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WHCNS-Veg Modelling of N_2O, NH_3 and NO_3^- Dynamics in a Vegetable Production System under Different Fertilization and Irrigation Regimes

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Abstract: Greenhouse vegetable production in China not only increases farmers' income, but also increases the risk of nitrogen losses due to excessive water and fertilizer input. Nitrogen losses, including the potent greenhouse gas nitrous oxide (N_2O), are driven by water content, soil temperature and pH; regulated by available organic carbon and inorganic nitrogen (N); and affected by management. Therefore, a process-based model was applied to explain the complex interaction of the factors affecting N losses in the form of N_2O, NH_3 and NO_3^- from a greenhouse vegetable production system in a northeast suburb of Beijing, China. We designed four treatments: two equal N input treatments with one flooding (FP) and the other drip irrigation (FPD) and two equal water input treatments (drip irrigation) with one 100% chemical N input (FPD) and the other 50% N input (OPTD). The last one was CK treatment (flooding without chemical N). We calibrated the WHCNS-veg model using year-round measurements of soil temperature, N_2O emission, NH_3volatilization, NO_3^- distribution and yields for greenhouse cucumber–tomato cultivation under farmers' practice (flooding + 100% chemical N, FP). Then, we validated the model using the data sets under drip irrigation (70% of flooding amount + 100% chemical N, FPD), reduced chemical N by 50% (drip + 50% chemical N, OPTD) and CK treatment. The WHCNS-veg model was able to capture the above processes under different treatments. Annual N_2O emissions were 5.47 and 3.76kg N ha^{-1} for the cucumber and tomato seasons under FP, respectively. Compared to FP, drip irrigation (FPD) decreased N_2O emissions by 19.0% and 45.5% in the two seasons, respectively. Compared to FPD, applying a lower rate of N (OPTD) further reduced N_2O emissions by 13.7% and 40.5%, respectively. According to the model simulation, N_2O emission was mainly controlled by nitrification/denitrification in the cucumber/tomato seasons, respectively. Compared to FP, drip irrigation (FPD) increased NH_3 volatilization by 54.2% in the cucumber season, while in the tomato season, there were no significant differences inNH_3 volatilization under the three fertilizer treatments. The nitrate leaching levels were 48.5 and 81.0 kg N ha^{-1} for the two seasons under FP treatment. Drip irrigation (FPD) decreased NO_3^- leaching by 20.6% in the cucumber season. Drip irrigation (FPD) and/or reducing chemical N (OPTD) did not compromise vegetable yields. In all, WHCNS-veg performed well in simulating N_2O, NH_3 and NO_3^- dynamics from the greenhouse vegetable field, which means that the model can be used to manage water and nitrogen precisely in greenhouse vegetable production systems by scenario analysis, and drip irrigation and/or lower N input can be applied in this area to secure yield and reduce N losses.

Keywords: nitrous oxide; ammonia volatilization; drip fertigation; optimized fertilization; greenhouse vegetable

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1. Introduction

Greenhouse vegetable production has been extensively used in China due to its high yield and high profit. Now, China produces more than half of all vegetables globally.

However, greenhouse vegetable production needs frequent fertilization and irrigation to keep up with the fast growth of vegetables and year-around high-yield production. Therefore, excessive fertilization and flooding is a common way to pursue a higher income by increasing production [1]. As a result, high N losses to the environment and low nitrogen use efficiency have become a great concern.

Nitrous oxide is a powerful greenhouse gas that can react with O_3 in the stratosphere, thereby destroying the ozone layer. A large amount of fertilizer combined with frequent irrigation provides much more substrate and humid conditions in the greenhouse vegetable system, which is suitable for N_2O emission by nitrification and denitrification [2]. However, contradictory results have been found for different water regimes. For example, drip irrigation decreased N_2O emission by denitrification due to the lower water content [3]; on the contrary, Kuang et al. [4] found that drip irrigation increased N_2O emission due to improved soil aeration, which is good for nitrification or prevents complete denitrification of N_2O to N_2. Aside from irrigation approaches, soil pH, temperature, moisture, microbial available C and N, and mineral N input also have great effects on N_2O emission [5–7]. In low-pH soil, N_2O emission is mainly controlled by denitrification, while in high-pH soil, nitrification is the dominant source of N_2O [5]. In addition, temperature combined with water content produces divergent effects on nitrification and denitrification [8]. However, the complex interactions of the regulating factors complicate the responses of N_2O under field conditions, where divergent water and fertilizer management types are applied.

China is the country with the largest NH_3 emissions, reaching 15 Tg N yr^{-1} [9]. Many studies have been performed on NH_3 volatilization in crop fields under different fertilizer types, amounts and irrigation approaches. However, few studies have been carried out in vegetable fields under drip irrigation. Under furrow irrigation, total NH_3 volatilization did not change when the irrigation amount was reduced by 30% in a long-term tomato–cucumber rotation [10], while under a tomato–watermelon rotation system, when the irrigation amount was reduced by 15%, NH_3 volatilization increased by 46.7% [11]. These contradictory results indicate that there is a need for further study on NH_3 volatilization in greenhouses under different irrigation conditions.

