Agricultural Water Management 212 (2019) 23–34

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Identifying optimal water and nitrogen inputs for high efficiency and low environment impacts of a greenhouse summer cucumber with a model method

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A R T I C L E I N F O

Keywords:
EU-Rotate_N model
Optimal water and fertilization management practices
Nitrogen use efficiency
Osculating value method

A B S T R A C T

High-input of water and nitrogen (N) fertilizers in intensive greenhouse vegetable production regions in China has successfully increased crop productivity in the past decades, but at a significant environmental cost and resource consumption. It is essential to choose best management practice (BMP) to meet multiple goals, such as keeping greenhouse vegetable yield stable, improving nitrogen use efficiency (NUE), and reducing the nitrogen pollution issue. However, the bottleneck is the capacity of predicting the simultaneous effects of different management practice scenarios on multiple goals and choosing BMP among scenarios. The object of this study was to identify BMP of water and N fertilizer for greenhouse summer cucumber in North China Plain using calibrated and validated EU-Rotate_N model. The data used to calibrate and validate the model were collected from a typical greenhouse summer cucumber field with four different water and N fertilizer treatments within the target domain region. A total of 240 varied scenarios of water use and fertilizer application were set up and then simulated by the model. An osculating value method was used to evaluate combinations of irrigation and fertilizer practices. Agronomic indices (yield, WUE and NUE), environmental indices (nitrate leaching and gaseous N loss), and economic index (value to cost ratio) were selected as the evaluation indices to identify the BMP. The results showed that cucumber yield increased to maximum value as water input reached to about 277 mm, then kept constant or even decreased under lower N fertilizer rates. Nitrogen started to lose as nitrate leaching when irrigation increased to 300–400 mm, and then nitrate leaching increased with irrigation increasing. The effects of water input on gaseous nitrogen loss were not significant. Regardless of N fertilizer rates, irrigating about 300 mm water can obtain the maximum NUE. Cucumber yield increased to maximum values as N fertilizer input reached to about 313 and 310 kg N ha^{-1} for furrow and drip irrigation, then was not affected by N fertilizer increase. The BMPs under furrow irrigation condition were to irrigate 300 mm with 300 kg N ha^{-1} and 250 mm with 300 kg N ha^{-1} under drip irrigation condition for greenhouse cucumber in the study area, respectively. Adopting the current BMPs, the applied nitrogen and irrigation water were at about 55 and 40% lower rates, respectively, than the current conventional use. Our study indicated that the EU-Rotate_N model combined with Osculating value method can be helpful to assess multi-goal effects of management alternatives and identify BMP.

1. Introduction

At present, the China's economy has developed rapidly and scientific innovations have been increasing continuously. However, the shortage of resources and environmental restrictions are the biggest challenges to China's economic growth. Hence, maintaining its rapid economic growth, China needs to transform the traditional high-consumption and high-pollution production pattern to the green development mode as rapidly as possible. To produce food in a highly efficient manner with the lowest possible environmental hazards, China's modern agriculture is shifting from a single-goal to a multi-goal strategy. A multi-goal management of the green agriculture is expected to simultaneously aim for the following four goals: (a) sustaining/enhancing productivity (crop yields); (b) reducing reactive nitrogenous

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https://doi.org/10.1016/j.agwat.2018.08.028
Received 23 May 2018; Received in revised form 19 August 2018; Accepted 20 August 2018

gases emissions to protect the air quality and the climate; (c) mitigating hydrological nitrogen losses (mainly nitrate leaching) to secure water quality; and (d) enhancing resource efficiency to reduce the cost and create higher values. However, single-goal management is obviously not environmentally friendly and thus unsustainable because of high water and nitrogen consumption and low use efficiencies. Therefore, best management practice (BMP) is highly essential, which includes the assessment of biogeochemical effects of various management practices, i.e., fertilization and irrigation. There are two challenges of identifying a BMP. One is how to quantify the biogeochemical effects of various management alternatives on the multiple goals stated above, and the other is how to identify the BMP from these management alternatives (Cui et al., 2014). Field experiments have played a key role in determining management practice effects. For example, various water and N fertilizer practices have been employed in field plot experiments to study their effects on nitrogen use efficiency and obtain an optimal water and nitrogen practice (Smith et al., 1998; Hu et al., 2010; Min et al., 2012; He et al., 2009; Pang et al., 2009). Surface drip or subsurface drip irrigation could not only reduce nitrate leaching by decreasing water drainage but also increase vegetable yield (Yohannes and Tadesse, 1998; Sharmasarkar et al., 2001). In addition, optimizing N fertilizer rates, application times and methods could further reduce nitrate leaching, gaseous nitrogen release and soil residue nitrogen content (Waddel et al., 2000; Halvorson et al., 2002; Muñoz et al., 2008; Zotarelli et al., 2009). Some studies also recommended the best nitrogen fertilizer application rates (e.g., Ren et al., 2010; Min et al., 2012). However, these experimental methods are costly and time-consuming, and some processes are difficult to measure due to the limited experimental treatments (Liu et al., 2016).

Alternatively, simulation models are a potentially useful approach for the development of management strategies to identify the BMP. Once calibrated and validated for a given agricultural system, they can be used to examine multiple management scenarios. They are also very effective tools for demonstrating the effects of improved management practices to growers, technical advisors and policy makers. Recently, many mechanistic models have shown good performance in simulating the soil water content, nitrogen loss and crop uptake nitrogen (Sabit and Rüstü Karaman, 2001; Gallardo et al., 2009; Zhang et al., 2009). For example, the EU-Rotate_N model based on the N_ABLE model has been proposed as a powerful tool for simulating water and nitrogen dynamics in soil-plant systems and crop growth (Nendel, 2009; Rahn et al., 2010). The EU-Rotate_N model has been validated and has been used to simulate water, nitrogen dynamics and vegetable growth in some studies conducted in various climatic regions (Guo et al., 2010; Sun et al., 2012, 2013; Soto et al., 2014). Sun et al. (2013) also used the EU-Rotate_N model to identify the BMP for a greenhouse tomato planting system in China in conjunction with the osculating value method.

The North China Plain is one of the major vegetable cultivation bases in China. For example, the vegetable cultivation area has increased to 65,000 ha in Beijing city (Beijing Municipal Bureau of Statistics, 2016). The severe environmental impact induced by the intensive vegetable production has increased over the last several years (Shi et al., 2009; Chen et al., 2004; Ju et al., 2006). Because of the notably different characteristics of vegetable production in greenhouse, such as more water and nitrogen input, higher water and N applied frequency, higher humidity, lower evaporative demand, and negligible wind speed, it is necessary to develop a model method that is expected to be applicable for such complicate cases. EU-Rotate_N is likely a valuable tool for the evaluation of changes in management on yields, environmental impacts, resource efficiency with, for example, a much larger number of scenarios and more complex responses of the goal variable. However, to date, the studies for the use of the EU-Rotate N model for greenhouse vegetables are still rare. Especially, very few studies on identifying the BMPs delimitate the contribution rate of economic cost.

To identify BMP for the greenhouse vegetables system in the North China Plain, we conducted a modeling case study at a greenhouse summer cucumber field in Beijing suburb, where simultaneous observations of cucumber yield, soil water content and soil nitrate concentration were available. Our objectives were to (a) validate and apply the EU-Rotate_N model using simultaneous observations, (b) use model simulation to analyze the biogeochemical effects of alternative irrigation (furrow and drip) and fertilization conditions, and (c) identify the best water and fertilizer N management practices aiming at our four goals stated above.

2. Materials and methods

2.1. Study area

The experiment was conducted at the Luxi Vegetable Research Institute demonstration site, Fangshan district (39.38°, 116.01 E), which is located in the southwest of Beijing Municipality in the Northern China. The annual average air temperature and total precipitation are 11.9 °C and 528.5 mm, respectively. The soil of the experimental field is classified as a Cambisol (FAO/Unesco, 1988). The annual average temperature in the greenhouse is 21.0 °C. The irrigation amounts and fertilizer application rates of greenhouse cucumber in farm practice are approximately 600–700 mm and 1000–1200 kg N ha^{-1} per growth season, respectively.

