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Assessing impacts of nitrogen management on nitrous oxide emissions and nitrate leaching from greenhouse vegetable systems using a biogeochemical model

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ABSTRACT

Greenhouse vegetable (GV) fields with intensive nitrogen application and frequent flood irrigation may substantially contribute to reactive nitrogen (Nr) losses, such as nitrous oxide (N_2O) emissions and nitrate (NO_3^-) leaching. In this study, we applied a biogeochemical model, Denitrification-Decomposition (DNDC), to assess impacts of N management on vegetable yields, N_2O emissions, and NO_3^--N leaching from GV systems. The model was evaluated using multi-year (2011–2013) field measurements of vegetable yields, N_2O emissions, and NO_3^--N concentrations in the surface soil layer and soil leachate under three treatments with different N management. The model evaluations demonstrated that the simulations of the vegetable yields and seasonal cumulative N_2O emissions were consistent with the corresponding observations after calibration. In addition, DNDC generally captured the seasonal variations of the N_2O fluxes and NO_3^--N concentrations in the surface soil layer and the seasonal patterns and magnitudes of the measured NO_3^--N concentrations in soil leachate in 2011. We then assessed impacts on the vegetable yields, N_2O emissions, and NO_3^--N leaching of different N management practices by conducting simulations under scenarios with changes in rate of the applied N-fertilizers and the application of nitrification inhibitor (NI). The results suggested that 1) the increasing of organic or synthetic N application rate generally increased the N_2O emissions and NO_3^--N leaching, but did not persistently increase the vegetable yields, 2) urea N application could induce more N_2O emissions and NO_3^--N leaching in comparison with organic N amendment, and 3) the NI application could decrease the N_2O emissions and NO_3^--N leaching while maintaining the vegetable yields at the GV fields. The optimum management practice identified in this study was applying organic manure at a rate of 320 kg N ha^{-1} four $season^{-1}$ and urea at a rate of 334 kg N ha^{-1} four $season^{-1}$, combined with the NI application. The optimum management practice reduced the rates of organic manure (1600 kg N ha^{-1} four $season^{-1}$) and urea (1670 kg N ha^{-1} four $season^{-1}$) under the farm's conventional practice by 80%. This practice maintained or slightly increased the yields and mitigated the N_2O emissions and NO_3^--N leaching by 81% to 90% and 92% to 95%, respectively, among different vegetable growing seasons.

1. Introduction

In order to maintain high crop productivities, intensive N applications are often applied in cropping systems in China. However, the high application rates of N fertilizers and low crop nitrogen use efficiency (NUE) lead to superfluous N accumulating in soils, which eventually releases into the atmosphere and/or water bodies, causing a series of environmental problems (Cassman et al., 2002; Galloway et al., 2003). Both nitrous oxide (N_2O) and nitrate (NO_3^-) are reactive N species, and croplands are important sources of these two species. N_2O is an important greenhouse gas, contributing to global warming and deterioration of the atmospheric environment (IPCC, 2013; Ravishankara et al., 2009). Globally, N_2O released from agriculture is approximately 4.1 Tg (10^{12} g) N yr^{-1} (IPCC, 2013), which is largely attributable to the use of synthetic N fertilizers and organic manure (Davidson, 2009). Increases in NO_3^--N leaching from agricultural lands have been

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Table 1
Application rate of N fertilizers, water from irrigation, and comparisons between modeled and observed seasonal total N_2O emissions.

Vegetable species (period)[a]	Treatments	N application rate[b] (kg N ha^{-1})			Irrigation (mm)	N_2O		
		Total	Organic manure	Synthetic		Observed (kg N ha^{-1})	Modeled (kg N ha^{-1})	AE[d]
Tomato (P1)	FP	1550	800	750	167	19.66[4.52][c]	18.37	6.56
	R	1100	800	300		11.33[2.94]	8.09	28.60
	R + DCD	1100	800	300		9.46[4.99]	8.27	12.58
Cabbage (P2)	FP	800	400	400	321	6.92[2.63]	10.56	52.60
	R	665	400	225		4.62[1.37]	7.46	61.47
	R + DCD	665	400	225		3.97[0.64]	6.33	59.45
Tomato (P3)	FP	1550	800	750	169	12.99[2.34]	15.61	20.17
	R	1100	800	300		8.06[2.11]	5.49	31.89
	R + DCD	1100	800	300		4.85[0.21]	4.93	1.65
Pakchoi (P4)	FP	120	0	120	140	2.09[0.35]	3.13	49.76
	R	48	0	48		1.13[0.29]	1.74	53.98
	R + DCD	48	0	48		0.94[0.26]	1.26	34.04
Lettuce (P5)	FP	800	400	400	123	5.53[2.10]	4.64	16.09
	R	560	400	160		3.55[0.47]	3.97	11.83
	R + DCD	560	400	160		2.33[0.45]	2.78	19.31
Tomato (P6)	FP	1550	800	750	129	14.43[1.37]	15.68	8.66
	R	1100	800	300		5.57[1.28]	7.28	30.70
	R + DCD	1100	800	300		5.00[0.55]	5.21	4.20
Cabbage (P7)	FP	800	400	400	174	4.28[0.94]	7.31	70.79
	R	560	400	160		3.83[1.45]	4.36	13.84
	R + DCD	560	400	160		2.17[0.78]	3.52	62.21

[a] Tomato (*Solanum lycopersicum*) was cultivated during P1 (Apr. 28 to Aug. 13, 2011), P3 (Feb.22 to Jul.27, 2012), and P6 (Feb.28 to Aug.13, 2013); cabbage (*Brassica oleracea L. var. capitata L.*) was cultivated during P2 (Sep. 12, 2011 to Jan. 12, 2012) and P7 (Aug. 24 to Nov. 19, 2013); pakchoi (*Brassica rapa chinensis*) was cultivated during P4 (Jul.28 to Oct.26, 2012); and lettuce (*Lactuca sativa var augustana*) was cultivated during P5 (Oct. 27, 2012 to Feb. 23, 2013). The first, second, and third rotation period was defined as the period from April 28, 2011 to February 21, 2012 (P1 and P2 periods), February 22, 2012 to February 27, 2013 (P3 to P5 periods), and February 28, 2013 to November 19, 2013 (P6 and P7 periods), respectively (Zhang et al., 2018).
[b] We applied urea (46.4% N) for both basal fertilizer application and topdressing, and applied cow manure for each basal fertilizer applications (Zhang et al., 2018).
[c] The data are means of three replicates with standard deviations listed in '[ ]'.
[d] AE, normalized absolute error, %.

observed worldwide (Wang and Li, 2019; Zhu et al., 2006), which has increased the risks of human cancer, water body hypoxia, and biodiversity loss (e.g., Seitzinger, 2008; World Health Organization, 2004).

During the past 30 years, greenhouse vegetable (GV) production developed rapidly in China. The cultivated area of GV reached 3.7 million ha in 2014 (Chinese Ministry of Agriculture, 2015). While economic benefits from GV productions are usually higher than productions of field crop or vegetable in open-air fields, GV fields have been recognized as hot spots of N_2O emissions and NO_3^--N leaching primarily due to high rates of N applications, frequent irrigations, and relatively high soil temperature and water content in GV systems (e.g., Fan et al., 2014; Rashti et al., 2015; Ju et al., 2006; Min et al., 2012a, 2012b). N_2O emissions and NO_3^--N leaching from GV systems are usually higher than those from field crops in nearby or similar regions (Zhang et al., 2018, Min et al., 2012a). Therefore, it is urgent to quantify and mitigate both N_2O emissions and NO_3^--N leaching from GV fields and develop optimum farming management practices (FMPs) for sustainable GV productions.

While a number of field studies have been performed to quantify N_2O emissions or NO_3^--N leaching from GV fields (e.g., Guo et al., 2012; Lou et al., 2012; Min et al., 2012a, 2012b; Zhang et al., 2018), large uncertainties still exist in these quantifications primarily due to the substantial spatial and temporal variations in the N_2O emissions and NO_3^--N leaching from GV fields. For example, the seasonal N_2O emissions and NO_3^--N leaching varied from 2.2 to 14.2 and 56.5 to 467.0 kg N ha^{-1} across different GV tomato fields (He et al., 2009; Guo et al., 2012; Lou et al., 2012; Zhao et al., 2012; Fan et al., 2014). Moreover, most of the field studies were limited in comprehensively quantifying impacts of different FMPs on both N_2O emissions and NO_3^--N leaching from GV fields because they usually focused on only N_2O emissions (He et al., 2009; Min et al., 2012b; Lou et al., 2012) or NO_3^--N leaching (Fan et al., 2014; Min et al., 2012a; Zhao et al., 2012). In addition, the identification of optimum N management practices for increasing NUE and mitigating both N_2O emissions and NO_3^--N leaching from GV fields are still lacking because limited treatments were often included in previous field studies.

Process-based models, such as the DeNitrification-DeComposition (DNDC) model, have been developed to extrapolate the measurements at specific sites and during specific periods to large regions or over extended time spans. These models have taken into account important factors regulating Nr losses, and thus have been recognized as useful tools to evaluate impacts of management practices on Nr losses from agricultural ecosystems (e.g., Brilli et al., 2017; Butterbach-Bahl et al., 2013; Giltrap et al., 2010). While process-based models have been widely evaluated against Nr losses from different cropping systems (e.g., Brilli et al., 2017; Deng et al., 2018; Dutta et al., 2016; Giltrap et al., 2010), large uncertainty still exists in applying these models to estimate N_2O emissions and NO_3^--N leaching from GV systems because model testing or applications were very limited for quantifying N_2O emissions and NO_3^--N leaching from GV systems.

During 2011 to 2013, we performed a multi-year experiment to quantify N_2O emissions and NO_3^--N concentrations in soil leachate under alternative N management practices at a typical GV field in Beijing, China (Zhang et al., 2018). Vegetable yields, N_2O fluxes, NO_3^--N concentrations in soil leachate, and soil environmental variables (i.e. soil temperature and moisture, and NO_3^--N contents in the surface soil layer) were measured through the experiment. However, we did not quantify NO_3^--N leaching fluxes, and did not identify optimum N management practices that can mitigate both N_2O emissions and NO_3^--N leaching while maintaining vegetable yields due to the setting of limited treatments. In this study, we integrated the field measurements and the DNDC model to assess the impacts of N management on N_2O emissions and NO_3^--N leaching from the GV system. We evaluated DNDC using the multi-year field measurements, including the vegetable yields, N_2O fluxes, NO_3^--N concentrations in soil leachate, and soil environmental variables, and then applied the model to investigate the impacts of different N management practices on N_2O emissions and NO_3^--N leaching and to identify optimum managements for these N losses.