Process-based models are useful tools to understand N dynamics in a greenhouse system. A few process-based models, such as the DNDC model, WHCNS-veg model and EU_Rotate -N model, have been developed to quantify N_2O emission and NO_3^- leaching in vegetable fields [2,12,13]. The WHCNS-veg model has been validated under a wide range of conditions and performs well in simulating water and nitrate leaching [1,14], dissolved organic nitrogen losses [15] and N_2O emission [2] in vegetable production systems, as well as water and nitrogen management in field crop systems [16–18]. However, large uncertainties still exist in deeply understanding N losses, especially NH_3 volatilization in vegetable fields. More data are needed to mechanically understand how N losses are controlled by key factors, which change in different management systems. We hypothesize that high organic and inorganic N input could promote N_2O emission, NH_3 volatilization and NO_3^- leaching due to the increase inavailable N and C for microbial processes. The objectives herein were to(a) use the WHCNS-veg model to simulate N_2O emission, NH_3 volatilization and NO_3^- transport in a cucumber–tomato rotation system under different fertilizer and water management conditions, and to(b) explain how fertilizer amount and irrigation methods affect N_2O emission, NH_3 volatilization and NO_3^- leaching, while exploring emission reduction measures.

In this paper, we calibrated the model with the 0–5 cm soil temperature, 0–15 cm water content, 0–100 cm nitrate content, N_2O emission and NH_3 volatilization under FP treatment. Then, we validated the model with the 0–5 cm soil temperature, 0–15 cm water content, 0–100 cm nitrate content, N_2O emission and NH_3volatilization under the FPD, OPTD and CK treatments. Because there were only eight vegetable yields, we put the calibration and validation results together for the vegetable yields.

2. Materials and Methods

2.1. Study Site

The study site is located in a northeast suburb(116°28′ E, 40°00′ N) of Beijing, China. The annual average temperature is 11.5 °C, and the annual average rainfall is 625 mm. The plastic greenhouse is a semi-arch circular greenhouse with a clay wall on one side and covered by a colorless transparent plastic film. The membrane is covered with felt to keep it warm at night in the cold season. The soil is tidal cinnamon soil, and the basic chemical properties are as follows: pH, 7.19; soil organic matter, 14.31 g kg^{-1}; total N, 1.17 g kg^{-1}.

2.2. Experiment Design and Data Collection

The experiment was designed with four treatments, namely, flooding irrigation without mineral N fertilizer (CK), flood irrigation + 100% mineral fertilizer (farmers' practice, FP), drip irrigation (70% flooding) + 100% mineral fertilizer (FPD) and drip irrigation + 50% mineral fertilizer (OPTD); each treatment had three replicates. Each plot was 6 m long and 4 m wide, and they were separated by plastic belts buried 1 m deep. The fertilizer and irrigation amounts are shown in Table 1.

Table 1. Field treatments and fertilizer and irrigation management for greenhouse cucumber–tomato cultivation.

Vegetable	Treatment	Manure kg N ha^{-1}	Mineral Fertilizer kg N ha^{-1}			Irrigation	Irrigation Amount (mm)
			N	P_2O_5	K_2O		
Cucumber	CK	500	0	120	200	Flood	365
	FP	500	700	120	200	Flood	365
	FPD	500	700	120	200	Drip	256
	OPTD	500	350	120	200	Drip	256
Tomato	CK	800	0	200	300	Flood	407
	FP	800	750	200	300	Flood	407
	FPD	800	750	200	300	Drip	285
	OPTD	800	375	200	300	Drip	285

CK, no mineral N, subject to flood irrigation; FP: local farmers' practice, subject to 100% mineral N and flood irrigation; FPD: 100% mineral N and drip irrigation, subject to 70% flood irrigation; OPTD: 50% mineral N and drip irrigation.

Mineral fertilizer was divided into basal fertilizer and four top-dressing fertilizers. Sheep manure (N 2.03%) and superphosphate were applied as a base fertilizer before vegetable transplanting and were ploughed into the arable layer, while potassium sulfate and urea were dissolved into the irrigation water and applied in five parts over the growth period. Cucumber (Zhongnong 12) was transplanted on 10 September 2017 and harvested on 28 December 2017. Tomato (Chaoza 32) was transplanted on 16 March 2018 and harvested on 16 July 2018. The soil physical and hydraulic properties related to the model were measured for the 0–100 cm soil profile (Table 2).

Table 2. Soil physical and hydraulic properties.