2.2. Experiment design

This field was used for greenhouse cucumber cultivation starting in 2012. Four irrigation and fertilizer treatments were designed: furrow irrigation + conventional fertilizer (farmer's practicF + C), drip irrigation + conventional fertilizer (D + C), furrow irrigation + optimal fertilizer (F + OPT), and drip irrigation + optimal fertilizer (D + OPT).The area of the experimental field was 155 m × 6 m. Each plot size was 6 m × 8 m. All of the treatments were set up in a randomized block designed with three replicates. The field data used to calibrate and validate the model in this study were collected from March 2014 to July 2014 over one growing season. During this time, the monthly average temperature was 19.9, 19.5, 23.0, 27.5, and 32.7 °C, respectively. The cucumber cultivar was Zhongnong26. Cucumber seedlings with two leaves were transplanted on 22 February 2014 and were harvested on 6 July 2014. The row spacing was 0.35 m, and the seedlings were spaced at 0.25 m within each row in all of the experimental treatments.

The details of the irrigation and fertilizer applications are shown in Table 1. Cattle manure was applied for all of the treatments at a rate of 500 kg N ha^{-1} as the basal fertilizer on 19 February 2014. The F + C and D + C treatments received 210 kg N ha^{-1} of urea as the basal fertilizer and 490 kg N ha^{-1} as the dressing fertilizer. The F + OPT and D + OPT treatments received 126 kg N ha^{-1} of urea as the basal fertilizer and 294 kg N ha^{-1} as the dressing fertilizer. In all of the treatments, 120 kg P_2O_5 ha^{-1} of calcium monophosphate and 200 kg K_2O ha^{-1} of potassium sulfate were applied as the basal fertilizer. For all of the treatments, the irrigation time and fertilizer application were based on the local farmers' practices, and the fertilizer was dissolved in irrigation water and then applied. For the drip irrigation treatments (D + C

Table 1
Water and fertilizer management for greenhouse cucumber cultivation in 2014.

Year	Treatments	Irrigation mm	Manure kg N ha^{-1}	Fertilizer kg N ha^{-1}
2014	F + C	513	500	700
	D + C	513	500	700
	F + OPT	313	500	420
	D + OPT	313	500	420

Table 2
Soil physical, chemical and hydraulic properties for the 0–100 cm soil profile.

Depth cm	BD g cm^{-3}	Particle fraction(%)			Texture (USDA)	θ_{fc} (cm^3. cm^{-3})	θ_{wp} (cm^3 c^{-3})	θ_s (cm^3 cm^{-3})	pH	OM (g kg^{-1})	TN (g kg^{-1})
		Sandy	Silt	Clay							
0–20	1.43	17	65	18	Silt loam	0.40	0.23	0.49	7.57	54.7	3.2
20–40	1.55	17	69	14	Silt loam	0.37	0.15	0.41	7.77	22.3	1.4
40–60	1.56	21	66	13	Silt loam	0.34	0.11	0.39	7.80	15.2	0.9
60–80	1.51	19	67	14	Silt loam	0.42	0.20	0.45	7.83	12.4	0.8
80–100	1.50	19	68	13	Silt loam	0.30	0.10	0.42	7.80	12.7	0.8

Note: *BD*, bulk density; θ_{fc}, soil water content at field capacity; θ_{wp}, soil water content at permanent wilting point; θ_s, soil saturation water content; OM, organic matter; TN, Total N.

and D + OPT), the amount of water used was 60% of that in the furrow irrigation treatments (F + C and F + OPT). For the F + OPT and D + OPT treatments, the amount of inorganic fertilizer was 60% of the F + C treatment which was recommended by the government.

2.3. Field sampling and soil properties measurement

We excavated a soil profile pit to 100 cm, and soil samples were collected at 20-cm intervals in the 0–100 cm soil profile before cucumber transplanting in 2014. The basic soil physical-chemical properties, including the bulk density, pH, organic matter, total nitrogen, available nitrogen, phosphorus and potassium, were measured. The soil bulk density and water content were measured by oven-drying for 24 h at 105 °C (Grossman and Reinsch, 2002). The soil pH was determined using a soil: water (1:2.5) slurry. The soil organic matter was determined by the potassium dichromate wet combustion procedure. Total nitrogen (TN) was measured by the Kjeldahl method. The soil saturated water content and the soil water retention curve for each layer were also measured. The results are presented in Table 2.

In each plot, the soil volumetric water content at 30-cm intervals in the 0- to 90-cm soil profile was measured every day using a sensor (SM300, Delta-T). Soil samples were collected to determine the nitrate content at a 30-cm depth from 25 to 35 cm soil layers once every 15 days. The soil samples were extracted with 0.1 mol l^{-1} KCl to determine the concentrations of NO_3-N by a continuous-flow analyzer (TRAACS 2000, Bran and Luebbe). The weather dataset in the greenhouse (air temperature, relative humidity, solar radiation and wind speed) was collected using an automatic weather station (WS-STD1).

2.4. Model description and inputs

The EU-Rotate_N model was used to simulate soil water movement, nitrogen transport, and plant growth in this study. The model has been embedded in the European Decision Support System as a tool for assessing the effects of fertilization and rotational practices on crop growth and nitrogen loss (Nendel, 2009; Rahn et al., 2010). The model contains modules for simulating various soil/plant processes, including root development, N mineralization from soil organic matter and crop residues, water and N uptake by roots, and water movement and N transport in soil. The crop growth module of the model was inherited from the N_ABLE model of Greenwood et al. (1996). The water demand of the crop was calculated with the Penman-Monteith method of the FAO (Allen et al., 1998). Soil water movement was simulated with the soil water balance method proposed by Ritchie (1998). Runoff was calculated with the approach recommended by the U.S. National Resource Conservation Service (NRCS, 2004). The N mineralization module was based on the routines in the DAISY model (Hansen et al., 1990). Ammonia volatilization from manure was described with an empirical equation used in the ALFAM model (Sϕgaard et al., 2002). Urea hydrolysis and gaseous N emission simulation were based on the AMOVOL model (Sadeghi et al., 1988).

Basic information was entered in the model, including: the site location (latitude, altitude), basic soil physical- chemical properties (soil bulk density, soil hydraulic properties, soil initial water and mineral nitrogen condition), crop data (crop species, row width, plant spacing, time of planting, number of harvest, harvest time), field management, and meteorological data (Sun et al., 2012).

2.5. Processes of model calibration and validation and performance criteria

We used the measured data from the F + C treatment to calibrate the model. The ‘trial and error’ method was used to adjust the model parameters until the values for the statistical procedures (*RMSE*, *NSE*, etc.) were good (Boote, 1999; Wang and Huang, 2008; Ma et al., 2012). The calibration process followed the order of soil water content, NO_3-N content, and crop yield. The measured soil hydraulic properties are shown in Table 2. For the cucumber crop, the default values of the coefficient (Table 3) related to the plant growth and nitrogen transport processes in the model (Nendel, 2009) are shown in Table 3. However, the values of these parameters were adjusted based on the measured

Table 3
Crop and nitrogen transformation parameters used in the EU-Rotate_N model.

Parameters	Description	Default Value	Calibration value
K_ini	Crop coefficient in initial stage	0.5	0.4
K_mid	Crop coefficient in middle stage	0.8	1.1
K_end	Crop coefficient in end stage	1.1	1.0
RLUX	Luxury N consumption coefficient	1.2	1.0
PNINF	Empirical parameter of luxury N consumption	1.35	1.2
B0	Empirical parameter of luxury N consumption	3	2.5
H_max	Maximum crop height (m)	0.2	1.5
L_ini	Length of the initial growth period (days)	20	30
L_dev	Length of the development period (days)	30	30
L_mid	Length of the middle period (days)	70	60
L_lat	Length of the late growth period (days)	15	15
AOM_FastUti_Eff	Substrate of add organic matter utilization efficiency (0-1)	0.4	0.8
Atmospheric_Resis	Atmospheric resistance parameter (s m^{-1})	25	35

cucumber yield and the soil NO_3-N content during the calibration processes. The adjusted cucumber growth and nitrogen transformation parameters are shown in Table 3. The calibrated model was then validated with the measured data that were collected from other three treatments (D + C, F + OPT, and D + OPT).