2. Materials and methods

2.1. The study site and field data

Field data used in this study were collected at a greenhouse vegetable field (latitude 39°36′N, longitude 115°56′E) in sub-urban Beijing, China. The field measurements were performed from April 2011 to November 2013 and spanned seven vegetable growing seasons (P1 to P7 in Table1). The study site has a sub-humid climate, with an average annual mean air temperature of 11.8 °C and annual total precipitation of 575 mm from 2010 to 2013. However, there was no water input through precipitation in the study field during the experimental period. The local soil is a silt-loam soil, with a bulk density of 1.4 g cm^{-3}, sand fraction of 14%, silt fraction of 63%, clay fraction of 23%, field capacity of 34% (in volumetric water content), wilting point of 9.1% (in volumetric water content), porosity of 0.485, total N content of 1.9 g N kg^{-1} (i.e., 0.19%), soil organic C content of 0.019 kg C kg^{-1} (i.e., 1.9%), pH of 8.0 in the top (0–20 cm) soil layer (Zhang et al., 2018).

The field data utilized to support the DNDC evaluation include vegetable yields, soil temperature and moisture, N_2O fluxes, soil NO_3^--N contents in the surface soil layer, and NO_3^--N concentrations in soil leachate under three treatments, including farmers' conventional fertilizer application (FP), reduced N fertilizer rate (R), and R combined with the nitrification inhibitor (NI) "dicyandiamide (DCD)" (R + DCD). The rate of N application was around 2400 kg N yr^{-1} under FP and around 1700 kg N yr^{-1} under R by following the local conventional and recommended FMPs, respectively (Zhao and He, 2009). The N fertilization rate for the R + DCD treatment was the same as R, but the DCD was applied additionally in each vegetable growing season under this treatment. Detailed information about N fertilization and other FMPs for the study field were described by Zhang et al. (2018).

Nitrous oxide fluxes were measured using the static chamber-gas chromatograph (GC) method once a week except for following special events of FMPs, such as irrigation, fertilization, and tillage. The N_2O fluxes were measured daily following each event of FMPs until the fluxes returned to the level before these events. For the days without measurements, the N_2O fluxes were estimated as the arithmetic mean fluxes of the two closest days when observations were carried out, and the daily fluxes from either the direct measurements or gap-filling were then summed to obtain total N_2O emissions for each vegetable growing season. We also measured soil temperature (0–5 cm) and moisture (0–16 cm), soil NO_3^-N concentration (0–20 cm), and vegetable yield. The soil samples for measuring NO_3^--N concentrations were taken once a week. The technical details regarding the measurements of N_2O fluxes, relevant soil environmental factors, and vegetable yield were described by Zhang et al. (2018).

The soil leachate for measuring NO_3^--N concentration was collected using ceramic suction cups (Poss et al., 1995; Perego et al., 2012). The suction cups were placed at 60 cm below the soil surface in each plot. In order to ensure a proper hydraulic connection between the ceramic suction cups and the soil, each cup was installed in a hole of similar diameter, and the borehole was then refilled using previously removed soil (Perego et al., 2012). During the experimental period, water samples in the suction cups were collected by applying suction of 80 kPa following each irrigation event. Then the NO_3^--N concentrations of the samples were measured using a continuous flow analyzer (continuous flow analyzer, Skalar Analytical B.V., Netherlands). The NO_3^--N concentrations of the samples generally represented the concentration of NO_3^--N in subsurface drainage water flows (Lord and Shepherd, 1993). However, the suction cups may collect water samples in the deep soil layers when there was no subsurface drainage water flow because of the suction applied. The NO_3^--N concentration of the samples may approximate to the NO_3^--N concentration in the deep soil layers during these periods (Ramos and Kuecke, 2001).

2.2. The DNDC model

The DNDC model (Li et al., 1992a, 1992b, 1994, 2000) was developed for simulating C and N dynamics in agro-ecosystems. It has been widely used to simulate crop yields, soil C sequestration, soil N concentration, water and N leaching, and greenhouse gas (GHG) emissions from terrestrial ecosystems during the last three decades (Gilhespy et al., 2014; Giltrap et al., 2010). DNDC is comprised of two components. The first component includes the soil climate, crop growth, and decomposition sub-models that simulate soil environmental factors, such as temperature, moisture, pH, redox potential, and substrate concentration based on the primary drivers (e.g. climate, soil properties, vegetation, and anthropogenic activity). The second component consists of the sub-models of the nitrification, denitrification, and fermentation that simulate C and N transformations mediated by soil microbes.

In DNDC, crop biomass is simulated by considering the effects on crop growth of several environmental factors, including radiation, air temperature, soil moisture, and N availability (Deng et al., 2014; Zhang and Niu, 2016). Soil N primarily exists in several pools – organic N, ammonium, ammonia, and nitrate. Dynamics of soil N in each pool are simulated at an hourly or daily time step through a series of biogeochemical reaction: decomposition, microbial assimilation, plant uptake, ammonia volatilization, ammonium adsorption, nitrification, denitrification, and NO_3^--N leaching. Fluxes of N gases (i.e., NH_3, NO, N_2O, and N_2) are predicted as either products or intermediate products by simulating the relevant N transformation processes. The DNDC model predicts NO_3^--N leaching by simulating both hydrological processes and N transformation, with NO_3^--N leaching directly driven by vertical water movement (Deng et al., 2011; Li et al., 2006). If water drainage occurs in a soil layer, the model distributes a fraction of the nitrate in the layer into the leachate, and therefore NO_3^--N leaching amount is controlled by both leaching water and soil NO_3^--N content (Li et al., 2006). Further details regarding the DNDC structure and the physical, chemical, and biogeochemical processes incorporated into the model were described by Li et al., 2000 and Li et al. (2006), Li et al. (2012).

2.3. Model evaluation

Field data, including the measured vegetable yields, soil temperature (0–5 cm) and moisture (0–16 cm), NO_3^--N concentrations in the surface soil layer (0–20 cm) and soil leachate, N_2O fluxes, as well as daily meteorological data, soil properties, and FMPs, were collected to support the DNDC evaluation. Daily meteorological data, including maximum and minimum ambient air temperature (Fig. 1) were recorded at a local climate station. Soil input parameters were determined using either on-site measurements (Section 2.1) or model default values. The required FMPs parameters included vegetable species, planting and harvest dates, tillage, fertilization, manure amendments, irrigation, management of greenhouse, and application of NI for R + DCD, and were derived from the field records. We set up the input parameters of FMPs by strictly following the field records to fully represent the FMPs applied into the fields. In order to simulate crop growth, DNDC requires several physiological parameters, including the maximum biomass production and its partitioning to shoot and root, the C/N ratio of plant, the accumulative temperature for maturity, and crop water demand. Although DNDC provides default values for the crop parameters, it is recommended to determine or estimate these crop specific parameters through field measurements or model calibration. Therefore, these parameters were estimated either using the field records or calibrating the simulated crop yields against the observed yields under the R + DCD treatments (Table 2). To simulate the effects of the NI application, DNDC requires the parameters regarding the

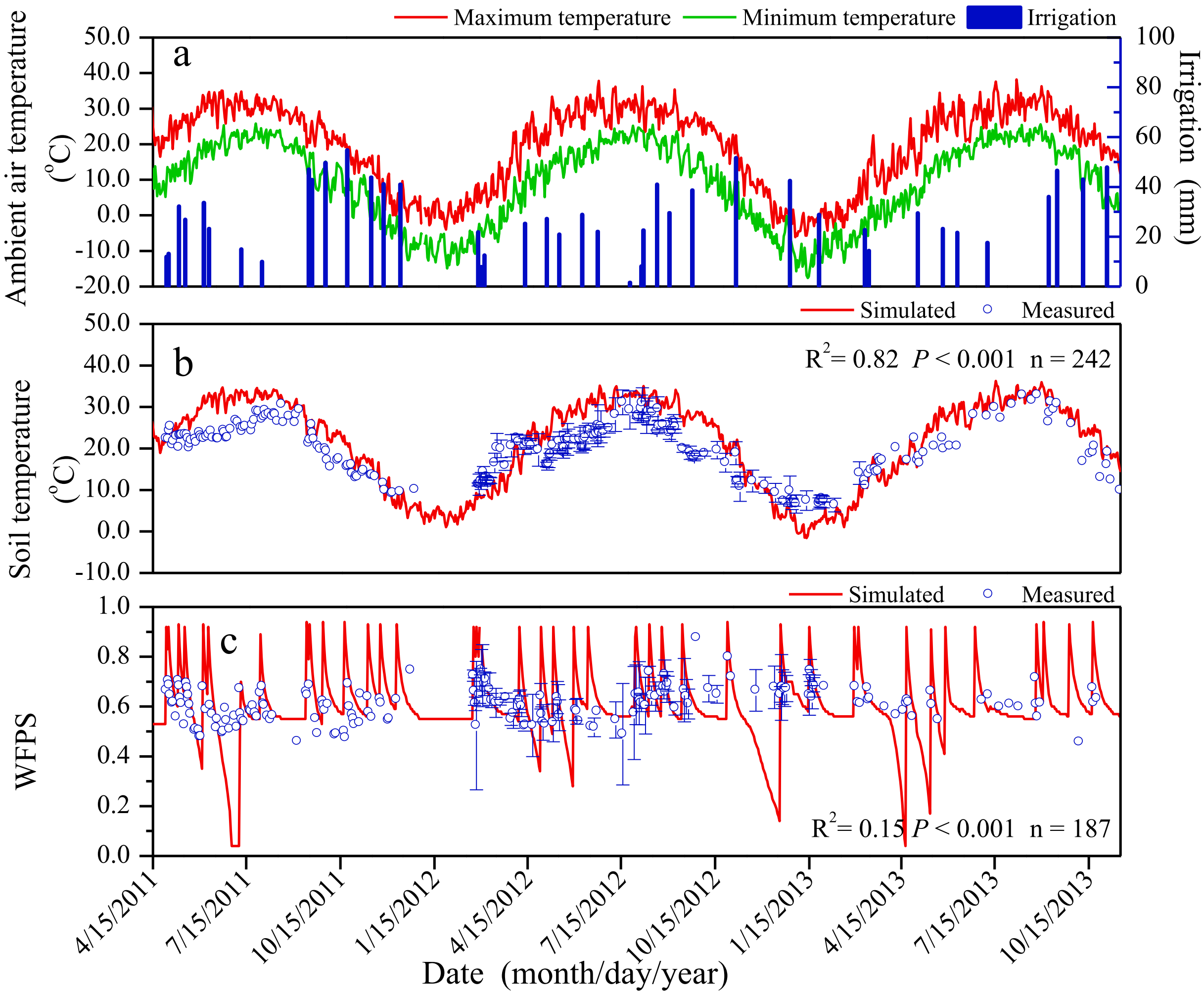

Fig. 1. Daily maximum and minimum ambient air temperature and irrigation (a), simulated and measured soil temperature (0–5 cm) (b), and simulated (10 cm) and measured (0–16 cm) soil water content (in water-filled pore space or WFPS) (c). Vertical bars in the panels b and c indicate standard deviations of three replicated measurements.