Soil Layer (cm)	SOM (g kg^{-1})	Bulk Density (g cm^{-3})	Clay Content (%)	θs ($cm^3 \cdot cm^{-3}$)	Ks ($cm \cdot d^{-1}$)
0–20	14.31	1.25	21.2	0.47	23.77
20–40	10.86	1.25	21.2	0.40	30.10
40–60	6.51	1.24	22.4	0.38	18.84
60–80	4.01	1.36	24.9	0.37	24.64
80–100	0.70	1.33	21.3	0.38	28.33

SOM: soil organic matter; θs: saturated water content; Ks: saturated hydraulic conductivity.

Nitrous oxide was collected using the static chamber method [19] two or three times a week. After irrigation and fertilization, sampling was continued for 7 days until there was no significant difference in gas concentration between treatments. Gas samples were collected between 8 a.m. and 10 a.m. and analyzed using a modified gas chromatograph (Agilent 7890A). During sampling, the temperature inside the box and the soil at a depth of 5 cm were recorded through the temperature sensor on the box. The calculation method for nitrous oxide flux can be found in [20]. The total N_2O emission was calculated via the addition method using simulated data.

Ammonia was collected using the aeration method [21] at the same frequency as N_2O collection. Samples were collected from 9 AM to 10 AM, and the NH_4^+-N concentration was measured using a continuous flow analyzer (Skalar Analytical B.V., Breda, The Netherlands). The calculation method for the NH_3 volatilization rate can be found in [21]. The total NH_3 volatilization was calculated via the addition method using simulated data. Weather was recorded using an automatic weather station (RR-9100). Irrigation water was recorded using a water meter; soil moisture (0–15 cm) was measured using TRIME-IPH at the same frequency as gas sampling. The vegetable fresh yield in each plot was recorded in batches.

Soil profile samples (0–100 cm) were collected at 20 cm intervals before vegetable planting, during key growth periods and after harvesting, and they were extracted with 1 mol L^{-1} KCL to measure the NO_3^--N and NH_4^+-N contents using a continuous flow analyzer (Skalar Analytical B.V., Breda, The Netherlands).

The leaching samples were collected using a leak meter. A soil pit with a length of 1.5 m, a width of 0.8 m and a depth of 0.9 m was dug in the plot, and then a cylinder with a depth of 0.4 m and a diameter of 0.3 m was dug in the middle of the bottom of the pit to place a bucket to collect a water sample. There were two outlets on the top of the bucket, which were used for pumping water and maintaining ventilation. The surrounding area of the pit was sealed with plastic sheeting to prevent the leakage of surrounding water, then the pit was filled with soil in the original layers. At 2–3days after each irrigation, the water samples in the bucket were pumped out using a vacuum pump, and the total amount of water in each plot was recorded; then, the NO_3^{-}-N and NH_4^+-N concentrations in the water samples were measured using a continuous flow analyzer (Skalar Analytical B.V., Breda, The Netherlands).

2.3. The WHCNS-Veg Model

Soil Water Heat Carbon and Nitrogen Simulator (WHCNS) V1.0 is a soil–crop–atmosphere system simulation software product [22]. The model includes seven modules: a weather module quoted from FAO; a soil water–heat–nitrogen co-transport module modified from RZWQM [23] and HYDRUS-1D [24]; a crop growth module imported from the EPIC model [25]; a soil organic matter module modified from the DAISY model [26]; a root uptake of water and N module derived from the EU_Rotate-N model [27]; a mineral nitrogen module modified from the DAISY [26] and DAYCENT 4.5 models [28]; and a field management module. Daily meteorological data drive the model to begin vegetable photosynthesis.

2.4. Model Calibration and Validation

The measured data (soil temperature, water content, nitrate content, NH_3 volatilization, N_2O emission and fresh yield) were calibrated under FP and validated under CK, FPD and OPTD. The parameters in the WHCNS-veg model were grouped into three parts: soil parameters, which control water movement, solute transport and heat conductivity; nitrogen transformation parameters, which control nitrification, denitrification and NH_3 volatilization; and crop parameters, which control crop growth, yield and N uptake. The optimized parameters from Liang et al. [22] for a cucumber–tomato rotation system were used as initial values, which they obtained by PEST optimizer using the default values in the EU_Rotate-N model. Then, key parameters that are sensitive to N_2O emission [2], N transformation and vegetable yield [22,29] were calibrated using a trial–error approach under FP treatment. Then, calibrated parameters were applied under FPD, OPTD and CK to evaluate the performance of the model. The performance was evaluated using the root-mean-square error (RMSE) and coefficient of determination (R^2).