Four statistical indices were used to assess the agreement between the predicted and observed data during the model calibration and validation:

(1) Root mean square error (*RMSE*)

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

Systematic root mean square error (*RMSEs*) (Willmott, 1981)

$$RMSEs = \sqrt{\sum_{i=1}^{n} \frac{(\hat{P}_i - O_i)^2}{n}} \quad (2)$$

Unsystematic root mean square error (*RMSEu*) (Willmott, 1981)

$$RMSEu = \sqrt{\sum_{i=1}^{n} \frac{(P_i - \hat{P}_i)^2}{n}} \quad (3)$$

(2) Nash-Sutcliffe modeling efficiency (*NSE*)(Nash and Sutcliffe, 1970)

$$NSE = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - O)^2} \quad (4)$$

(3) Agreement index (*d*)(Willmott, 1981)

$$d = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (|P_i - O| + |O_i - O|)^2} \quad (5)$$

(4) Percent bias (*PBIAS*) (Moriasi et al., 2007)

$$PBIAS = \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} O_i} \times 100 \quad (6)$$

where n is the number of samples, P_i and O_i are the predicted and observed values, and O is the mean of the observed data. $\hat{P}$ is derived from $\hat{P} = a + bO_i$ and a and b are the intercept and slope of a least-squares regression between the predicted and observed values. The closer the root mean square error (*RMSE*) value is to 0, the more accurate the model. When $RMSEs < RMSEu$, a good simulation is indicated. The modeling efficiency (*NSE*) ranges from $-\infty$ to 1. The agreement index (d) represents the ratio of the mean square error and the potential error. When $NSE = 1$ or $d = 1$, a perfect simulation of the results is indicated. *PBIAS* reveals whether there is a systematic bias, a positive value of *PBIAS* indicates the model underestimation bias, and a negative value indicates the model overestimation bias.

2.6. Alternative water and N fertilizer scenarios

In this study, the scenarios of the water and N fertilizer inputs in the furrow and drip irrigation methods were tested. The timing of irrigation and fertilization is the same for the two irrigation methods, which is in agreement with experimental practices. The investigated paradigms included: (1) single factor variation with different water inputs, (2) single factor variation with different N fertilizer application rates, and (3) two-factor variation with different water and N fertilizer inputs. The amounts of fertilizer P and K applications met the cucumber growth requirements, both were fixed under each scenario. The simulation scenarios for each irrigation method were:

(1) Varying the total irrigation amount from 50 to 600 mm in increment of 50 mm.
(2) Varying the total fertilizer N application rate from 60 to 1200 kg N ha^{-1} in increments of 60 kg N ha^{-1}.

The number of scenarios for the water and fertilizer inputs was 12 and 20, respectively, and the total number of scenarios combination of water and nitrogen fertilizer applications was 240 for each irrigation method. The above-described scenarios were conducted by solely varying the mentioned parameters while holding the values of the other parameters at the default levels. The cucumber yield, water drainage, nitrate leaching, gaseous N emission, WUE and NUE were simulated or calculated.

2.7. Assessment of the simulation results with the osculating value method

Previous studies confirmed that the osculating value method was useful for assessing the effects of the agricultural practices on groundwater quality, crop yield, and nitrogen loss (Wang, 1989; Lou, 2002; Sun et al., 2013). Hence, the osculating value method was selected to obtain a best water and N fertilizer practice for cucumber production in this study. To work with the osculating value method, we first built an initial decision matrix consisting of some indicators. Considering cucumber production, maximization of the economic benefit and minimization of environmental pollution, the agronomy factor (AF), environment factor (EF) and value to cost ratio (VCR) were used as the indicators in the initial decision matrix. Specifically, the cucumber yield, WUE and NUE were selected to calculate the AF. The weights of the yield, WUE and NUE were set as +0.6, +0.2, +0.2, respectively (Hu et al., 2010; Sun et al., 2013). The three indices (cucumber yield, WUE and NUE) were normalized with a range of 0–1. AF was calculated by summing the product of the normalized indices and their corresponding weights. Gaseous N loss and nitrate leaching were selected to calculate EF. The weight of gaseous N loss and nitrate leaching were set as +0.5 and +0.5. EF was calculated in the same way for calculation of the AF. The VCR was calculated by Eq. (7):

$$VCR = \frac{(W \times WP + OF \times OFP + IF \times IFP)}{(Y \times YP)} \quad (7)$$

where W is the irrigation amount (mm), WP is the water price (yuan m^{-3}), OF is the amount of organic fertilizer application (kg), OFP is the organic fertilizer price (yuan kg^{-1}), IF is the amount of inorganic fertilizer application (kg), IFP is the inorganic fertilizer price (yuan kg^{-1}), Y is the cucumber yield (kg ha^{-1}), and YP is the cucumber price (yuan kg^{-1}). The price of water, organic fertilizer, inorganic fertilizer and cucumber were 0.35 yuan m^{-3}, 0.5 yuan kg^{-1}, 5 yuan $kg^{-1}$and 1.0 yuan kg^{-1}, respectively.

Following the normalization of each element of the initial matrix, we obtained a dimensionless decision matrix. For a water and fertilizer management study there are n scenarios (Q_1, Q_2, …Q_n) and m assessment indices (A_1, A_2, …A_m). Firstly, we established an initial decision matrix, then normalized each element, as a dimensionless decision matrix (8) that can be written as:

$$C = \begin{array}{c} \\ Q_1 \\ Q_2 \\ \cdots \\ Q_n \end{array} \begin{array}{c} A_1 \quad A_2 \quad \cdots A_m \\ \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1m} \\ C_{21} & C_{22} & \cdots & C_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ C_{n1} & C_{n2} & \cdots & C_{nm} \end{bmatrix} \end{array} \quad (8)$$

where C_{ij} is the value of normalized assessment indices ($i = 1, 2, \ldots, n$; $j = 1, 2, \ldots m$).

Secondly, a target value can be calculated by:

$$r_{ij} = \pm C_{ij} / \sqrt{\sum_{i=1}^{m} C_{ij}^2} \quad (9)$$

where the symbol "+" indentifies forward factor, "–" indentifies backward factor. Therefore, the dimensionless decision matrix (6) was established:

$$R = (r_{ij})_{m \times n} \quad (10)$$

Thus, a theoretical optimal value set, Q_G, and the worst value set, Q_B, then were shown as (Lou, 2002):

$$Q_G = (r_{ij})_G = (\min\{r_{i1}\}, \min\{r_{i2}\}, \cdots, \min\{r_{in}\}) \quad (i = 1, 2, \ldots, m) \tag{11}$$

$$Q_B = (r_{ij})_B = (\max\{r_{i1}\}, \max\{r_{i2}\}, \cdots, \max\{r_{in}\}) \quad (i = 1, 2, \ldots, m) \tag{12}$$

Thirdly, the distances between the assessment indices and the theoretical optimal value set, $d_{i\text{-}G}$, and the worst value set, $d_{i\text{-}B}$, were determined by Eqs. (13) and (14):

$$d_{i-G} = \left\{ \sum_{j=1}^{n} \omega_j \bullet [r_{ij} - (r_{ij})_G]^2 \right\}^{1/2} \tag{13}$$

$$d_{i-B} = \left\{ \sum_{j=1}^{n} \omega_j \bullet [r_{ij} - (r_{ij})_B]^2 \right\}^{1/2} \tag{14}$$

where ω_j is the weight of assessment index j, $\sum_{j=1}^{n} \omega_j = 1$. In this study, the weights of the three indicators (AF, EF and VCR) were set as 0.6, 0.2, and 0.2, respectively (Sun et al., 2013).