Table 2
The physiological parameters used to simulate vegetable growth.

Crop	MP[a]	SRF[b]	C/N[c]				TDD[d]	WR[e]
			Grain	Leaf	Stem	Root		
Tomato	2350	0.80/0.20	26	26	26	45	2000	300
Cabbage	1634	0.87/0.13	15	20	20	50	500	300
Pakchoi	1240	0.87/0.13	15	20	20	50	1500	300
Lettuce	760	0.78/0.22	12	12	12	23	500	300

[a] MP, the maximum biomass production under optimum growing conditions (unit: kg C ha^{-1}), was estimated by calibrating the simulated crop yields against the observed yields under the R + DCD treatment.

[b] SRF, the shoot to root fraction of the biomass at maturity, was determined using the field records.

[c] C/N, carbon to nitrogen ratio of the plant biomass, was determined using the field records.

[d] TDD, the required cumulative air temperature heat sum (in °C days) above a 0 °C threshold during the growing period, was estimated by calibrating the simulated crop yields against the observed yields under the R + DCD treatment.

[e] WR, amount of crop water requirement for producing dry matter (in g water g^{-1} dry matter), was estimated by calibrating the simulated crop yields against the observed yields under the R + DCD treatment.

efficiency and effective duration days of the NI. We set these two parameters as 1.0 and 18 days, respectively, according to the model calibration against the measured N_2O fluxes during the first rotational year under R + DCD. Using these input parameters, DNDC was run for four years from 2010 to 2013. The simulations were compared against the soil temperature and moisture, the crop yields under FP and R, the NO_3^--N concentrations in the surface soil layer and soil leachate, and the N_2O emissions (all the data under FP and R and the data during the second and third rotational years under R + DCD) for model validation. Because the NO_3^--N concentration of the leachate collected by the suction cups may approximate the NO_3^--N concentration either in subsurface drainage water flows or in deep soil layers when there was no drainage event (Ramos and Kuecke, 2001), we compared the measurements of the NO_3^--N concentration with the simulated NO_3^--N concentration in the subsurface water flows or in the deep soil layers (40–50 cm below the surface) when the model did not simulate a leaching water flux. The simulated NO_3^--N concentrations in the subsurface water flows or the deep soil layers were calculated through dividing the simulated NO_3^--N leaching fluxes by the leaching water fluxes or dividing the simulated soil NO_3^--N contents by the water contents between the 40 and 50 cm layers, respectively. We used zero-intercept liner regression between simulations and observations to evaluate the DNDC's performance. The slope and determination coefficient (R^2) of the regressions indicate the consistency and correlation between simulations and observations, respectively (Moriasi et al., 2007). The normalized root mean square error (RMSE) and absolute error (AE) were also used for quantitative comparisons between simulations and observations.

2.4. Scenarios of fertilization

In order to investigate the impacts of N management on vegetable yields, N_2O emission, and NO_3^--N leaching from GV systems, we designed a series of scenarios by changing rates of the applied N-fertilizers and the NI application. The simulation from July 2012 to November 2013 (covering P4, P5, P6, and P7) under FP was selected as the simulation of baseline, in which the rates of N application were 120, 800, 1550, and 800 kg N season^{-1}, respectively, for pakchoi, lettuce, tomato, and cabbage (Table 1). The total amount of the applied organic manure and urea was 1600 and 1670 kg N ha^{-1}, respectively, during these four growing seasons (Table 1).

Alternative scenarios were designed by setting the N application rates as 0, 20%, 40%, 60%, 80%, and 100% of the rates under the full organic manure (1600 kg N ha^{-1} four seasons^{-1}; Table 1) and urea applications (1670 kg N ha^{-1} four seasons^{-1}; Table 1), and by applying or not applying NI. Therefore, we set totally seventy-two scenarios (6 × 6 × 2) with alternative N management practices. We varied a single N management practice for each scenario while keeping other conditions (i.e. climate, soil, vegetable, and FMPs) consistent with baseline. The DNDC simulations were performed for four years from 2010 to 2013 under the baseline and alternative scenarios. The modeled results of vegetable yields, N_2O emissions, and NO_3^--N leaching during P4 to P7 were collected for analysis.

2.5. Identification of optimum management practice

The optimum N management practice for GV productions was identified by considering vegetable yields, N_2O emission, NO_3^--N leaching, NUE (calculated as dividing vegetable N uptake by total amount of N applications), and yield-scaled N_2O emission and NO_3^--N leaching (calculated as dividing cumulative N_2O emissions or NO_3^--N leaching by fresh vegetable yields) from a relatively short-term (i.e. P4 to P7). The objective was to simultaneously mitigate N_2O emission and NO_3^--N leaching while increasing or maintaining the vegetable yields through optimizing N application rate. Because the NO_3^--N concentration in soil leachate was regulated to be lower than 20 mg NO_3^--N L^{-1} based on the Quality Standard for Ground Water in China (GB/T14848-1993), the optimum N management practice was identified by considering this regulation. Specifically, we calculated the NO_3^--N concentration in the leachate using the simulated amounts of total NO_3^--N leaching and soil water leachate during each vegetable growing season. The optimum N management practice was then identified by choosing the scenario that showed the highest NUE and efficiencies in mitigating the total N_2O emission and NO_3^--N leaching, the lowest yield-scaled N_2O emission and NO_3^--N leaching, while maintained or increased the total vegetable yields over the four vegetable growing seasons.

Because the optimum management practice was identified based on the simulations over a relatively short period, it may be not able to represent long term impacts on the vegetable yields, N_2O emissions, and NO_3^--N leaching in the GV system. We therefore conducted additional simulations from 2010 to 2019 to investigate if the optimum practice could maintain the vegetable yields and mitigate N_2O emission and NO_3^--N leaching over a decadal scale by using the meteorological data at the local climate station. The additional simulations were conducted under the scenarios with the FP, the optimum practice, and the optimum practice but without the NI application. The actual vegetable systems during P1 to P7 were adopted for the years before 2014. The vegetable systems from 2014 to 2019 were set by rotationally planting the vegetable species during P4 to P7 three times because there was no record of FMPs from 2014 to 2019.

3. Results

3.1. Model evaluation

3.1.1. Soil temperature and moisture

The simulations of daily soil temperature (0–5 cm) were comparable with the measurements (Fig. 1b). The calculated statistical indices (R^2 = 0.82, P < 0.001) indicated that the simulated soil temperatures were significantly correlated with the measurements. However, the slope of the zero-intercept liner regression between the simulated and measured soil temperatures was 1.15, indicating that the model slightly overestimated the observed soil temperatures (Fig. 1b).

The modeled soil moisture contents were also generally comparable with the field observations (Fig. 1c), although there remained some discrepancies. In comparison with the field measurements, the model overestimated some peaks of soil water content following the irrigation events (e.g., April 30, 2011, May 10, 2011 and June 3, 2011, Fig. 1c). In addition, the DNDC underestimated the soil moisture during several periods (e.g. June 26, 2011 and May 14 and 15, 2013, Fig. 1c). The slope and R^2 of the zero-intercept liner regression between the simulated and measured soil moisture were 1.13 and 0.15 (P < 0.001), respectively.

3.1.2. Vegetable yields

Modeled vegetable yields were in good agreement with observations for both the calibration (R + DCD) and validation (FP and R) datasets (Fig. 2). The calculated AE values ranged from 1.4% to 37.4% (mean: 21.7%) for R + DCD (calibration), and 0.2% to 16.3% (mean: 6.6%) and 7.7% to 37.8% (mean: 17.6%), respectively, for FP and R (validation). The modeled impact on the vegetable yields of different treatments was also consistent with the measurements. Both the simulations and field observations did not show significant difference in the vegetable yields among the treatments (Zhang et al., 2018).

3.1.3. Nitrous oxide emission

The N_2O flux measurements (Fig. 3) showed similar seasonal patterns across the studied treatments, with frequent N_2O peaks primarily induced by fertilization and/or irrigation events and relatively low N_2O fluxes during the winter seasons. In comparison with the measurements, DNDC generally captured the seasonal patterns of daily N_2O fluxes, although both over-predictions (e.g., the N_2O peaks around April 28, 2011 and September 12, 2011) and under-predictions (e.g., the N_2O peaks around July 9, 2011, July 31, 2011 and June 15, 2012) remained during some periods (Fig. 3). The R^2 between the simulated and observed daily N_2O fluxes were 0.40 for FP, 0.28 for R, and 0.30 for R + DCD. In addition, DNDC successfully predicted the observed impacts of N management on the N_2O emissions. Both the simulated and measured N_2O fluxes indicted that reducing the N input and/or applying DCD mitigated the N_2O fluxes (Fig. 3 and Table 1; Zhang et al., 2018).

