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# Multiple-year nitrous oxide emissions from a greenhouse vegetable field in China: Effects of nitrogen management

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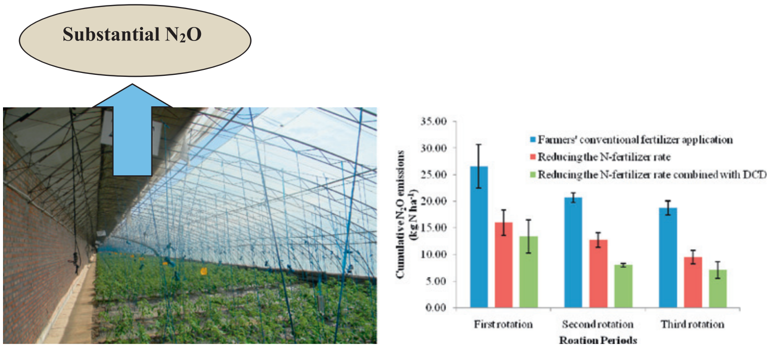
## HIGHLIGHTS

- Multi-year $N_2O$ emissions from greenhouse vegetable (GV) fields were quantified.
- $N_2O$ mitigation efficiencies of alternative N managements were evaluated.
- GV fields with intensive N and water managements may be hot spots of $N_2O$ emission.
- Reducing the N input and/or applying DCD may mitigate $N_2O$ emissions from GV fields.

## GRAPHICAL ABSTRACT



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## ABSTRACT

The greenhouse vegetable (GV) field is an important agricultural system in China. It may also be a hot spot of nitrous oxide ($N_2O$) emissions. However, knowledge on $N_2O$ emission from GV fields and its mitigation are limited due to considerable variations of $N_2O$ emissions. In this study, we performed a multi-year experiment at a GV field in Beijing, China, using the static opaque chamber method, to quantify $N_2O$ emissions from GV fields and evaluated $N_2O$ mitigation efficiency of alternative nitrogen (N) managements. The experiment period spanned three rotation periods and included seven vegetable growing seasons. We measured $N_2O$ emissions under four treatments, including no N fertilizer use (CK), farmers' conventional fertilizer application (FP), reduced N fertilizer rate (R), and R combined with the nitrification inhibitor “dicyandiamide (DCD)” (R + DCD). The seasonal cumulative $N_2O$ emissions ranged between 2.09 and 19.66, 1.13 and 11.33, 0.94 and 9.46, and 0.15 and 3.27 kg N ha$^{-1}$ for FP, R, R + DCD, and CK, respectively. The cumulative $N_2O$ emissions of three rotational periods varied from 18.71 to 26.58 (FP), 9.58 to 15.96 (R), 7.11 to 13.42 (R + DCD), and 1.66 to 3.73 kg N ha$^{-1}$ (CK). The R and R + DCD treatments significantly ($P < 0.05$) reduced the $N_2O$ emissions under FP by 38.1% to 48.8% and 49.5% to 62.0%, across the three rotational periods, although their mitigation efficiencies were highly variable among different vegetable seasons. This study suggests that GV fields associated with intensive N application and frequent flooding irrigation may substantially contribute to the $N_2O$ emissions and great $N_2O$ mitigations can be achieved through reasonably reducing the N-fertilizer rate and/or applying a nitrification inhibitor. The large variations in the $N_2O$ emission and mitigation across different vegetable growing seasons and rotational periods

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stress the necessity of multi-year observations for reliably quantifying and mitigating $N_2O$ emissions for GV systems.

## 1. Introduction

Nitrous oxide ($N_2O$) plays an important role in global warming. It is a long-lived gas with strong global warming potential (298 kg $CO_2$-equivalents $kg^{-1}$ $N_2O$ at a 100-year timescale) (IPCC, 2013). $N_2O$ also contributes to deterioration of the atmospheric environment by depleting stratospheric ozone (Ravishankara et al., 2009). The atmospheric concentration of $N_2O$ has increased from 270 ppbv ($10^{-9}$) to 319 ppbv from the preindustrial age to 2005 (IPCC, 2007). This was mainly attributed to an increase of nitrogen (N) fertilizers applied into agricultural soils as a result of the expansion and intensification of agriculture (Kroeze et al., 1999; Mosier et al., 1998). Globally, agricultural soils are considered as an important source of $N_2O$ entering the atmosphere, releasing approximately 3.9 Tg ($10^{12}$ g) N $yr^{-1}$ (FAO, 2014). Therefore, there is an urgent need to quantify and mitigate $N_2O$ emissions from croplands.