Finally, the optimal osculating value $E_{i\text{-}G}$ (15) and the worst osculating value $E_{i\text{-}B}$ (16) were obtained:

$$E_{i-G} = \frac{d_{i-G}}{\min\limits_{1 \le i \le m}\{d_{i-G}\}} - \frac{d_{i-B}}{\max\limits_{1 \le i \le m}\{d_{i-B}\}} \tag{15}$$

$$E_{i-B} = \frac{d_{i-B}}{\min\limits_{1 \le i \le m}\{d_{i-B}\}} - \frac{d_{i-G}}{\max\limits_{1 \le i \le m}\{d_{i-G}\}} \tag{16}$$

The scenario with the lowest $E_{i\text{-}G}$ and the highest $E_{i\text{-}B}$ was the best water and N fertilizer practice for greenhouse cucumber cultivation in this study.

2.8. Calculation of water use efficiency (WUE) and nitrogen use efficiency (NUE)

The WUE was calculated with the Eq. (17) (Ertek et al., 2006):

$$WUE = \frac{Y}{ET} \tag{17}$$

where Y is cucumber fruits yield (kg ha^{-1}), ET is evapotranspiration (soil evaporation + crop transpiration, mm), WUE is water use efficiency (kg m^{-3}).

The NUE was calculated with the Eq. (18) (Hu et al., 2010):

$$NUE = \frac{Y}{N_{LOSE}} \tag{18}$$

where N_{LOSE} in apparent N loss, it is the sum of uptake N + leaching N + Gaseous N.

3. Results and discussions

3.1. Model calibration and validation

The measured dataset (soil water content, nitrate concentration in the soil profile and crop data, etc.) from the F + C treatment was used to calibrate the model. We used the 'trial and error' method to adjust the model parameters until the simulated values agreed well with the measured data. The simulated and measured soil water content, nitrate concentration, and cucumber yield for the F + C treatment are shown in Figs. 1–3. Firstly, the crop coefficients of cucumber in the model were adjusted according to the measured cucumber yield. Fig. 1 compared the simulated and observed yields of greenhouse cucumber in all treatments. As the figure illustrates, there was a good agreement between simulations and observations of the yields, with a slope of 0.918. Values of RMSE were 0.11. As the observations demonstrated, irrigation method and fertilizer input had significant effects on cucumber yield.

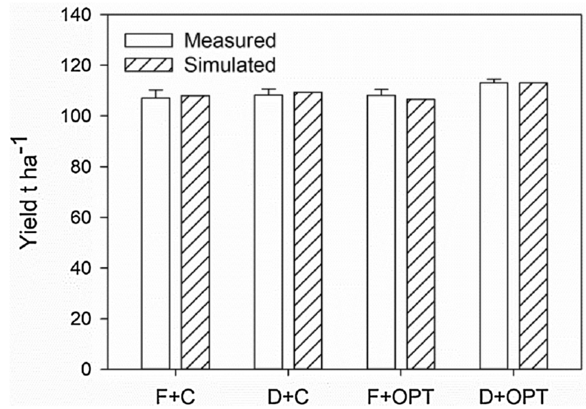

Fig. 1. Simulated and measured cucumber yields for the 4 different treatments, with the vertical bars indicating the standard errors of 3 replicates.

The yields from the D + OPT treatment were higher by about 13% compared to the F + C treatment, and water and fertilizer inputs under the D + OPT treatment were reduced by about 39% and 40% in comparison with the F + C treatment. Cucumber yields did not significantly decrease in response to further application rates of nitrogen fertilizers down the conventional level. Actually, cucumber yield increased by 8～13% when saving 40% fertilizer N and 39% water inputs combining drip irrigation compared to farmer's practice. This feature was properly reflected by the model simulation as well, which confirmed the ability of the model to simulate the effects of fertilizer and water addition on crop yields.

Additionally, nitrogen transformation parameters were adjusted by comparing the simulated and measured values of soil nitrate concentration. The comparisons between the measured and simulated values of the soil water content and soil nitrate concentration for the F + C treatment were also shown in Figs. 2 and 3. The statistical indices also indicated that good agreement was observed among them (Table 4). After the parameter calibration, the RMSE, NSE, d, and PBIAS values of soil water content and nitrate concentration for all soil depths were acceptable.

And then, the dataset from the other treatments (D + C, F + OPT and D + OPT) were used to validate the model. Fig. 2 presents the comparison of simulated and measured soil water content under the F + C and D + OPT treatments. The simulated and measured nitrate concentrations under D + C, F + OPT and D + OPT treatments are shown in Fig. 3. The statistical indices for the predicted soil water content and nitrate concentrations for all of model validation treatments are shown in Table 5. For the whole soil profile, the *RMSE* value of the soil water content was 0.021, indicating a good agreement between the simulated and measured soil water content (Fang et al., 2008). The *RMSE* value for soil nitrate concentration was relatively larger, but was acceptable (Nangia et al., 2008; Guo et al., 2010). Willmott (1981) proposed that a lower *RMSEs* value compared with the *RMSEu* value indicated acceptable model performance. In this study, the *RMSEs* values of the soil water content and nitrate concentration were lower than their *RMSEu* (Table 5). Moreover, the *NSE* values of the soil water content and nitrate concentration were 0.460 and 0.338, respectively. Because of the complexity of N turnover in soil, low *NSE* values of the soil nitrate concentrations were usually found in the model calibrations (Wang and Huang, 2008; Fang et al., 2008; Guo et al., 2010). Additionally, it has been reported that lower *NSE* values were acceptable for estimating the relative effects of different management methods on nitrate loss with a model (Thorp et al., 2007). The *PBIAS* values of the soil water content and soil nitrate concentration were 0.181% and 4.575%, respectively. The *d* values were all higher than 0.80 (Table 5). Ma et al. (2012) suggested that the simulated results were satisfactory when $NSE > 0.7$, $d > 0.7$ and $-15\% < PBIAS <$

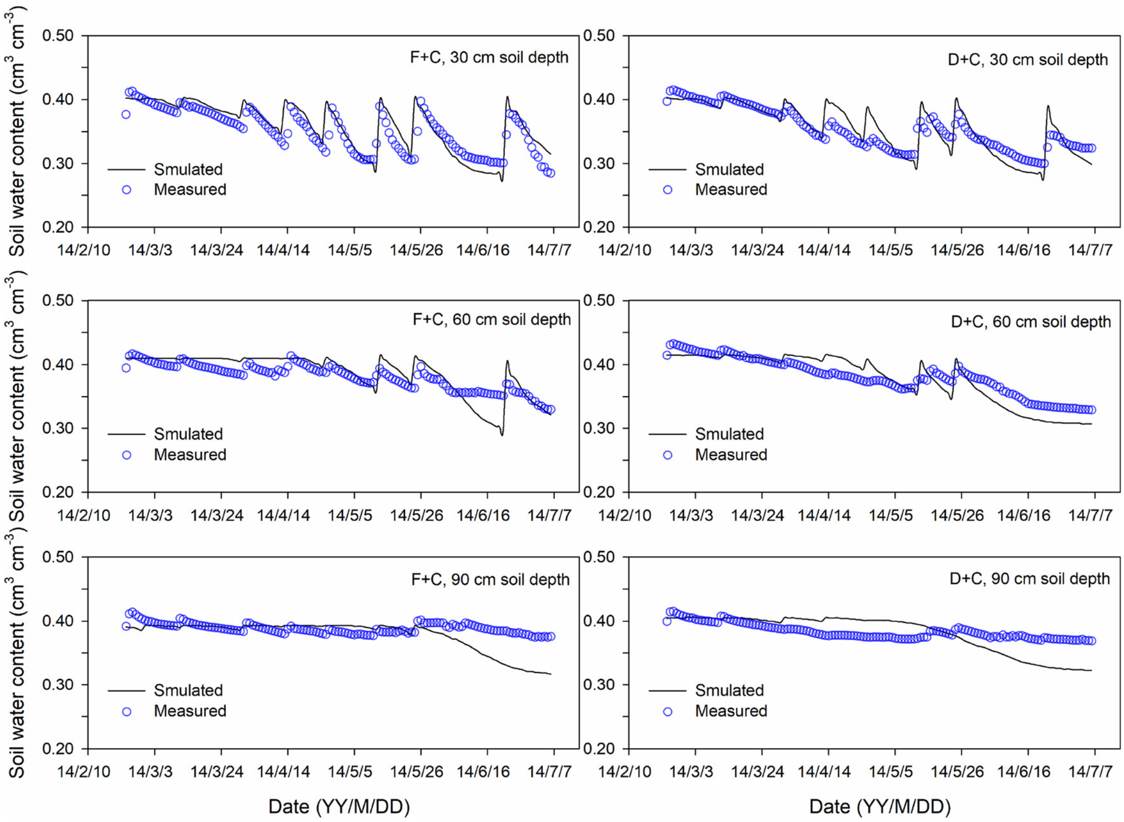

Fig. 2. Comparisons of the simulated and measured soil water contents in soil profiles at the 0–30 cm, 30–60 cm, and 60–90 cm depth under the F + C and D + C treatments.