The measurements of the seasonal cumulative N_2O emissions ranged from 0.94 to 19.66 kg N ha^{-1} (Table 1). The simulated seasonal cumulative N_2O emissions varied from 1.26 to 18.37 kg N ha^{-1} that agreed with the variations of the field observations (Table 1). The AE values between the simulated and measured seasonal cumulative N_2O emissions ranged from 1.7% to 71% (mean: 31%). Relatively high AE values (e.g., > 40%) often appeared in cabbage and pakchoi growing seasons when relatively low seasonal cumulative N_2O emissions were observed (Table 1), because a relatively small absolute error of low N_2O emissions could result in a high relative error. The discrepancies were primarily due to the model over-estimating for the N_2O flux peaks induced by the fertilization and/or irrigation events during these seasons (e.g. September 12, October 19, 2011, July 28, August 12, 2012, and August 24, 2013). As the Fig. 4 illustrated, there existed zero-intercept linear regressions between the simulated seasonal cumulative N_2O emissions and the corresponding observations for both all datasets

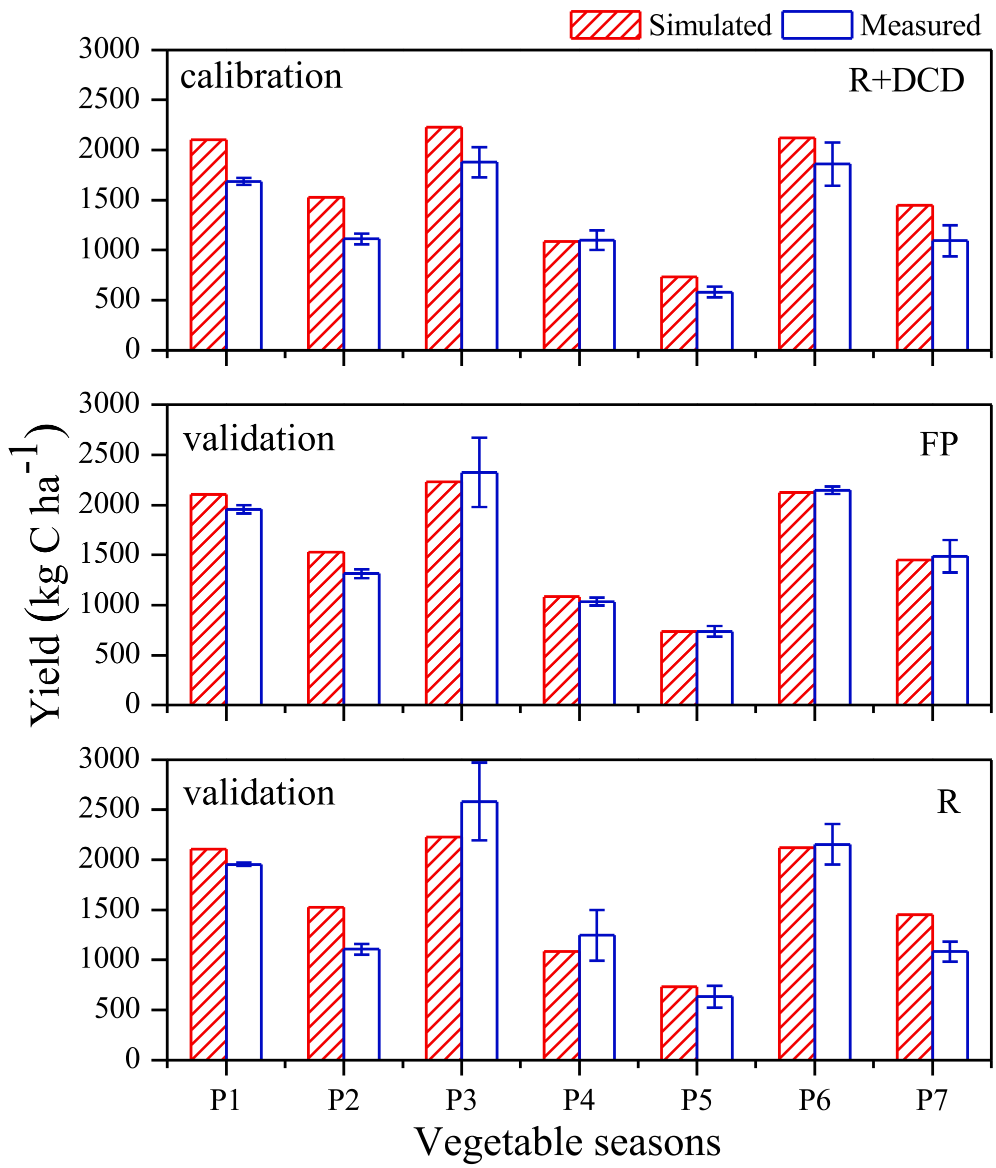

Fig. 2. Comparisons of the simulated and measured vegetable yields (kg C ha^{-1}) under the R + DCD, FP, and R treatments. The definitions of vegetable species from P1 to P7 are presented in Table 1. Vertical bars of the measurements indicate standard deviations of three replicates. The measurements under R + DCD were used for calibrating the crop parameters, and the measurements under FP and R were used for model validation.

(slope = 1.026, R^2 = 0.952, P < 0.001) and the datasets for model validation datasets (slope = 1.032, R^2 = 0.953, P < 0.001). The correlations were significant and the slopes of the regression lines were close to 1.0, suggesting that the DNDC model successfully captured the cumulative N_2O emissions across different vegetable growing seasons and treatments.

3.1.4. Soil NO_3-N contents

DNDC generally captured the measured seasonal patterns and magnitudes of the soil NO_3^--N concentrations (0–20 cm) for FP, R and R + DCD, although the simulations were lower than the corresponding measurements during the winter season in 2011 (Fig. 5). The measurements of the soil NO_3^--N concentration ranged from 24.1 to 328.9 (mean: 123.5), 15.6 to 176.0 (mean: 76.2) and 17.9 to 177.4 (mean: 80.0) mg kg^{-1}, respectively, under the FP, R and R + DCD treatments. The corresponding simulations were consistent with the observations, and varied from, 0.5 to 387.1 (mean: 126.7), 0.2 to 166.9 (mean: 57.9) and 0.2 to 169.1 (mean: 57.0) mg kg^{-1}, respectively. The RMSE values between the simulated and measured soil NO_3^--N concentrations were 70%, 57% and 55%, respectively, under the FP, R and R + DCD treatments. Both the DNDC simulations and field measurements indicated significantly higher soil NO_3^--N concentrations under the FP treatment in comparison with R or R + DCD.

3.1.5. NO_3^--N concentration in soil leachate

The capability of DNDC for simulating NO_3^--N leaching flux was evaluated by comparing the simulations against the observations of the NO_3^--N concentrations in soil leachate because the field measurement of NO_3^--N leaching flux was not available. DNDC generally captured the seasonal patterns and magnitudes of the measured NO_3^--N concentrations in soil leachate in 2011. Both the simulations and observations showed relatively higher NO_3^--N concentrations in June and July 2011 (Fig. 6). In addition, the DNDC model captured the measured decreasing trend of the NO_3^--N concentration along with the reduction of the N application rate among the treatments. However, it seems that the model underestimated the measured NO_3^--N concentrations in late summer and fall of 2012 and 2013, although only a few measurements were available during these periods (Fig. 6). The RMSE values between the simulated and measured NO_3^--N concentration in soil leachate were 50%, 62% and 50%, respectively, under the FP, R and R + DCD

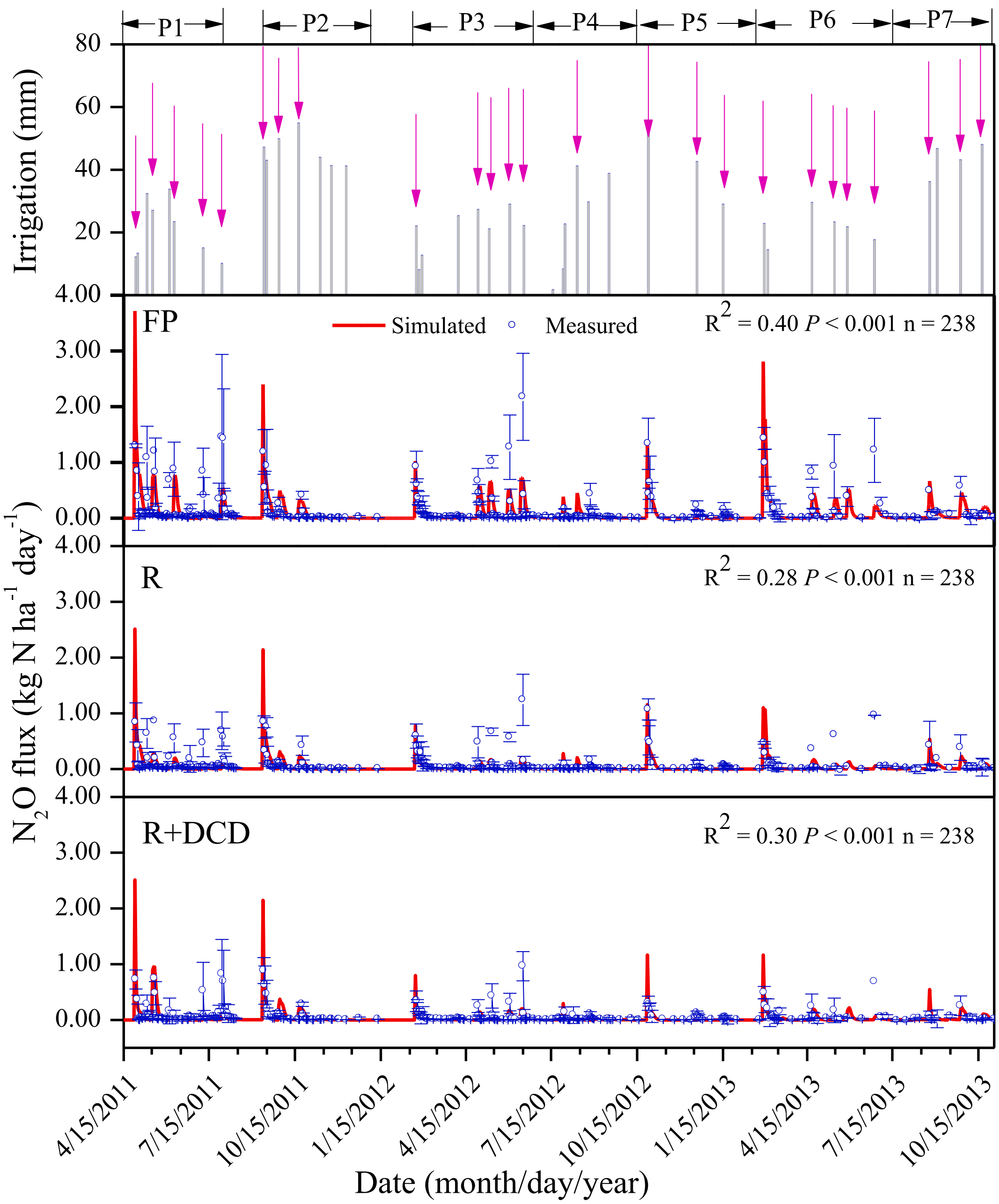

Fig. 3. Irrigation, and simulated and measured N_2O fluxes under the FP, R and R + DCD treatments. The arrows indicate dates of fertilization events. The measured N_2O fluxes are means of three replicates, and vertical bars indicate standard deviations of the replicates. The measurements during the first rotational year under R + DCD treatment were used for calibration, and all the data under FP and R and the data during the second and third rotational years under R + DCD were used for model validation.

treatments.