3. Results

3.1. Model Calibration

Soil N transformation is sensitive to soil temperature, especially N_2O and NH_3 emission. Therefore, the model performance for soil temperature was evaluated under FP (Figure 1). The WHCNS-veg model could capture the dynamics of soil temperature. The RMSE values were 2.01 and 2.77 °C for the cucumber and tomato seasons, respectively (Table 3). The changes in soil water in the surface layer were captured by the model, with RMSE values of 0.04 and 0.05 for water. The nitrate distribution in the soil profile (0–20, 20–40, 40–60, 60–80, 80–100 cm) matched well with the observed data, with the RMSE ranging from 9.6 to 18.1 mg kg^{-1} in the cucumber season and from 14.3 to 25.3 mg kg^{-1} in the tomato season (Table 3). Nitrous oxide emission also compared well with observed data, with RMSEs of 0.023 and 0.019 kg N ha^{-1} for cucumber and tomato, respectively. The predicted NH_3 volatilization was able to catch the peak time after fertilization and irrigation but could not simulate lag in the measured data; therefore, the RMSE values were 0.34 and 0.12 kg N ha^{-1} d^{-1} for cucumber and tomato, respectively (Table 3).

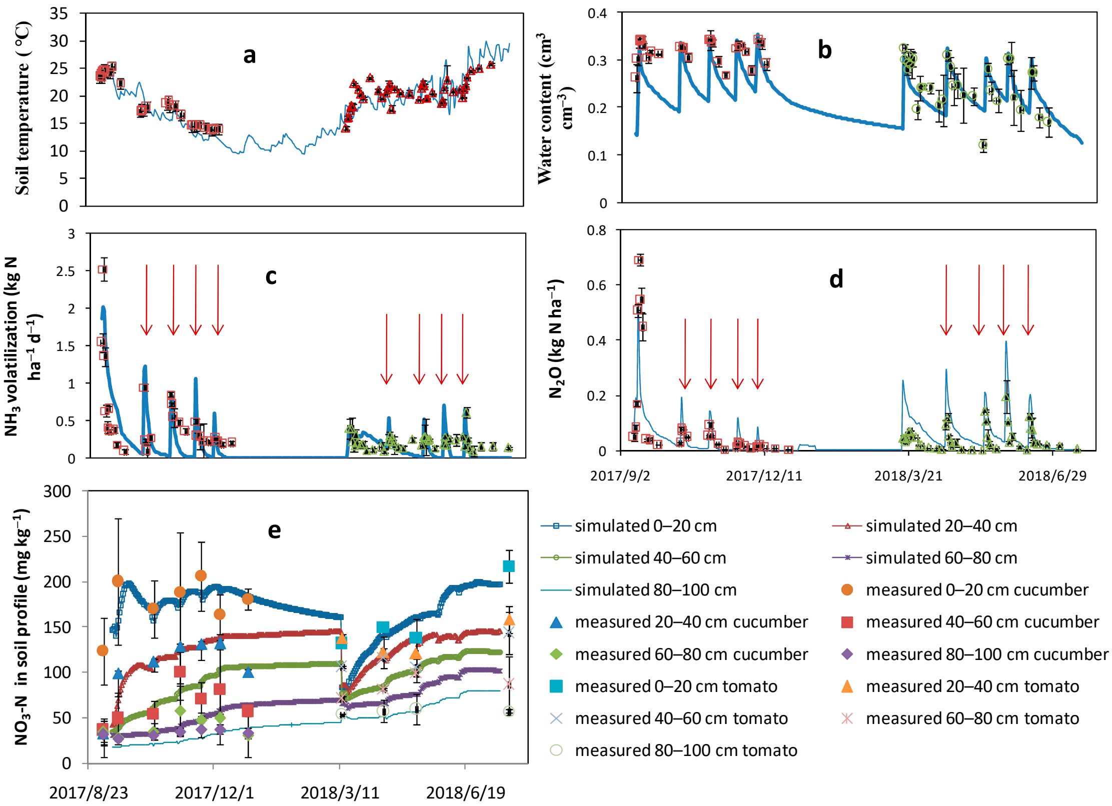

Figure 1. Comparison of measured and calibrated (**a**) soil temperature (0–5 cm), (**b**) soil water content (0–20 cm), (**c**) ammonia (NH_3) volatilization, (**d**) nitrous oxide (N_2O) emission and (**e**) nitrate (NO_3^-) distribution in the soil profile for the annual greenhouse cultivation of cucumber and tomato under farmers' practice. Arrows in c and d indicate the top-dressing time. Definitions of the treatment codes are referred to in Table 1 and in the text. The vertical bars for measured data denote standard errors.

The WHCNS-veg model simulated vegetable yield well under the four treatments (Figure 2). The calibrated parameters are shown in Table 4. For other parameters, we used the same optimized parameters in Liang et al. [22] or default values in EU_Rotate-N for cucumber and tomato.

Table 3. Model performance for the simulation of soil water content, soil nitrate content, N_2O emission, NH_3 volatilization and soil temperature.