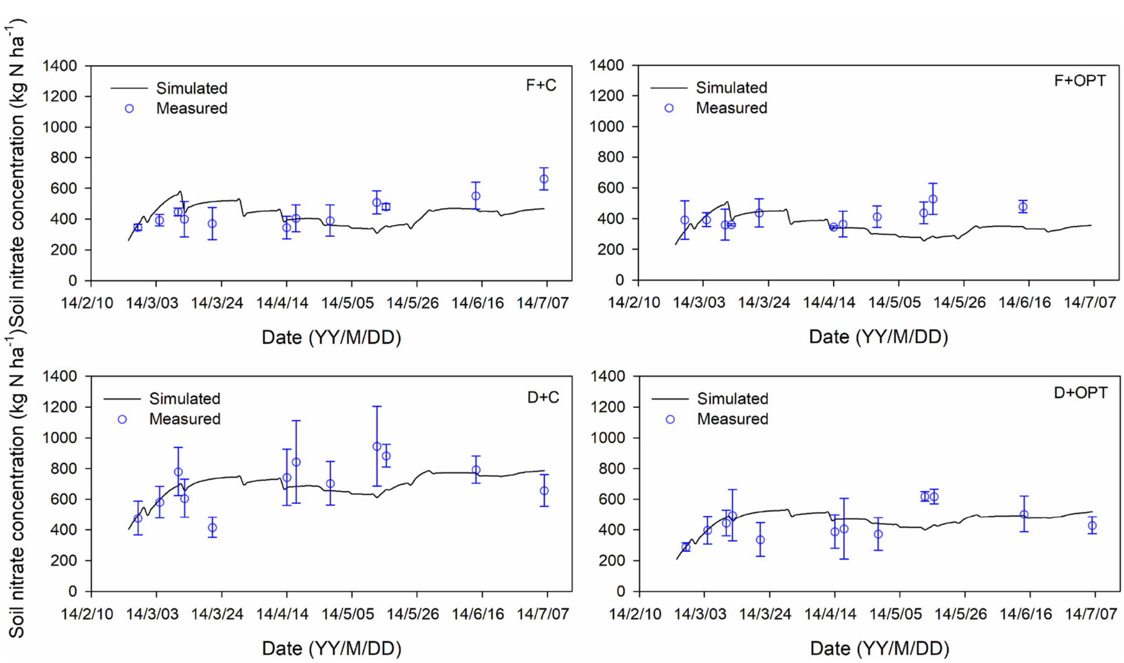

Fig. 3. Comparison of the simulated (line) and measured (circle) soil nitrate concentration at the 0–30 soil layer under 4 different treatments.

Table 4
Statistical indices for the predicted soil water content and nitrate concentration for the model calibration treatment (F + C treatment).

Items	*RMSE*	*RMSEs*	*RMSEu*	*NSE*	*d*	*PBIAS* (%)
Water content	0.021	0.001	0.021	0.422	0.872	0.137
Nitrate concentration	110.739	39.713	86.759	0.388	0.449	3.933

Table 5
Statistical indices for the predicted soil water content and nitrate concentration for all of the model validation treatments.

Items	*RMSE*	*RMSEs*	*RMSEu*	*NSE*	*d*	*PBIAS* (%)
Water content	0.021	0.001	0.021	0.460	0.886	0.181
Nitrate concentration	126.516	74.660	102.136	0.388	0.801	4.575

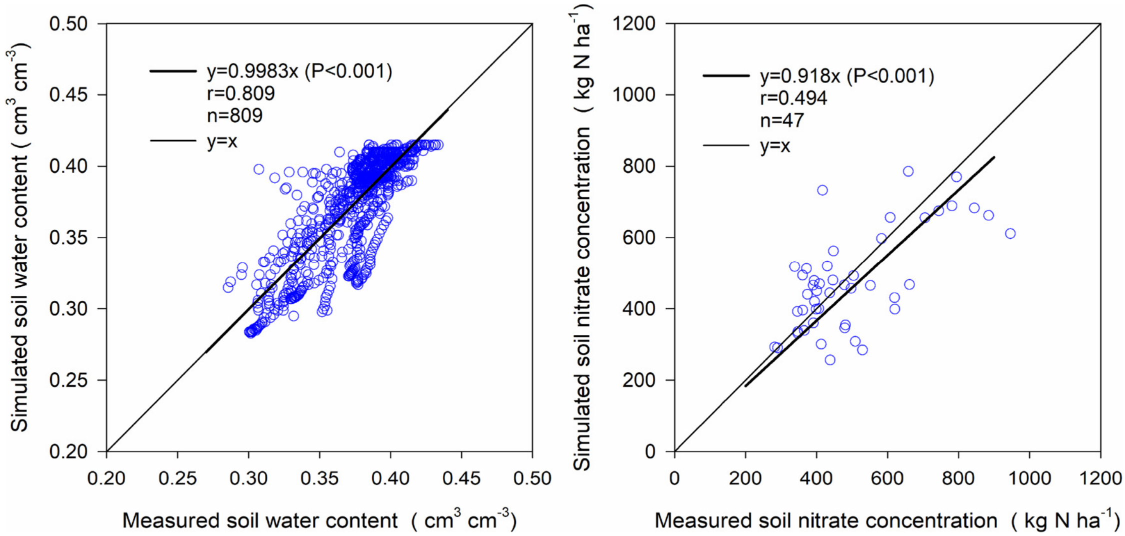

Fig. 4. Relationships of the simulated and measured soil water content and nitrate concentration.

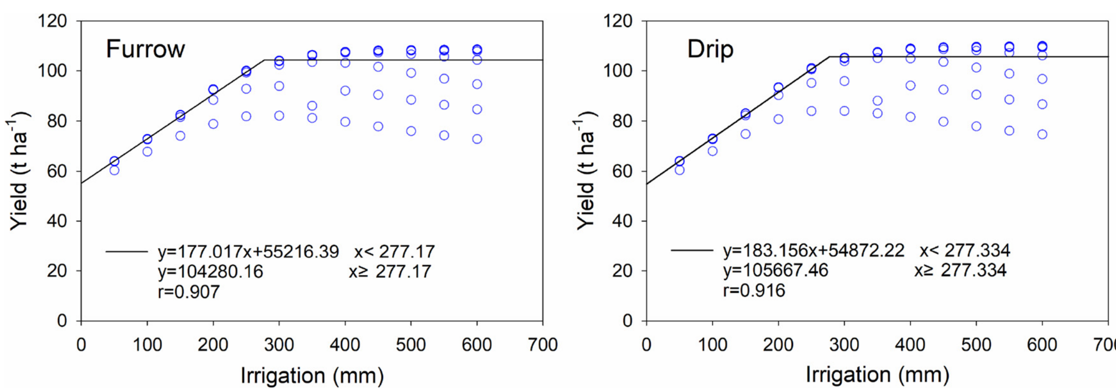

Fig. 5. Responses of the cucumber yield to water inputs with various N fertilizer rates under furrow and drip irrigation condition. The number of scenarios for the water and fertilizer inputs was 12 and 20, respectively. Each irrigation level includes 20 yield values due to 20 scenarios of fertilizer inputs.

15% for a point model, such as RZWMQ2. Furthermore, the correlation coefficients for the soil water content and nitrate concentration were also analyzed, which were 0.809 and 0.494, respectively, with significant at $P < 0.001$ (Fig. 4). It indicated that the calibrated model performed reasonably well in predicting simulated and measured soil water content and nitrate concentration.