3.2. Yield, N_2O emissions, and NO_3^--N leaching under different fertilization

3.2.1. Yield under different fertilization

The modeled yields of pakchoi, lettuce, tomato, and cabbage were 1084, 734, 2122, and 1451 kg C ha^{-1}, respectively, under the baseline scenario. The corresponding simulations under alternative scenarios varied from 806 to 1084, 321 to 735, 644 to 2126, and 657 to 1465 kg C ha^{-1}, respectively (Fig. 7a–h). The simulated vegetable yields generally increased along with the increasing organic or synthetic N application rate. However, the increasing trends stagnated when the N application rates were higher than the threshold values that are specific for the different vegetable species. As a result, the vegetable yields were lower than the yields under baseline only when the N application rates were lower than 24 kg urea N ha^{-1} for pakchoi, 160 kg organic N ha^{-1} or 80 kg urea N ha^{-1} for lettuce, 480 kg organic N ha^{-1} or 150 kg urea N ha^{-1} for tomato, and 160 kg organic N ha^{-1} or 80 kg urea N ha^{-1} for cabbage (Fig. 7a–h). The DNDC simulations also demonstrate that the DCD application did not noticeably influence the vegetable yields if the N application rates were not changed (Fig. 7).

3.2.2. N_2O emissions under different fertilization

The simulated seasonal N_2O emissions under baseline were 3.17, 4.59, 15.59 and 7.34 kg N ha^{-1}, respectively, for pakchoi, lettuce, tomato, and cabbage. The seasonal N_2O emissions varied under the different fertilizer scenarios from 0.25 to 3.40, 0.06 to 4.59, 0.20 to 15.59,

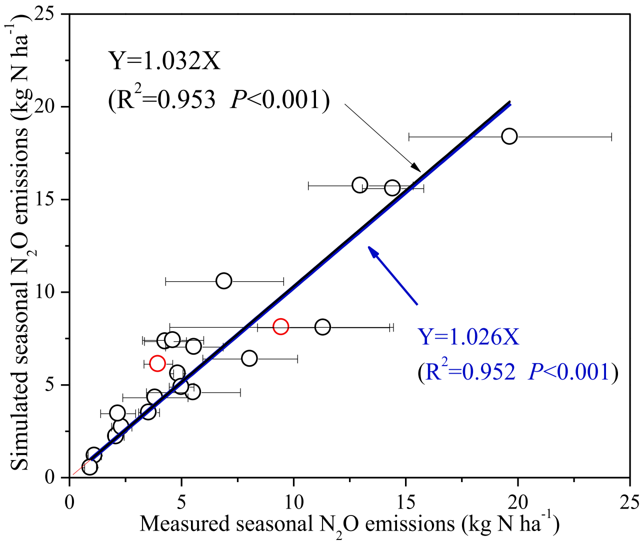

Fig. 4. Comparisons of the simulated and measured seasonal total N_2O emissions. The blue and black lines represent the zero-intercept linear regression lines between the simulations and observations for all field data (black and red points) and the data for model validation (i.e., excluding the data during the first rotational year under R + DCD; black points only), respectively. The functions shown describe the corresponding regression lines. The measurements were means of three replicates, and horizontal bars indicate standard deviations of the replicates.

and 0.28 to 7.34 kg N ha^{-1}, respectively, for pakchoi, lettuce, tomato, and cabbage, and generally increased along with the increases in synthetic or organic N application rate (Fig. 8a–h). In addition, the DNDC simulations demonstrate that applying DCD reduced the seasonal N_2O emissions. In comparison with the scenarios without the DCD application, the DCD application reduced the total N_2O emissions by 23 to 42%, 16 to 81%, 0 to 71%, and 0 to 37%, respectively, for the pakchoi, lettuce, tomato, and cabbage growing seasons.

3.2.3. NO_3^--N leaching under different fertilization

The NO_3^--N leaching under the baseline scenario were 435.1, 314.6, 186.3, and 755.4 kg N ha^{-1}, respectively, for pakchoi, lettuce, tomato, and cabbage. The simulated NO_3^--N leaching under different N management practices varied from 3.1 to 435.1, 2.4 to 314.6, 2.8 to 186.3, and 10.8 to 755.4 kg N ha^{-1}, respectively, during the pakchoi, lettuce, tomato, and cabbage growing seasons (Fig. 9a–h). Either decreasing the rate of urea or organic N application generally reduced the simulated NO_3^--N leaching from the studied GV systems. In comparison with the scenarios without the DCD application, the NO_3^- leaching under the scenarios with DCD decreased by 0.6 to 3.7%, 0.2 to 51.3%, 19.3 to 53.0%, and 0.03 to 7.0%, respectively, during the pakchoi, lettuce, tomato, and cabbage growing seasons. The results suggest that applying DCD mitigated NO_3^--N leaching from the GV fields although the efficiency of mitigation varied among different vegetable growing seasons.

3.3. Identification of optimum management practices

The optimum management practice was identified as applying 20% urea and 20% organic N fertilizers under FP combined with the DCD application (Table 3). The simulated vegetable yields were 1084, 734, 2125, and 1455 kg C ha^{-1}, respectively, for pakchoi, lettuce, tomato, and cabbage under the optimum management practice (Table 3). In comparisons with FP, the optimum management practice significantly mitigated the N_2O emissions and NO_3^--N leaching by 85% and 94%, respectively, for pakchoi, 90% and 95%, respectively, for lettuce, 89% and 94%, respectively, for tomato, and 81% and 92%, respectively, for cabbage. The simulated average NO_3^--N concentrations in soil leachate (range: 0.75–3.07 mg NO_3^--N L^{-1}) under the optimum management practice were lower than the regulation value of 20 mg NO_3^--N L^{-1} for the four vegetable growing seasons (Table 3).

Over the whole investigation period covering P4 to P7, the simulated NUE was 63% and the simulated N_2O emission and NO_3^--N leaching were 4.09 kg N ha^{-1} and 111.2 kg N ha^{-1}, respectively, under the optimum management practice. The corresponding yield-scaled N_2O emission and NO_3^--N leaching were 17 g N Mg^{-1} and 475 g N Mg^{-1}, respectively (Table 3). The highest NUE and the lowest N_2O emission, NO_3^--N leaching, yield-scaled N_2O emission, and yield-scaled NO_3^--N leaching were predicted under the optimum management practice (Table 3). Other practices with identical or similar N application rates either resulted in more N_2O emission and NO_3^--N leaching (e.g., 5.71 kg N ha^{-1} of the N_2O emission and 115.8 kg N ha^{-1} of the NO_3^--N leaching under the practice applying 20% urea and organic N fertilizers but without DCD, 7.09 kg N ha^{-1} of the N_2O emission and 318.0 kg N ha^{-1} of the NO_3^--N leaching under the practice applying 40% urea and 0% organic N fertilizers combined with the DCD applications) or did not consistently maintain the vegetable yields (e.g., the reduction of the pakchoi yield by 23% and the lettuce yield by 17% under the practice applying 0% urea and 40% organic N fertilizers). Therefore, these practices were not qualified as an optimum practice.

The simulations from 2010 to 2019 demonstrate that the optimum practice maintained the vegetable yields over the 10-year simulations in comparison with the FP. In addition, it consistently mitigated the N_2O emissions by 23% to 30% and NO_3^--N leaching by 0.6% to 3.7% among the different vegetable growing seasons, in comparison with the scenario with the identical N inputs but without the NI application. These results suggest that the identified optimum practice is sustainable for maintaining the vegetable yields and mitigating the N_2O emissions and NO_3^--N leaching over a decadal scale.

4. Discussion

4.1. Model performance

In this study, we evaluated the DNDC model using the multi–year measurements of vegetable yields, soil temperature and moisture, N_2O emissions, soil NO_3^--N concentration, and NO_3^--N concentration in soil leachate at a typical GV system. In comparisons with the field measurements, the model successfully captured the impacts on the vegetable yields, seasonal total N_2O emissions, and NO_3^--N concentrations in the surface soil layer and leachate of the setting treatments with different applications of N rates or NI. However, there still existed a few discrepancies between the simulations and observations on a daily basis.

As Fig. 1c demonstrates, the DNDC overestimated the moisture of the top soil layer following some irrigation events. This discrepancy could be partially due to the underestimated soil moisture of the field measurements because the soil moisture measurements were not timely (usually with one day delay) observed following some irrigation events. The over-predictions of the soil moisture could also because the model did not simulate preferential flows (Uzoma et al., 2015) although the study fields were often wet due to frequent irrigations and therefore the preferential flow induced by soil cracks may be rare at the fields. In addition, there were uncertainties in the simulated evapotranspiration under greenhouse environments, and the discrepancies in simulating the soil moisture could result from potential bias in simulating the evapotranspiration.

Compared to the measured daily N_2O fluxes, DNDC over-predicted some peaks of N_2O fluxes following the basal fertilizations with both urea and organic manure (e.g. late April 2011 in P1, mid-September 2011 in P2, late February 2013 in P6; Fig. 3), while under-predicted some peaks of N_2O fluxes following the topdressing events with the