Vegetable	Treatments	SWC (cm^3 cm^{-3})		SNC (kg N ha^{-1})		N_2O (kg N ha^{-1})		NH_3 (kg N ha^{-1})		ST (°C)	
		RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2
Cucumber	FP	0.04	0.75	9.6–18.1	0.63	0.023	0.74	0.34	0.65	2.01	0.86
	FPD	0.03	0.64	5.6–19.6	0.58	0.037	0.72	0.34	0.57	-	-
	OPTD	0.03	0.67	9.3–22.2	0.58	0.027	0.67	0.29	0.59	-	-
	CK	0.04	0.69	10.3–23.4	0.77	0.033	0.69	0.27	0.54	-	-
Tomato	FP	0.05	0.71	14.3–25.3	0.67	0.019	0.73	0.12	0.56	2.77	0.81
	FPD	0.03	0.69	17.4–30.1	0.68	0.016	0.68	0.37	0.55	-	-
	OPTD	0.02	0.69	14.3–32.1	0.65	0.011	0.71	0.34	0.57	-	-
	CK	0.03	0.71	16.3–29.6	0.66	0.015	0.68	0.46	0.55	-	-

SWC, soil water content; SNC, soil nitrate content; ST, soil temperature. There was no significant difference in the measured soil temperature under the different treatments.

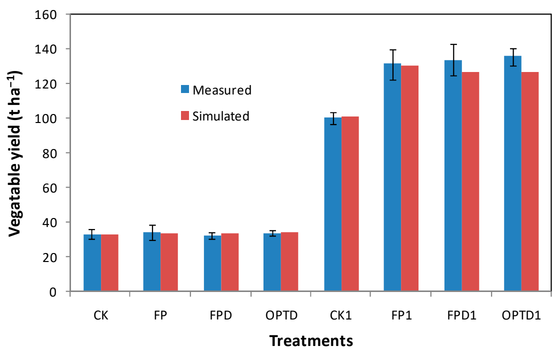

Figure 2. Observed and simulated vegetable yields of cucumber and tomato (treatments with number 1) under different fertilization and irrigation treatments. Definitions of the treatment codes are referred to in Table 1 and in the text. The vertical bars for measured data indicate standard errors.

Table 4. Optimized input parameters of WHCNS-veg.

	Parameter	Description	Cucumber	Tomato
Crop parameters	Tsum	Accumulated temperature (°C)	1100	1440
	Tbase	Base temperature (°C)	14.5	14.8
	C_{DM}	Dry matter content (%)	4	6
	Nmin	Minimum N content in plant (%)	1.98	3
N transformation parameters	Vn	Maximum nitrification rate (mg L^{-1} d^{-1})	30	30
	Kn	Half saturation coefficient (mg L^{-1})	100	100
	Kd	Denitrification kinetic constant (mg mg^{-1})	0.5	0.5
	Ad	An empirical proportionality factor	0.1	0.1
	Kv	First-order kinetic constant for volatilization (d^{-1})	0.025	0.005

3.2. Model Validation

For the water content, NO_3^- distribution, NH_3 volatilization and N_2O emission, the optimized results were comparable with the measured data under CK, FPD and OPTD (Figure 3). Using optimized parameters, the predictions could explain more than 64% of the variation in the soil water content under CK, FPD and OPTD. The largest RMSE values were 0.04 and 0.03 for the cucumber and tomato seasons, respectively (Table 3). The dynamic pattern of soil water at 0–20 cm was similar over the cucumber growth period under flooding and drip irrigation, but it decreased quickly in the tomato season under drip irrigation.

