter rape (*Brassica napus* L.) in Guanzhong plain with different crop models. *Trans. China Soc. Agric. Mach.* **2019**, *50*, 306–314.
38. Li, Z.K.; Li, X.Y.; Zhou, S.; Yang, X.F.; Fu, Y.Y.; Miao, C.Y.; Wang, S.; Zhang, G.; Wu, X.C.; Yang, C.; et al. A comprehensive review on coupled processes and mechanisms of soil-vegetation-hydrology, and recent research advances. *Sci. China Earth Sci.* **2022**, *65*, 2083–2114. [CrossRef]
39. Meng, J.H.; Wang, Y.N.; Lin, Z.X.; Fang, H.T. Progress and perspective of crop growth models. *Trans. China Soc. Agric. Mach.* **2024**, *55*, 1–15+27.
40. Lei, C.X.; Li, W.H. Effects of water and nitrogen coupling under film drip irrigation on the water consumption intensity and nitrogen uptake and distribution of processing tomatoes. *J. Shihezi Univ.* **2021**, *39*, 54–61. [CrossRef]
41. Wang, H.B.; Cao, H.X.; Hao, S.X.; Pan, X.Y. Responses of plant nutrient and photosynthesis in greenhouse tomato to water-fertilizer coupling and their relationship with yield. *Sci. Agric. Sin.* **2019**, *52*, 1761–1771.
42. Li, J.M.; Pan, T.H.; Wang, L.H.; Du, Q.J.; Chang, Y.B.; Zhang, D.L.; Liu, Y. Effects of water-fertilizer coupling on tomato photosynthesis, yield and water use efficiency. *Trans. China Soc. Agric. Eng.* **2014**, *30*, 82–90.
43. Song, N.; Wang, F.; Yang, C.F.; Yang, K.J. Coupling effects of water and nitrogen on yield, quality and water use of potato with drip irrigation under plastic film mulch. *Trans. China Soc. Agric. Eng.* **2013**, *29*, 98–105.
44. Xing, Y.Y.; Zhang, F.C.; Zhang, Y.; Li, J.; Qiang, S.C.; Wu, L.F. Effect of irrigation and fertilizer coupling on greenhouse tomato yield, quality, water and nitrogen utilization under fertigation. *Sci. Agric. Sin.* **2015**, *48*, 713–726.