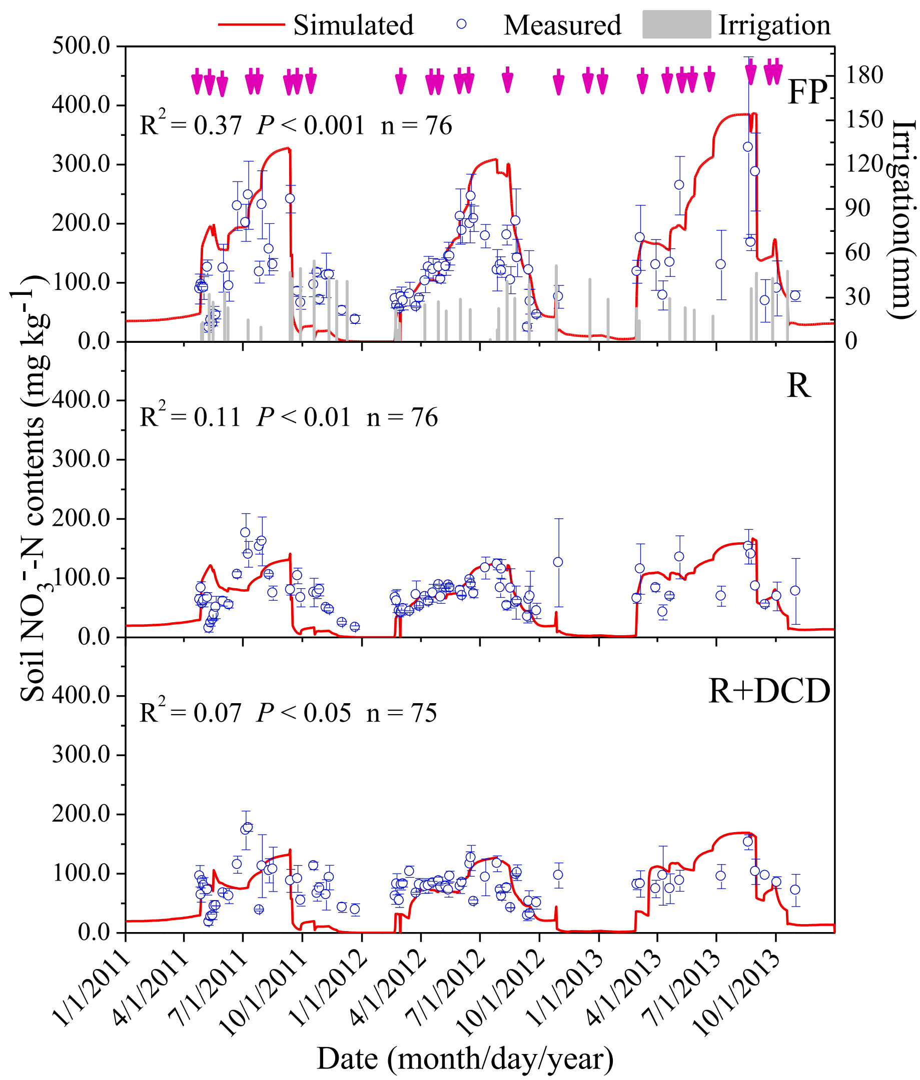

Fig. 5. Simulated and measured soil NO_3^--N concentrations (mg kg^{-1}) under the FP, R, and R + DCD treatments. The arrows indicate dates of fertilization events. The measurements were the average NO_3^--N concentrations (0–20 cm) from three replicates, and vertical bars indicate standard deviations of the replicates.

exclusively urea application (e.g. July to August 2011 in P1, May to June 2012 in P3, December 2012 to January 2013 in P5, May to June 2013 in P6; Fig. 3). Because the peaks of N_2O fluxes were likely primarily from denitrification at the study field (Zhang et al., 2018), the discrepancies in simulating the N_2O peaks were primarily due to discrepancies in simulating denitrification and associated N_2O production and consumption. Possible explanations for the discrepancies may include:(1) discrepancies in simulating the duration of soil anaerobic conditions and/or the sensitivity of denitrification rate to changes in soil anaerobic conditions, (2) discrepancies in simulating other environmental factors (e.g., soil temperature) and/or concentration of substrates (e.g., soil nitrate, dissolved organic carbon (DOC)) for denitrification during these occasions, and (3) the complex and uncertain mechanisms of denitrification and associated N_2O production and consumption (Butterbach-Bahl et al., 2013), which were not comprehensively represented in the model. However, the successful simulations of the seasonal cumulative N_2O emissions (Fig. 4) and the observed impacts of N management on the N_2O emissions demonstrated that the discrepancies in simulating the daily N_2O flux did not largely influence the consistency in simulating the seasonal cumulative N_2O emissions.

The DNDC captured the seasonal patterns and magnitudes of the NO_3^--N concentrations of the top soil layer, although it underestimated the corresponding observations during the winter season in 2011 (Fig. 5). The simulated low NO_3^--N concentrations during that winter seasons were induced by the frequent irrigation events with large amounts of water (Fig. 5) which moved the soil NO_3^--N in the surface layer into deeper layers. While the field study also observed the reductions of the surface soil NO_3^--N following the irrigation events during all the winters, less reductions were observed in 2011 in comparison with the other seasons even though there were more waters from irrigation in 2011. On contrary, DNDC simulated more reductions as a result of the larger amounts of the irrigation water, causing the discrepancy in simulating the soil NO_3^--N concentrations during the winter season in 2011.

There were uncertainties in the simulations of NO_3^--N leaching because the simulations were not directly evaluated against NO_3^--N leaching flux due to the absence of the NO_3^--N leaching measurements. In addition, DNDC underestimated the measured NO_3^- concentrations in late summer and fall of 2012 and 2013. The disagreements between the simulated and measured NO_3^--N concentrations in soil leachate could be partially due to the deviations of the field measurements because the samples collected using ceramic suction cups cannot fully represent soil leachate and there were significant uncertainties in the samples due to limited coverage or sample volume when applying the method of ceramic suction cups (Lord and Shepherd, 1993; Poss et al., 1995). In addition, there were limitations in the model settings because DNDC assumed a uniform profile for some soil physical properties (e.g.,

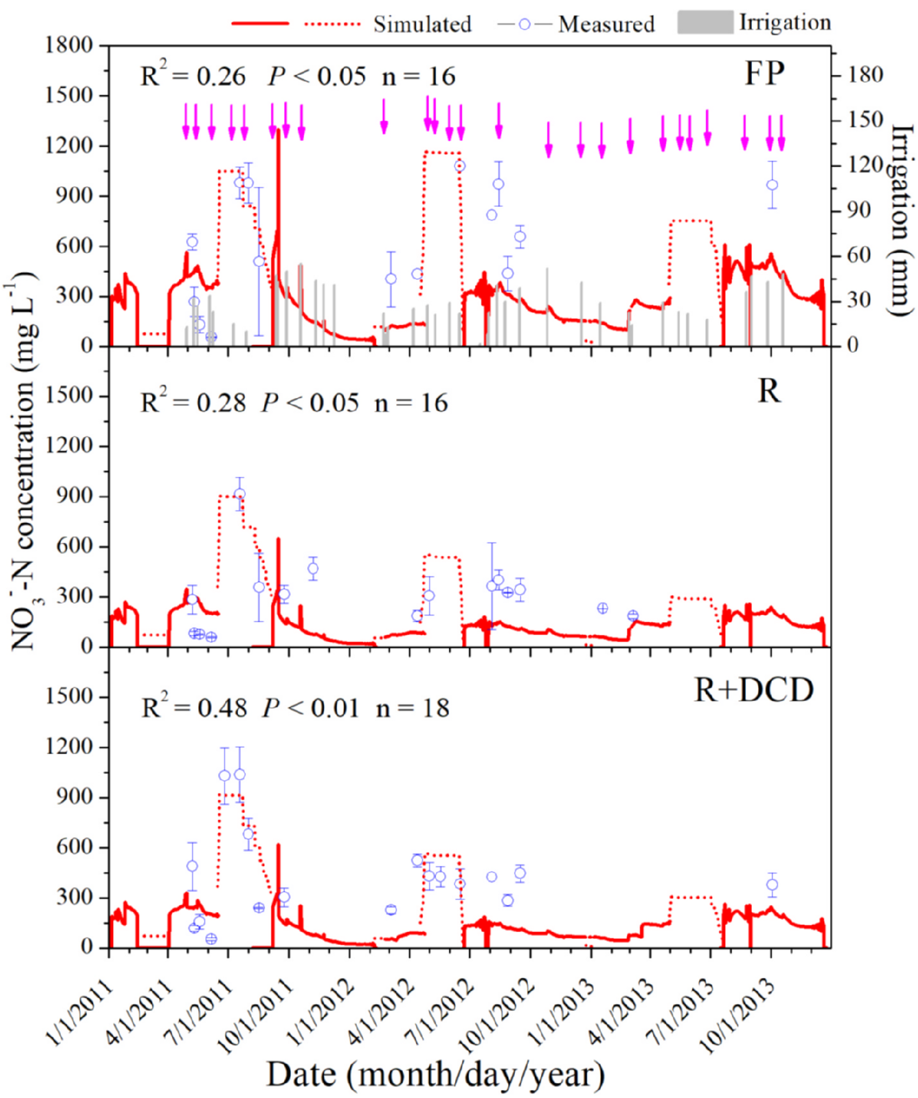

Fig. 6. Simulated NO_3^--N concentrations (mg L^{-1}) in subsurface drainage water flows (solid line) or in deep soil layers when there was no simulated drainage event(dotted line), and measured NO_3^--N concentrations (mg L^{-1}) in leachate collected by suction cups under the FP, R, and R + DCD treatments. The simulated NO_3^--N concentrations in the subsurface water flows or the deep soil layers were calculated through dividing the simulated NO_3^--N leaching fluxes by the leaching water fluxes or dividing the simulated soil NO_3^--N contents by the water contents between the 40 and 50 cm layers, respectively. The arrows indicate dates of fertilization events. The measurements were the means of three replicates, and vertical bars indicate standard deviations of the replicates.

porosity, field capacity, and wilting point) although they may be variable among different soil layers. This limitation may affect the simulations of soil water in deep layers, and then affect the simulations of NO_3^--N leaching via subsurface drainage flow (Li et al., 2014). Previous studies also suggested that heterogeneities across the soil profile would be a major obstacle for applying models for simulating NO_3^--N leaching flux (Li et al., 2006; Qiu et al., 2011). Therefore, further studies need to focus on improving parameterizations of hydrological and NO_3^--N leaching related processes and improving the accuracy of setting the related parameters to simulate NO_3^--N leaching accurately.

4.2. Impacts of N management

The DNDC simulations demonstrate that the amount of N-fertilizers exerted large impacts on both the N_2O emissions and NO_3^--N leaching from the studied GV systems. Significant positive correlations were identified between the rates of N application and the simulated N_2O emissions (e.g. Fig. 8a and e, R^2 = 0.996; P < 0.001) or NO_3^--N leaching (e.g. Fig. 9a and e, R^2 = 0.995; P < 0.001). In addition, we calculated the fraction of N inputs converted to N_2O emissions or NO_3^--N leaching based on the simulations. We found that the fractions were generally larger for the larger N inputs under the scenarios with solely urea applications, as a result of excess mineral N accumulation in the study field. The fraction of the N_2O emissions increased from 1.1% to 1.4% and the fraction of the NO_3^--N leaching increased from 21% to 72% when the urea N inputs increased from 334 to 1670 kg N ha^{-1}. These results suggest that reducing the rate of synthetic N application can effectively mitigate the N_2O emissions and NO_3^--N leaching through directly reducing the concentration of soil mineral N, as identified in this study and other vegetable systems with intensive N input (e.g., Deng et al., 2013, 2018; Wang et al., 2018).