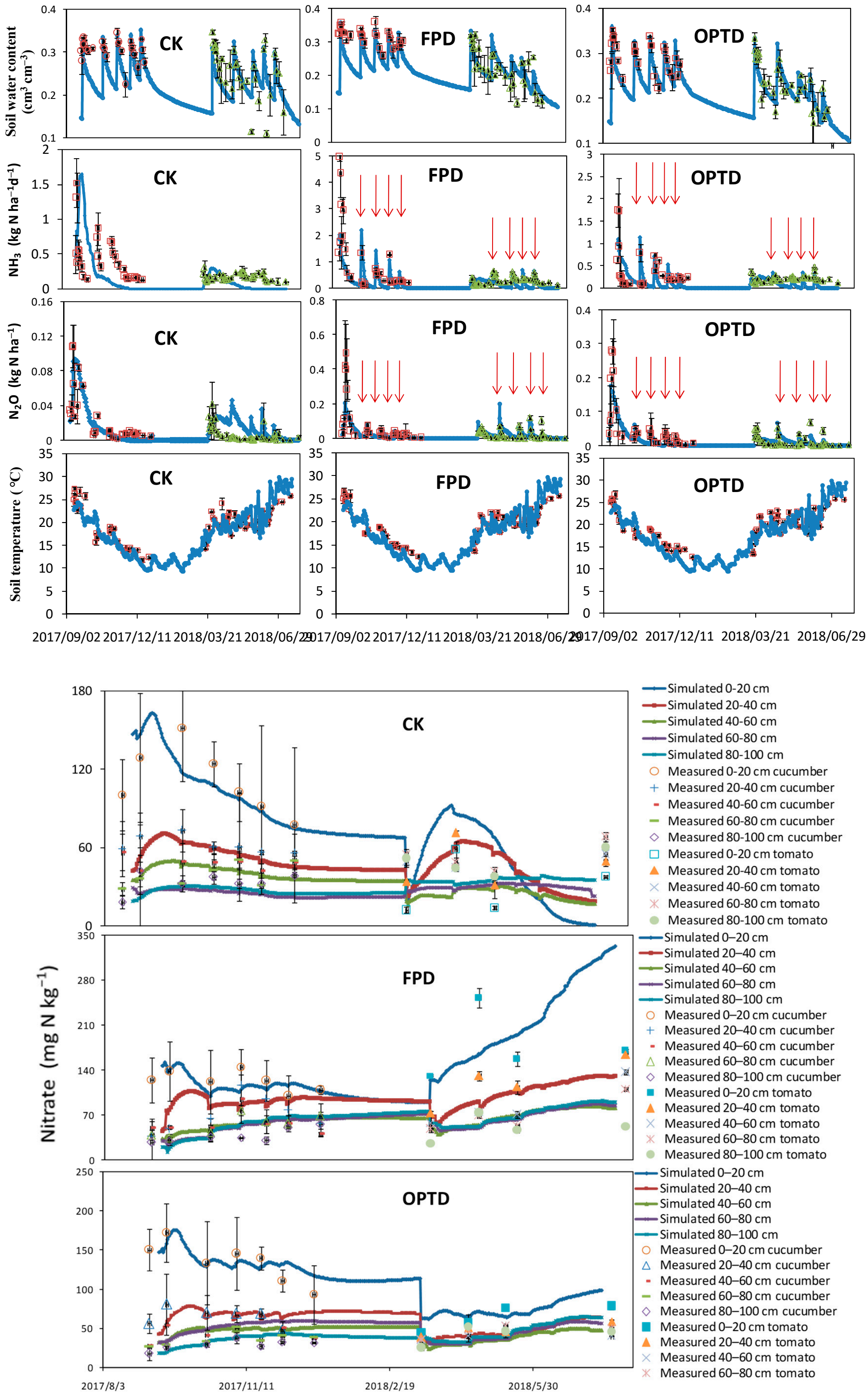

Figure 3. Comparison of observed and simulated soil water content at 0–20 cm, NH_3 volatilization,

N_2O emission, soil temperature at 5 cm (**upper figure**), and NO_3-N distribution in the 0–100 cm profile for annual greenhouse cultivation of cucumber and tomato under different fertilization and irrigation treatments (**lower figure**). Arrows in N_2O emission and NH_3 volatilization indicate top-dressing. Definitions of the treatment codes are referred to in Table 1 and in the text. The vertical bars for measured data denote standard errors.

In the whole rotation period, the N_2O emission peak appeared after irrigation and fertilization (Figure 3). N_2O emission in the cucumber season was significantly higher than that in the tomato season. Moreover, the emission with base fertilizer was much higher than that with top-dressing in the cucumber season. The total N_2O emissions for the different treatments were in the order FP > FPD > OPTD > CK (Figure 4a). The total N_2O emissions decreased 19% and 45.5% under drip irrigation (FPD) in the cucumber and tomato seasons, respectively, compared to those under flood irrigation (FP). The model simulation was able to explain more than 67% of the variation inN_2O emission, with RMSE values of 0.037 and 0.016 kg N ha^{-1} for cucumber and tomato, respectively (Table 3).

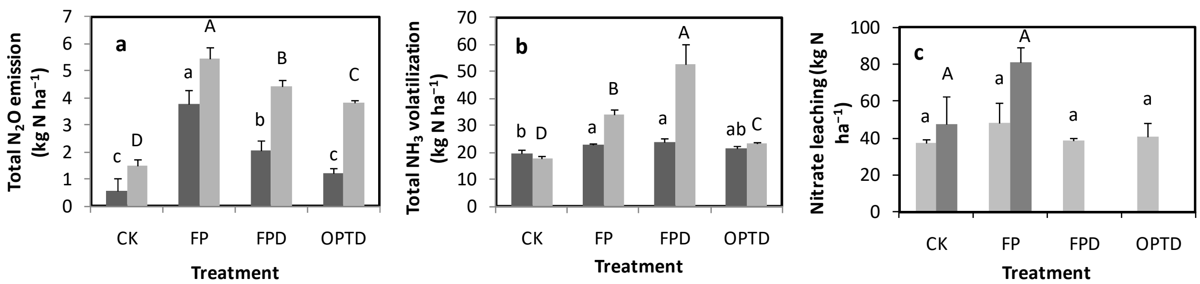

Figure 4. Total losses of N_2O (**a**), NH_3 (**b**) and NO_3-N (**c**) in the cucumber (light color) and tomato (dark color) seasons under different fertilizer and irrigation treatments. The vertical bars denote standard errors. Letters above column means significant difference between treatments in cucumber season (Capital) and tomato season (lower case).