From the simulated results, it can be concluded that the EU-Rotate_N model performed reasonably well in predicting the responses of cucumber yield and tracking the fates of nitrogen under different water and fertilization field practices, and thus the model could be used to identify BMP of vegetable production in this study area.

3.2. Responses of the cucumber growth, nitrate leaching and gaseous nitrogen release to irrigation options

The simulated responses of the cucumber yield to irrigation under furrow and drip irrigation with different N fertilizer rates are shown in Fig. 5. Greenhouse crops are different from open field crops, and irrigation is their only supply of water. Under furrow or drip irrigation below the critical water input (277 mm), the cucumber yield increased with the increasing water input and reached a maximum regardless of the N fertilizer application. However, the cucumber yield was unchanged or slightly decreased with an increasing amount of irrigation water to more than the critical level. We can use a linear model with a plateau to describe the relationships between the cucumber yield and irrigation amount ($R = 0.91^{**}$ for furrow irrigation and $R = 0.92^{**}$ for drip irrigation, n = 240).

The amount of nitrate leaching is positively related to the amount of water drainage (Wang et al., 2010; Sun et al., 2012). We also presented the water drainage against the irrigation amount in Fig. 6. We found that similar relationships between water drainage and irrigation water amount occurred with the furrow or drip irrigation methods. It should be observed that more water drainage would occur with furrow irrigation, especially with relative high irrigation options. In practice, the same amount of irrigation requires a shorter time to saturate the soil for furrow irrigation compared with drip irrigation; thus, soil is easily saturated in the former method. However, there is no irrigation time setup for different methods in the module for simulating water movement in the model. Therefore, water drainage may be overestimated for scenarios with higher water input. We observed that little water drainage occurred when < 250 mm of irrigation water was applied, and then, the amount of drainage sharply increased along with increasing irrigation water.

Nitrate leaching changes with water input are shown in Fig. 6. For various N fertilizer options, nitrogen started to decrease with nitrate leaching when the irrigation was increased to 300–400 mm, and then, nitrate leaching continuously increased with increasing irrigation. Nitrate leaching resulted in a nitrogen shortage for cucumber growth under lower N fertilizer input, which reduced the cucumber yield (Fig. 5). Our results also indicated that serious nitrate leaching occurred when one-third of the irrigated water was drained. The effects of the water input on the gaseous nitrogen loss were not significant. For all of the N fertilizer options, an increase in gaseous nitrogen loss was found when the amount of N fertilizer increased from 50 kg N ha^{-1} to 100 kg

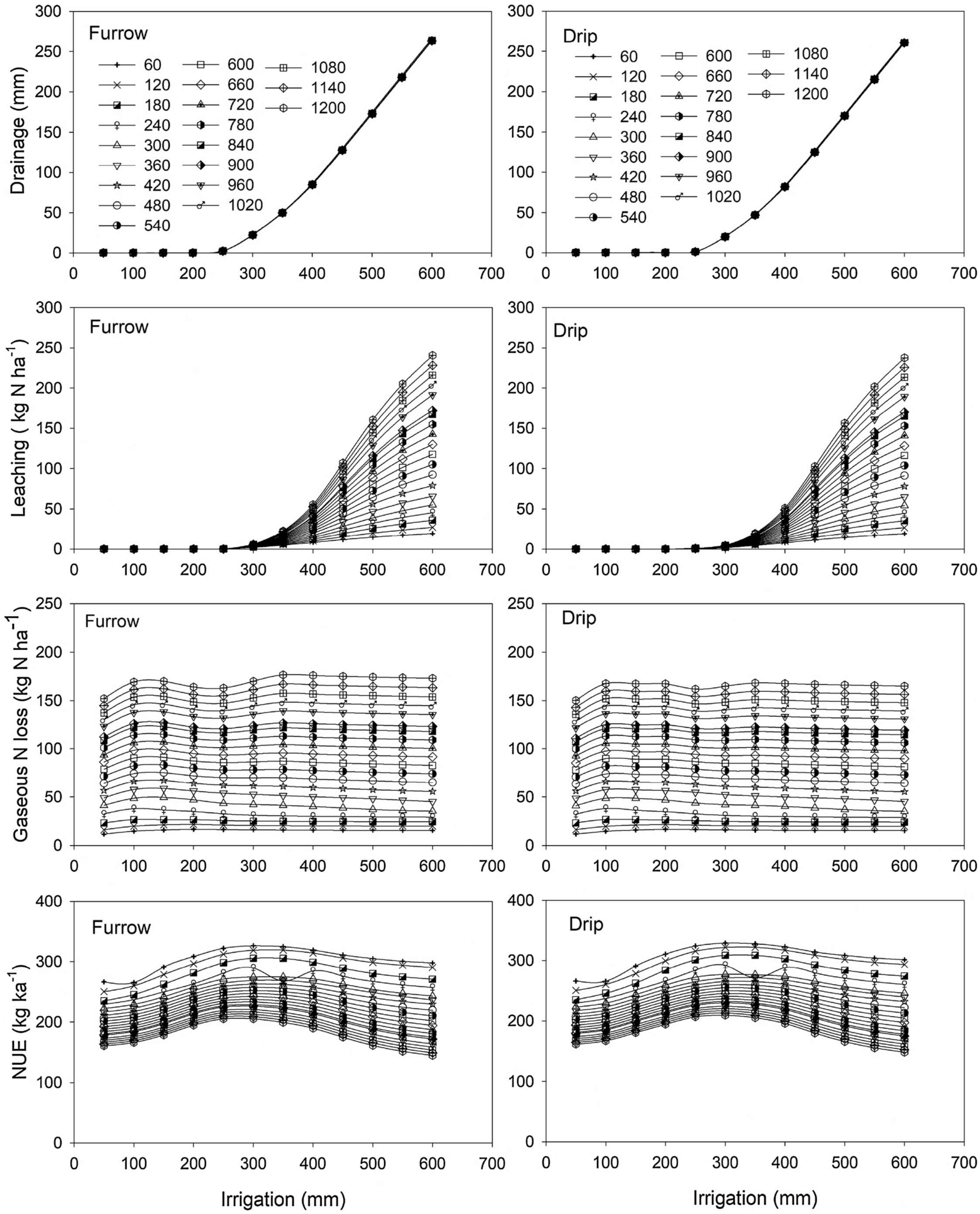

Fig. 6. Responses of water drainage, nitrate leaching, gaseous N release, and NUE to water inputs with various N fertilizer input rates under furrow and drip irrigations.

N ha^{-1}.

The relationships between NUE and amount of irrigation could be described as approximate parabolic curves (Fig. 6). For a fixed amount of fertilizer application, the NUE showed a rapidly increasing trend with increasing irrigation amounts and approached a maximum value when the irrigation amount was approximately 300 mm. If the irrigation rate was higher than that value, the NUE showed a decreasing trend with an increasing amount of irrigation.

3.3. Responses of cucumber growth, nitrate leaching and gaseous nitrogen release to the N fertilizer options

The simulated responses of the cucumber yield to the amount of N fertilizer under furrow and drip irrigation at different irrigation rates are shown in Fig. 7. The relationships between the cucumber yield and fertilizer inputs are similar to the relationship between the cucumber yield and irrigation inputs. However, the cucumber yield was not found to decrease with increasing N fertilizer for any irrigation application. We also used a linear model with a plateau to describe the relationships between the cucumber yield and fertilizer amount (R = 0.90** for furrow irrigation and R = 0.89** for drip irrigation, n = 240). Under