Furthermore, in comparisons with the manure amendment, the application of synthetic N fertilizers generally exerted larger impacts on increasing the yields, N_2O emissions, and NO_3^--N leaching at the studied GV systems. For example, the simulated vegetable yields were 451 and 729 kg C ha^{-1} for lettuce, 1483 and 2125 kg C ha^{-1} for tomato, and 936 and 1410 kg C ha^{-1} for cabbage, respectively, under the scenarios with the application of solely organic manure or synthetic fertilizer at a rate of 80 kg N ha^{-1}. The simulated seasonal total N_2O emissions were 0.26 and 1.46 kg N ha^{-1} for tomato and 0.62 and 1.25 kg N ha^{-1} for cabbage under the application of solely organic manure or synthetic fertilizer at a rate of 80 kg N ha^{-1}. The corresponding simulated seasonal NO_3^--N leaching were 3.9 and 7.9 kg N ha^{-1} for lettuce, 5.0 and 10.4 kg N ha^{-1} for tomato, 13.9 and 27.7 kg N ha^{-1} for cabbage. The larger impacts on increasing the yields, N_2O emissions, and NO_3^--N leaching from the synthetic N applications can also be testified by the fact that the increases of urea N application rate generally resulted in the higher increasing rates of the yields, N_2O emissions, and NO_3^--N leaching as compared to the increases of the manure amendment rate (Figs. 7–9). In addition, the

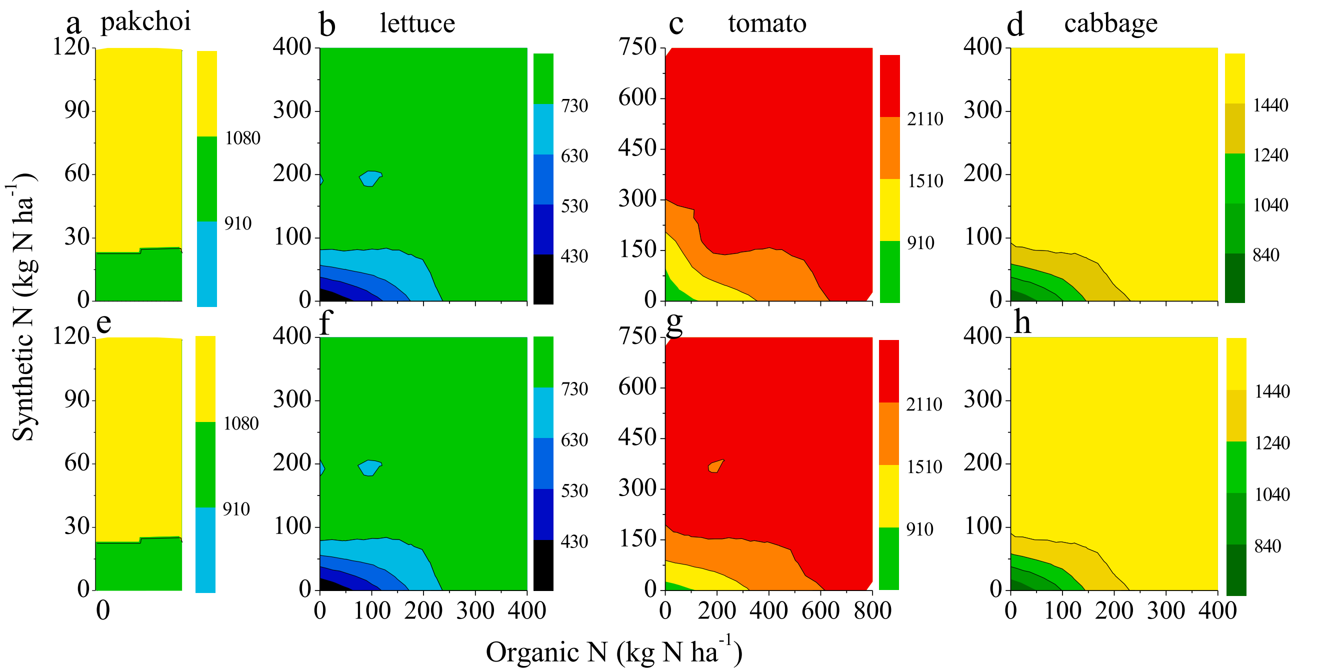

Fig. 7. Simulated vegetable yields for pakchoi, lettuce, tomato and cabbage. The data shown are the simulations under the scenarios without (a–d) and with (e–h) nitrification inhibitor application. The simulations under the baseline are shown on the top (for pakchoi) or upper-right (for the other vegetables) of each panel. Note that there was no scale of the x axis for the plots a and e.

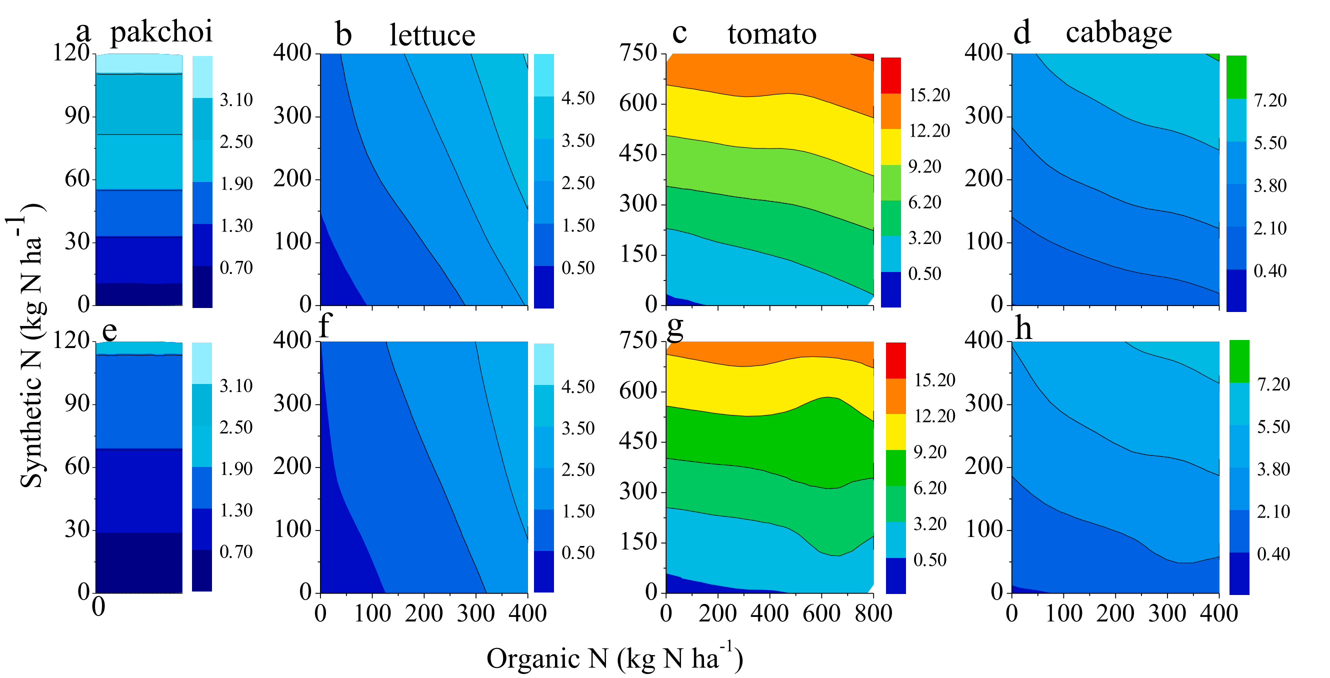

Fig. 8. Simulated seasonal total N_2O emissions (kg N ha^{-1}) for pakchoi, lettuce, tomato, and cabbage. The data shown are the simulations under the scenarios without (a–d) and with (e–h) nitrification inhibitor application. The simulations under the baseline are shown on the top (for pakchoi) or upper-right (for the other vegetables) of each panel. Note that there was no scale of the x axis for the plots a and e.

fraction of N inputs converted to N_2O emissions or NO_3^--N leaching was generally higher when the relative proportion of urea N in total N inputs was higher. For example, the simulated total N_2O emissions were 0.85% and 1.26% of the total N inputs under the scenarios with the proportion of urea N as 41% and 81%, respectively. The corresponding fractions of the total N inputs converted to NO_3^--N leaching were 37% and 61%, respectively. The larger impacts of urea as compared to organic manure were probably due to the faster release of NH_4-N following the urea application. The faster NH_4-N releases directly accelerated nitrification and increased the soil NO_3-N concentrations. Because both soil NH_4-N and NO_3-N provide the nutrients for vegetable uptake and the substrates for soil N_2O production and NO_3-N leaching, the model predicted the larger impacts on increasing the yields, N_2O emissions, and NO_3^--N leaching under the urea applications.

The DNDC simulations also indicate that the DCD application decreased the N_2O emissions and NO_3^--N leaching while maintained the vegetable yields at the GV fields (Figs. 7–9). This conclusion is consistent with those studies that reported the NI application can mitigate