Ammonia volatilization showed a similar trend toN_2O emission, with a peak appearing after fertilization and irrigation. The volatilization rate in the cucumber season was at least two times higher than that in the tomato season (Figure 3). The average NH_3 volatilization rates were in the order FPD > FP > OPTD > CK (Figure 4b). Reduced N input (OPTD) decreased the total NH_3 volatilization by 56% compared to FPD. The model simulation was able to match the dynamics, except for those of CK, but it could not catch the peak amount and lag; therefore, the RMSEs were high for cucumber (0.34 kg N ha^{-1}) and tomato (0.46 kg N ha^{-1}) (Table 3).

The measured and simulated nitrate contents in the 0–100 cm soil layers are shown in Figure 3. The predicted nitrate in the soil profile compared well in the cucumber season, but it was over-predicted (FPD) or under-predicted (CK) in the top layer in the tomato season, even after we used measured data before tomato transplanting as the initial value to predict the nitrate distribution. The RMSEs ranged from 9.3 to 23.4 kg N ha^{-1} in the cucumber season and from 17.4 to 32.1 kg N ha^{-1} in the tomato season (Table 3). We did not further adjust soil organic matter pools because of uncertainties in the pool sizes and the decomposition rate of manure in the soil.

4. Discussion

4.1. Model Performance

Soil water and temperature are key factors controlling soil C (providing a substrate for heterotrophic microbes) and N dynamics; therefore, we predicted two processes first. Our evaluation showed that the WHCNS-veg model provided accurate predictions of temperature and water, with RMSEs comparable to those reported by Zhang et al. [2,12]. The good prediction of the water content is similar to previous findings [29] obtained when soil hydraulic parameters were correctly optimized.

Our RMSE values for average N_2O emissions in the cucumber and tomato seasons were 0.023 and 0.019 kg N ha^{-1}, respectively, which are lower than those found in other vegetable systems using the WHCNS-veg model [2]. Our results showed that N_2O emission was much higher in the cucumber season, which is similar to results by Ni et al. [20] but contradictory to reports by Zhang et al. [2]. There were discrepancies in the timing of the predicted and measured N_2O flux in the tomato season under CK (Figure 3). This result was comparable with that by Smith et al. [30] in a field crop using the APSIM model. The predicted N_2O emission after basal fertilization was much lower than the observed data under drip irrigation (FPD and OPTD, Figure 3), which was contradictory to results by Zhang et al. [12] under flood irrigation. The reason for this may be manure application. In the greenhouse, a large amount of compost was applied, which contained a large amount of water. However, the WHCNS-veg model only considers the carbon content of manure. Thus, water from manure provides a suitable environment for microbial activity, which increased the measured N_2O data under drip irrigation. Compared to that in the cucumber season, the much lower soil temperature produced a suitable environment for low N_2O emission in the tomato season when basal fertilizer was applied.

Our RMSEs for the nitrate distribution in the soil profile were higher than those obtained by Zhang et al. [2] and similar to those obtained by Liang et al. [1]. Long fallowing during the summer season had profound effects on the nitrate distribution when tomatoes were transplanted; therefore, further efforts are needed to improve the simulation of nitrate movement in the soil profile under drip irrigation. Ammonia volatilization is mainly controlled by one parameter (a first-order kinetic parameter) in the WHCNS-veg model. The parameter adjustment was able to match the peak times after fertilization and irrigation but could not compare well with values from lagging, which were higher than predicted data.

4.2. N Input Affected N_2O Release, NH_3 Volatilization and NO_3^- Leaching

Higher temperature, moisture and N input in the greenhouse provide optimal conditions not only for plant growth but also for microbial activity. In the greenhouse, higher N input increased N_2O emission in the same season when the total irrigation amount or irrigation approach was the same (FPD and OPTD, Figure 4). This is comparable to results by Li et al. [31–33]. They found that N_2O emission was exponentially related to N input. However, comparing the two seasons, N_2O emission in the tomato season (with much higher manure Napplied) was much lower than that in the cucumber season; the reason for this may be as follows: (1) Composted manure decreases nitrifiers and denitrifiers, which significantly reduces N_2O emission [5].(2) N_2O release was controlled by the soil temperature/water content in the cucumber/tomato seasons according to stepwise regression [34]. Soil temperature has a significant positive correlation with N_2O emission [35]. When manure was applied as a basal fertilizer in the cucumber season, the soil temperature was high (around 25 °C, Figure 2); therefore, N_2O emission was high. During the tomato season, in soil irrigated after a long dry-fallow season, the water content was lower or the wet area was less compared to those in the cucumber season, which weakened the denitrification potential [20]. (3) During the tomato season, the soil temperature was already more than 20 °C, and it increased daily; therefore, tomatoes grew much faster than cucumbers (soil temperature decrease from 25 to 15 °C), and the fresh yield was almost four times that of cucumber. Thus, the tomatoes needed much more nitrate than the cucumbers, which reduced the potential for N_2O emission by nitrification and decreased the NH_3 volatilization potential.