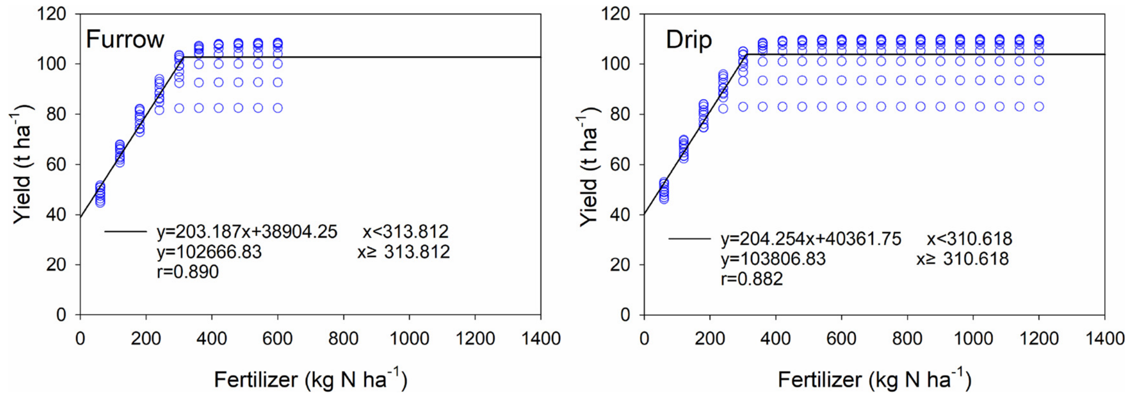

Fig. 7. Responses of the cucumber yield to water inputs with various N fertilizer rates under furrow and drip irrigations. The water input range from 0 to 700 mm. The number of scenarios for the water and fertilizer inputs was 12 and 20, respectively. Each fertilizer rate level includes 12 yield values due to 12 scenarios of water inputs.

furrow or drip irrigation below the critical N fertilizer input (313.8 and 310.6 kg N ha^{-1}), the cucumber yield increased with increasing nitrogen input and reached a maximum. However, the cucumber yield did not change with increasing N fertilizer above the critical level.

The hydraulic properties of soil and water status determine directly the water movement in soil profile. Therefore, the interaction of water and fertilizer on water drainage is not considered in the EU-Rotate N model (Rahn et al., 2010). Although the ability of uptake water of crop is influenced by the condition of growth closely related to N input, no directly relationships between water drainage and N application ratio still were observed (Sun et al., 2012, 2013). We thought EU-Rotate N model had less errors in estimating water drainage in this study. As a result, the water drainage is mainly determined by the irrigation amount, which was confirmed by that the relationship between water drainage and the N fertilizer inputs paralleled the X axis (N fertilizer inputs) (Fig. 8).

Changes in nitrate leaching with N fertilizer inputs are shown in Fig. 8. The amount of nitrate leaching increased linearly with the increasing N fertilizer application rates under furrow or drip irrigation. Moreover, their relationships were controlled by the water input. For lower water input options, the amount of nitrate leaching changed slowly with increasing N fertilizer input because of less water drainage and more N residue in the soil (Fig. 8). We also found that the rate of nitrate leaching increasing with the N fertilizer application rate under drip irrigation was smaller compared with that under furrow irrigation, which with relatively lower nitrate leaching under drip irrigation. Because there was no significant relationship between the water input and gaseous nitrogen release, the lines describing the changes of gaseous nitrogen loss with N fertilizer input overlapped together. Gaseous nitrogen loss increased linearly with N fertilizer input, and a relatively lower amount was observed under drip irrigation.

The relationships between NUE and the N fertilizer rates could be approximately described as a power function (Fig. 8), decreasing with increasing N fertilizer input. For a given amount of irrigation, the NUEs showed a decreasing trend with increasing fertilizer inputs. At the lower fertilizer application level, the NUEs were much higher than those of the others, but the cucumber yields were very low (Fig. 6). The amounts of nitrate leaching and gaseous nitrogen loss were the lowest under the lower fertilizer application, which yielded the highest NUE.

3.4. Optimal water and nitrogen fertilizer management

It was clearly shown that the more water and N fertilizer inputs that were applied, the more water drainage and nitrogen loss were observed (Figs. 6 and 8). Therefore, the scenarios with the lowest irrigation and N amounts (50 mm water and 60 kg N ha^{-1}) had the lowest OOV (the optimal osculating value) and the highest WOV (the worst osculating value), but low cucumber yields. The basic requirement for the options was that the cucumber yield was more than the average yield of this cucumber variety in this study area (100 ton ha^{-1}) (Table 6).

Under both irrigation methods, the treatments with more than 550 mm of irrigation and more than 1100 kg N ha^{-1} of fertilizer yielded approximately 110 ton ha^{-1} of cucumber. The amounts of nitrate leaching and gaseous nitrogen release were very high, resulting in a higher OOV and a lower WOV. Additionally, the VCR was very low with regard to these options.

When drip irrigation was applied, the amounts of irrigation and fertilizer application were reduced to 250 mm and 300 kg N ha^{-1}, respectively, and the cucumber yield was maintained at 100.600 ton ha^{-1}, but was reduced by 8.5% compared to the maximum yield (Table 6). However, the NUE significantly increased from 152.51 to 272.12 kg kg^{-1} N^{-1}; nitrate leaching and gaseous nitrogen release were reduced by 99% and 73% to only 0.55 and 43.79 kg N ha^{-1}, while the VCR was 27.94. Furthermore, the values of OOV and WOV were the lowest and greatest, respectively. For furrow irrigation, the treatment with 300 mm of irrigation and 300 kg N ha^{-1} of fertilizer had the lowest OOV and the highest WOV (Table 6). In this situation, the cucumber yield reached 102.45 ton ha^{-1}, which was only reduced by 5.7% in comparison to the maximum yield. Nitrate leaching and gaseous nitrogen release were only 2.96 and 42.23 kg N ha^{-1}, while the NUE was 274.41 kg kg^{-1} N^{-1} and the VCR was up to 27.14 (Table 6). Therefore, application of 250 mm of water and 300 kg N ha^{-1} was optimal for greenhouse cucumber yields under drip irrigation practice. Comparatively, more water input was required, and 300 mm of water with 300 kg N ha^{-1} was better under furrow irrigation.

For greenhouse cucumber production in the Beijing region, Gao et al. (2010) proposed that the highest WUE and NUE and good yield and quality were obtained under the application of 300 mm of water and 240 kg N ha^{-1} in a similar cultivation season based on a field experiment. Moreover, an N recommendation system based on the N target value was employed for greenhouse vegetable production in China, which was useful for reducing nitrogen loss and improving NUE (Chen et al., 2005; He et al., 2007, 2009; Guo et al., 2008; Ren et al., 2010). Guo et al. (2008) reported that approximately 300 kg N ha^{-1} under furrow irrigation was recommended by the system for cucumber growth from March to July in Beijing. From our simulation results, the recommended optional practices were 300 kg N ha^{-1} with 250 or 300 mm of water under drip or furrow irrigation, respectively.

4. Conclusions

After calibration and validation using the data collected from a greenhouse field in the Beijing region, the EU-Rotate_N model can be used as a helpful tool for multi-goal estimation, such as the responses of