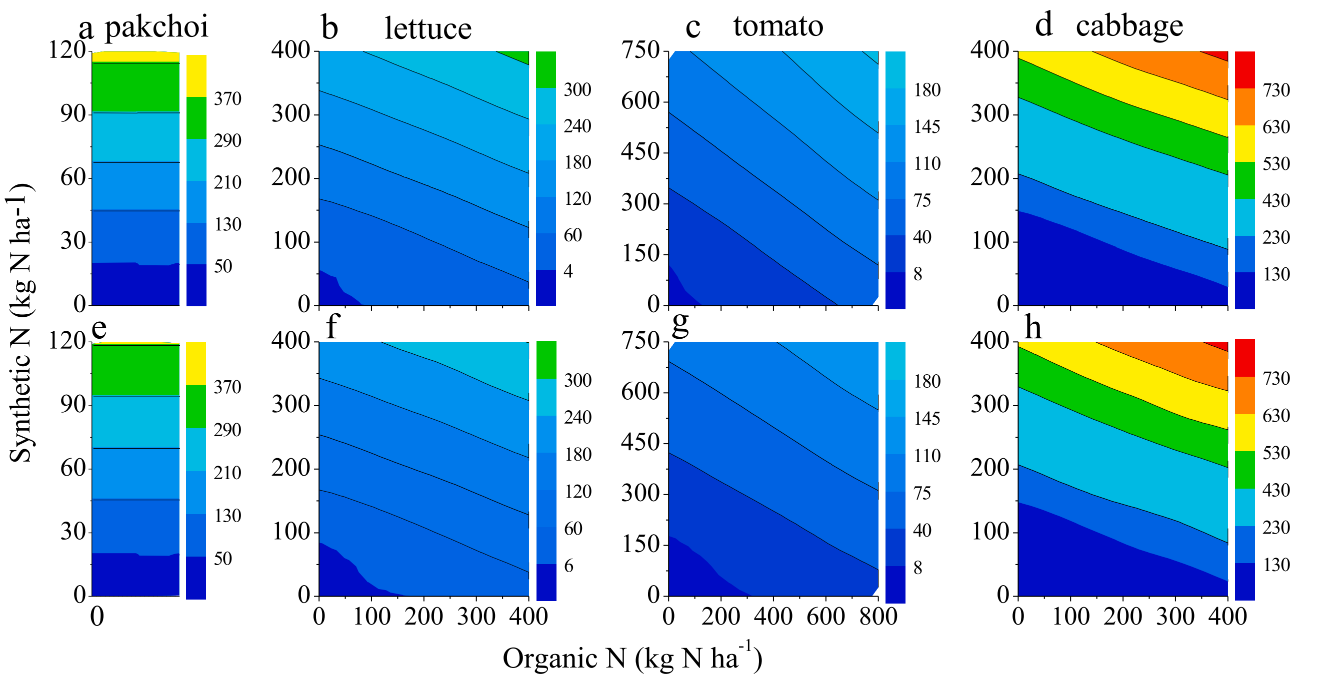

Fig. 9. Simulated nitrate leaching (kg N ha^{-1}) for pakchoi, lettuce, tomato and cabbage. The data shown are the simulations under the scenarios without (a–d) and with (e–h) nitrification inhibitor application. The simulations under the baseline are shown on the top (for pakchoi) or upper-right (for the other vegetables) of each panel. Note that there was no scale of the x axis for the plots a and e.

both N_2O emissions and soil NO_3^--N leaching (e.g., Cui et al., 2011; Qiao et al., 2015). Applying NI can reduce N_2O emissions by directly reducing nitrification rate (Bhatia et al., 2010; Kleineidam et al., 2011). It is also helpful for retaining the soil mineral N as the NH_4^+-N form, reducing soil NO_3^--N concentration and NO_3^--N leaching, and thereby reducing denitrification rate and the associated N_2O production (Bhatia et al., 2010; Qiao et al., 2015). However, we note that the DNDC model simulated the large variations in efficiencies of mitigating the N_2O emissions (0–81%) or NO_3^--N leaching (0–53%) through applying DCD across the different scenarios and vegetable growing seasons. The large variations in the mitigating efficiencies were due to differences in soil temperature and moisture, vegetable species, and N fertilizations (Akiyama et al., 2010; Kou et al., 2015) that could lead to different N_2O emissions and NO_3^--N leaching under NI or non-NI application. Soil temperature can affect the duration of DCD and the impacts of DCD application on N_2O emissions and NO_3^--N leaching (Cui et al., 2011), although the impacts were not simulated by DNDC. Anyhow, the varied impacts of using the NI suggest that these factors need to be considered to identify conditions and strategies favorable for exerting the inhibitory impacts of NI in GV croplands.

4.3. *Optimum management practices for mitigating N_2O emissions and NO_3^--N leaching*

The optimum management practice identified in this study was reducing the rate of organic manure and urea under FP by 80% while applying DCD. This practice significantly increased the vegetable NUE and mitigated both the N_2O emissions and NO_3^--N leaching under FP (Table 3). In addition, it maintained the vegetable yields and mitigated the N_2O emissions and NO_3^--N leaching over a decadal scale. The simultaneous mitigations of the N_2O emissions and NO_3^--N leaching were due to the positive correlation between the N_2O emissions and NO_3^--N leaching at the GV fields. While N_2O emissions and NO_3^--N leaching showed a negative correlation for some field cropping systems (e.g., Zhou et al., 2013), both high N_2O and NO_3^--N leaching peaks often appeared within several days following N fertilizations (Figs. 3 and 6) for the GV fields due to joint applications of N fertilizer(s) and irrigation. As a result, the peaks of the N_2O flux and NO_3^--N leaching were positively correlated under FP ($P < 0.01$, Fig. 10). These indicate it is feasible to simultaneously reduce the peaks of the N_2O flux and NO_3^--N leaching at the GV fields. The optimum practice (80% reduction of the N application rate) reduced N_2O emissions and NO_3^--N leaching by 87% and 93%, respectively, over the whole investigation period covering P4 to P7. Deng et al. (2013) demonstrated that a 25% reduction of N rate resulted in a 31% decreasing of N_2O emissions for an open vegetable field. Wang et al. (2018) reported that high NO_3^--N leaching rates could be mitigated approximate 86% by manure amendments or 57% by replacing part of synthetic fertilizers using manure in GV systems. These studies and our results suggest a high potential for reducing N_2O emissions and NO_3^--N leaching from vegetable systems through improving N management.

We note that the adequate fertilizer amounts for vegetable growth were largely variable for the different vegetable species (Table 3), and therefore determining the optimum N management practices should consider crop demand, soil N content, climate conditions, and other FMPs. The DNDC model can comprehensively consider influences of these factors on vegetable growth and N losses, indicating the potential of using DNDC to determine optimum N management for reducing N losses while maintaining optimum vegetable yields. However, we note that the optimum practice was identified by focusing on vegetable growth, N_2O emission, and NO_3^--N leaching, and further studies need to identify practices that can mitigate the NH_3 and NO losses and improve other ecosystem service, such as carbon sequestration.

5. Conclusions

The biogeochemical model, DNDC, was evaluated using multi-year field measurements of vegetable yields, N_2O emissions, and NO_3^--N concentrations in the surface soil layer and soil leachate under three treatments with different N management. The model evaluations demonstrated that the simulations of the vegetable yields and seasonal cumulative N_2O emissions were consistent with the corresponding observations after calibration. In addition, DNDC generally captured the seasonal variations of the N_2O fluxes and NO_3^-- N concentrations in the

Table 3
N fertilizations, nitrogen use efficiency (NUE), and the simulated vegetable yields, N_2O emissions, NO_3^--N leaching, yield scaled N_2O emissions, yield scaled NO_3^--N leaching, and NO_3^--N concentration in soil leachate under the optimum and baseline management practices.

	Vegetable growing season or period	Organic N fertilizer (kg N ha^{-1})	Synthetic N fertilizer[a] (kg N ha^{-1})	Yields (kg C ha^{-1})	NUE[b] (%)	N_2O emissions (kg N ha^{-1})	NO_3^--N Leaching (kg N ha^{-1})	Yield scaled N_2O emissions[c] (g N Mg^{-1})	Yield scaled NO_3^- leaching[c] (g N Mg^{-1})	NO_3^--N concentration in soil leachate (mg NO_3^--N L^{-1})
Optimum management practice	Pakchoi (P4)	–	24	1084	240.8	0.47	26.9	6	351	1.77
	Lettuce (P5)	80	80	734	41.6	0.48	14.5	23	714	0.75
	Tomato (P6)	160	150	2125	67.1	1.74	11.4	20	130	1.60
	Cabbage (P7)	80	80	1455	48.6	1.40	58.4	29	1201	3.07
	P4 to P7	320	334	5398	62.7	4.09	111.3	17	475	1.84
Baseline management practice	Pakchoi (P4)	0	120	1084	48.2	3.17	435.1	41	5670	28.65
	Lettuce (P5)	400	400	734	8.3	4.59	314.6	226	15,496	16.35
	Tomato (P6)	800	750	2122	13.4	15.59	186.3	177	2113	26.02
	Cabbage (P7)	400	400	1451	9.7	7.34	755.4	152	15,617	39.76
	P4 to P7	1600	1670	5391	12.5	30.68	1691.5	131	7241	27.91

[a] DCD was applied in each vegetable season for the optimum management practices, but not applied for the baseline management practices.
[b] NUE was calculated as dividing vegetable N uptake (kg N ha^{-1}) by total amount of N applications (kg N ha^{-1}). The NUE could be higher than 100% due to vegetable uptake of soil residue N from previous growing seasons.
[c] Yield scaled N_2O emissions or NO_3^- leaching were calculated by dividing cumulative N_2O emissions or NO_3^- leaching by fresh vegetable yield (g N Mg^{-1}).

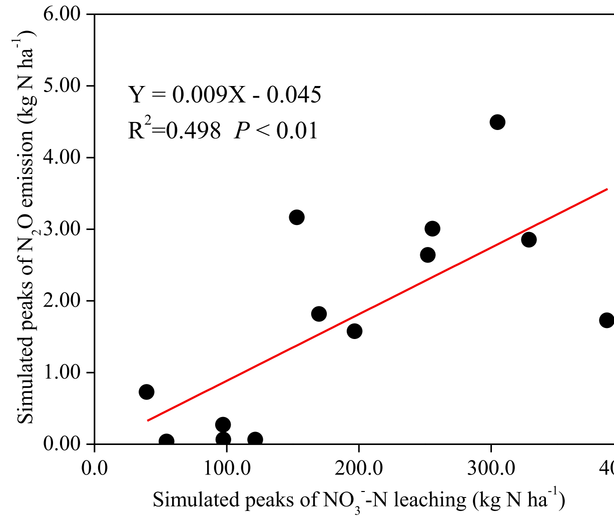

Fig. 10. The relationship between the simulated peaks of N_2O flux and NO_3^--N leaching under the FP treatment. The peaks of N_2O flux and NO_3^--N leaching were calculated by summing the daily N_2O and NO_3^--N leaching fluxes that were higher than the levels before the events of fertilization and/or irrigation.

surface soil layer and the seasonal patterns and magnitudes of the measured NO_3^--N concentrations in soil leachate in 2011. However, the model underestimated the measured NO_3^--N concentrations in soil leachate in late summer and fall of 2012 and 2013. We then assessed impacts on the vegetable yields, N_2O emission, and NO_3^--N leaching of different N management practices. The results suggested that 1) the increasing of organic or synthetic N application rate generally increased the N_2O emissions and NO_3^--N leaching, but did not persistently increase the vegetable yields, 2) urea N application could induce more N_2O emissions and NO_3^--N leaching in comparison with organic N amendment, and 3) the NI application could decrease the N_2O emissions and NO_3^--N leaching while maintaining the vegetable yields at the GV fields. We identified the optimum management practice as reducing the rates of organic manure and urea under the farm's conventional practices by 80% combined with the NI application. The optimum management practice mitigated the N_2O emissions and NO_3^--N leaching by 85% and 94%, 90% and 95%, 89% and 94%, and 81% and 92%, respectively, during the pakchoi, lettuce, tomato, and cabbage growing season.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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