Fertilizer application affects NH_3 volatilization mainly by controlling the ammonium content in the soil. Therefore, 50% less N input (OPTD) reduced NH_3 volatilization by 55.9% and 8.7% in the two seasons without jeopardizing vegetable yield. This result is consistent with previous findings [11]. In addition, high N input accelerates the speed of soil acidification, which would promote NH_3 volatilization due to a negative relationship between soil pH and NH_3 volatilization [36].

Leaching is a main path of N loss in intensive vegetable production systems. Combining fertilizer with irrigation (whether flooding or drip irrigation) in a vegetable field promotes mineral N or dissolved N movement with water infiltration. By meta-analysis, Qasim et al. [32] found that nitrate leaching in an unfertilized control is positively controlled by the soil organic matter and irrigation amount. This may explain the relatively large amount of nitrate leaching under the CK treatment, where a large amount of manure N was applied each season (Figure 4). Under fertilization conditions, nitrate leaching exponentially increased with the fertilizer N application rate [32]. However, this process depends on irrigation: when drip irrigation was applied, NO_3^- accumulated slowly in the 0–100 cm soil profile without leaching in the tomato season (Figure 4).

4.3. Irrigation Approaches Affected N_2O and NH_3 Release and Nitrate Leaching

Irrigation approaches, such as flooding or drip irrigation, not only affect the amount of water applied but also impact the alternation of dry and wet. Drip irrigation (FPD) significantly reduced soil N_2O emissions compared to flooding fertilization (FP) when the total N input was equal. This is similar to the results of other studies [37,38]. Ni et al. [20] found that drip irrigation had no impact on N_2O emission in a greenhouse. In fact, N_2O is produced via different pathways under divergent irrigation approaches. When the soil is rapidly and fully wetted by flood irrigation, an anaerobic environment easily forms, which makes denitrifying bacteria more active [38], thereby increasing the N_2O produced by denitrification [39]. On the contrary, drip irrigation reduces the soil pore water content (Figure 3), which inhibits the N_2O produced by denitrification [38]. In addition, under drip irrigation, a region with high humidity easily forms near the emitter. When the soil WFPS near the emitter is greater than 80%, the N_2O produced will be further reduced to N_2 [40], thus reducing the production of N_2O under drip irrigation. Furthermore, drip fertigation directly transports nutrient to crop roots through pipelines, which promotes the absorption and utilization of nitrogen by crops, thus reducing the mineral N concentration for nitrification and denitrification reactions, thus reducing N_2O emissions [41].

Drip fertilization increased soil NH_3 volatilization by 54.2% in the cucumber season compared to flooding fertilization. This result is comparable with previous findings [42]. (1) Drip irrigation slowly increases the soil water content; therefore, more NH_4 can be kept at the soil surface. Meanwhile, flooding irrigation increases the water content by a large amount of water; therefore, inorganic nitrogen will enter deeper soil with the infiltration of water, which makes it more difficult to volatilize NH_3 to the surface and to the air. (2) Compared to drip irrigation, flood irrigation quickly saturates soil, which prevents NH_3 volatilization [43]. (3) The soil water content in the flooding fertilization treatment was significantly higher than that in the drip fertilization treatment (Figure 3), which linearly decreased soil NH_3 volatilization.

5. Conclusions

This study confirmed that farmers' practice with high fertilization and flood irrigation can contribute greatly to N_2O emission, NH_3 volatilization and NO_3^- leaching in greenhouse vegetable production. Drip irrigation, which reduced the irrigation water amount by 30%, increased NH_3 volatilization by 20 kg N ha^{-1} but decreased N_2O emission by 1 kg N ha^{-1} and NO_3^- leaching by 75 kg N ha^{-1}. Combining drip irrigation with a 50% reduction in chemical N significantly decreased greenhouse gas emissions without sacrifice vegetable yields. Therefore, finding an optimal N input (amount and scheme) and combining it with drip irrigation is an environmentally friendly strategy in intensive greenhouse vegetable production systems. Future research could use scenario analysis to predict how water and nitrogen management affect nitrogen losses and crop yield. Another future research direction is to improve the model structure by providing more parameters to simulate NH_3 volatilization (as there is currently only one parameter for controlling NH_3volatilization).

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