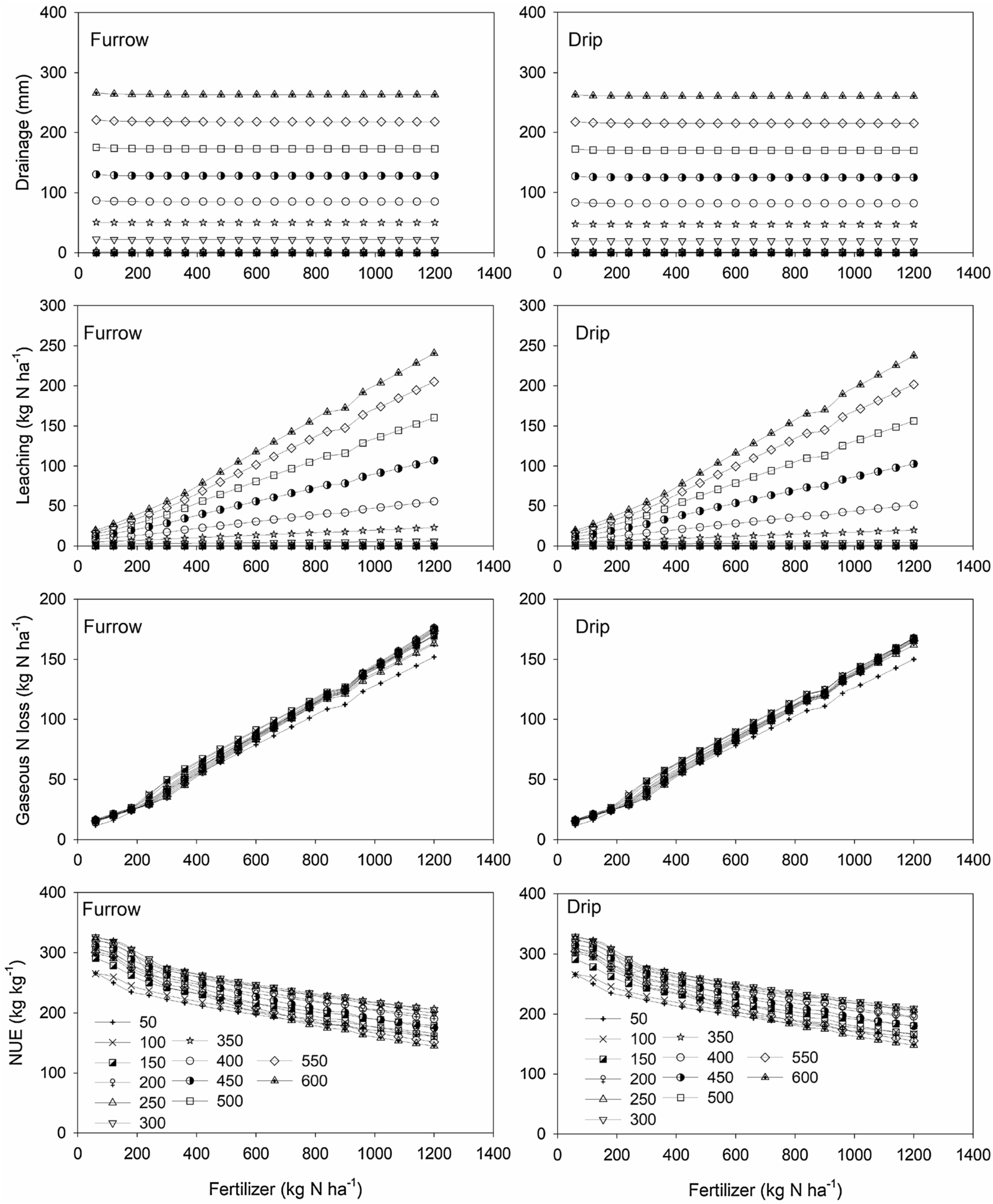

Fig. 8. Responses of water drainage, nitrate leaching, gaseous N release, and NUE to N fertilizer rates with various water input rates under furrow and drip irrigation.

the cucumber yield, nitrate leaching, gaseous nitrogen release, and NUE to various water and N fertilizer rates under furrow or drip irrigation conditions. The simulated results indicated that the cucumber yield increased to the maximum value as water or N fertilizer application reached a critical level, but no further increase in yield with higher rates of water or N fertilizer inputs, and meanwhile, the environmental risk and economic cost increased linearly with increasing water input and N fertilizer rates. Based on results from the assessment with the osculating value method, the BMP for greenhouse cucumber production in the Beijing could be consist of 300 mm of irrigation water with 300 kg N ha^{-1} of fertilizer for the furrow irrigation method. Under this management, the yield, WUE and NUE were 102.4 ton ha^{-1}, 40.47 kg m^{-3}, and 274.41 kg kg^{-1}, respectively. And for the drip irrigation method it could be 250 mm of irrigation water with 300 kg N ha^{-1} of fertilizer. Under the condition, the yield, WUE, and NUE were 100.6 ton ha^{-1}, 47.98 kg m^{-3} and 272.12 kg kg^{-1}, respectively. While we were encouraged by the EU-Rotate_N model for the multi-goal estimation, we realized that there were still limitations for widespread application of this tool. Firstly, the model were only calibrated and validated for water and nitrate dynamics in soil profile but not for thoroughly tested against N leaching and gases emission although the simulations of these variables were critical. However, the datasets used in this study were the best ones currently available. Secondly, soil heterogeneity and climate varieties would be the major obstacle for applying the model across sites. Thirdly, the calibrated model, however, still slightly underestimated or overestimated soil nitrate content under the different treatments due to some model assumptions. Fourthly, the output uncertainties associated with the quality of the available input parameters

Table 6
Integrated evaluation index for the selected scenarios simulated with the EU-Rotate_N model in drip and furrow irrigation.

Irrigation method	Irrigation mm	Fertilizer kg N ha^{-1}	Yield ton ha^{-1}	Leaching kg N ha^{-1}	Gaseous kg N ha^{-1}	NUP kg N ha^{-1}	Evaporation mm	Transpiration mm	WUE kg m^{-3}	NUE kg kg^{-1}	VCR	OOV	WOV
Drip	250	300	100.60	0.55	43.79	325.35	25.47	184.85	47.98	272.12	27.94	0.77	2.52
	300	300	103.87	2.48	41.99	330.68	25.06	228.48	41.01	276.89	27.51	0.82	2.49
	350	300	105.07	7.66	41.33	331.32	24.89	262.45	36.57	276.29	26.60	0.90	2.41
	250	360	100.97	0.58	54.76	326.20	25.48	184.84	48.01	264.65	24.36	0.91	2.40
	300	360	105.05	2.61	52.37	332.78	25.05	228.47	41.46	270.91	24.32	0.94	2.39
	600	1020	110.02	201.41	139.42	339.57	24.79	303.39	36.60	159.72	8.95	2.67	0.19
	550	1200	109.92	201.75	165.61	339.46	24.80	300.27	36.61	155.52	8.57	2.76	0.12
	600	1080	110.05	213.46	147.93	339.57	24.79	303.39	36.27	157.00	9.24	2.77	0.10
	600	1140	110.05	225.55	156.48	339.57	24.79	303.39	36.27	152.51	8.84	2.87	0.04
	600	1200	110.02	237.52	165.09	339.57	24.79	303.39	36.27	148.25	8.46	2.97	0.00
Furrow	300	300	102.45	2.96	42.23	328.16	27.87	225.29	40.47	274.41	27.14	0.98	2.49
	350	300	103.55	8.57	41.29	327.43	27.68	258.01	36.25	274.45	26.21	1.05	2.41
	300	360	103.85	3.19	52.61	330.57	27.87	225.24	41.03	268.79	24.04	1.09	2.39
	400	300	103.25	17.10	40.06	323.44	27.61	278.79	33.70	271.28	25.03	1.12	2.30
	350	360	106.12	9.50	51.38	333.91	27.68	258.02	37.15	268.81	23.61	1.14	2.33
	600	1020	108.72	203.87	144.73	337.26	27.53	298.12	33.39	158.52	9.57	2.74	0.18
	550	1200	108.60	205.15	173.71	337.16	27.55	295.02	33.67	151.67	8.47	2.83	0.12
	600	1080	108.72	216.09	153.92	337.27	27.53	298.12	33.39	153.72	9.13	2.84	0.10
	600	1140	108.72	228.31	163.40	337.27	27.53	298.12	33.39	149.15	8.73	2.94	0.04
	600	1200	108.72	240.47	173.11	337.27	27.53	298.12	33.39	144.80	8.36	3.03	0.00

Note: NUP, crop N uptake; WUE (water use efficiency) = Yield / (Evaporation + Transpiration); NUE (nitrogen use efficiency) = Yield / (Leaching + Gaseous + NUP); VCR, value to cost ratio; OOV, the optimal osculating value; WOV, the worst osculating value.

needed to be lessened. This requires more efforts in the future. Anyhow, this study will make the revised model an increasingly useful tool for evaluating multi-goal management and providing BMP options for vegetable production in China. We hope this paper will fuel more interest in this research area.

Acknowledgements

This study was gratefully supported by the National Key Research & Development Plan (Grant No.: 2016YFD0800101, 2016YFD0201204, 2018YFD0800402), National Natural Science Foundation of China (Grant No. 41671303, 31270486), and the International Scientific and Technological Cooperation Projects of China (Grant No. S2016G0053). We give many thanks to a large number of Chinese and American researchers who participated in the decades-long collaborative efforts by joining the field campaigns, mega-data collection and analysis, or model modifications. We thank Dr. Richard Whalley (Rothamsted Research, UK) for his kind help of revising the language.

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