Vegetable production is an important agricultural sector in China. The areas of vegetable growing in China were $2.1 \times 10^7$ ha in 2015 (NBSC, 2015), which was around 9.5 and 210.0 times, respectively, of that in Europe ($2.2 \times 10^6$ ha; Eurostat Database, 2015) and Canada ($1.0 \times 10^5$ ha; AAFC, 2014). During the past 30 years, greenhouse vegetable (GV) production developed rapidly in China (Lou et al., 2012) due to that economic benefits are usually higher for greenhouse cultivations in comparison with vegetable productions in open-air fields (Guo et al., 2012). GV cultivations are different from open-air vegetable systems in farming managements and physical environments (Hosono et al., 2006; Lou et al., 2012). Farming management practices (FMPs) in GV production are often more intensive than that in open-air vegetable systems, with higher fertilizer input and more frequent tillage and irrigation (Rashti et al., 2015a; Ju et al., 2006; Min et al., 2012). For instance, N application rates in GV fields usually can reach 1000 to 2800 kg N $ha^{-1}$ $yr^{-1}$ (e.g., Ju et al., 2004, 2006; Xiong et al., 2006), while are often lower than 1300 kg N $ha^{-1}$ $yr^{-1}$ in open-air vegetable systems (e.g., Mei et al., 2011; Deng et al., 2012). Temperature and soil water content are usually higher in GV fields compared with open-air fields (Liu et al., 2013). High rates of N application are far more than vegetable's requirements, and N use efficiency (NUE) of GV production is often $<$10% (Zhu et al., 2005). The excess N, in combination of appropriate temperature and soil water, might led to substantial $N_2O$ losses from GV fields (e.g., Guo et al., 2012; He et al., 2007; Liu et al., 2013; Lou et al., 2012).

To meet the requirements of quantifying and mitigating $N_2O$ emissions from GV fields in China, a number of field studies have been performed (e.g., Guo et al., 2012; He et al., 2007, 2009; Lou et al., 2012). However, most of these studies quantified $N_2O$ emissions based on short-term observations, which cannot fully capture seasonal and inter-annual characteristics of $N_2O$ emissions exhibiting large temporal variability (Bouwman et al., 2002; Stehfest and Bouwman, 2006). For example, $N_2O$ emissions were quantified using observations of two to four months in the studies by Guo et al. (2012) and Lou et al. (2012). Few studies measured $N_2O$ emissions over several growing seasons, but these observations often focused on an individual vegetable species (e.g., He et al., 2007, 2009). Because $N_2O$ emissions may be variable across different vegetable species due to different environmental conditions and management practices applied, the studies with a focus of an individual vegetable species cannot provide knowledge on $N_2O$ emissions from multiple vegetable cropping rotations. In addition, side-by-side comparisons quantifying efficiency of alternative managements for mitigating $N_2O$ emissions are still lacking because limited treatments were often included in previous studies. These studies only reported $N_2O$ emissions from GV fields under local conventional managements (e.g., Liu et al., 2013; Yan et al., 2014) or $N_2O$ mitigation efficiencies of reducing rate of synthetic N applications (e.g., Min et al., 2012; Lou et al., 2012). To our knowledge, there is no study reported multiple year $N_2O$ emissions under alternative N managements with an application of nitrification inhibitor (NI) for GV systems although applying NI is regarded as a potential strategy for mitigating $N_2O$ emissions from other agricultural ecosystems (e.g., Di and Cameron, 2012; Ding et al., 2011; Weiske et al., 2001). Due to scarcity of long-term measurements under different FMPs, large uncertainty exists in the quantification and mitigation of $N_2O$ emissions from GV fields.

During April 2011 to November 2013, we conducted a multi-year experiment to quantify $N_2O$ emissions under different managements of N fertilization from a GV field in suburban Beijing. Our objectives were to a) quantify $N_2O$ emissions from GV systems under conventional intensive FMPs, b) investigate the $N_2O$ emission characteristics and identify key factors regulating the $N_2O$ emissions from GV fields, and c) evaluate mitigation efficiency of alternative N managements. We hypothesized that the GV field is a hot spot of $N_2O$ emission due to intensive N application and frequent flooding irrigation, and reducing the N-fertilizer application rate and/or applying DCD can mitigate the $N_2O$ emissions from GV systems considering the low NUE in GV productions.

## 2. Materials and methods

### 2.1. Study site and treatments

The experiment was set up in sub-urban of Southwest Beijing, China (latitude 39°36′N, longitude 115°56′E). The field site experiences a typical monsoon sub-humid climate, with an average annual mean temperature of 11.9 °C and total precipitation of 635 mm. The field has a silt-loam soil, with a bulk density of 1.2 g $cm^{-3}$, sand fraction of 13.7%, silt fraction of 63.3%, clay fraction of 22.9%, total N content of 1.9 g $kg^{-1}$, organic matter content of 34.0 g $kg^{-1}$, and pH of 8.0 in the top (0–20 cm) soil layer (Table 1). The selected poly-tunnel greenhouse (150 m × 7 m) was a typical greenhouse without any lighting and heating facilities in local areas. It was made of clay wall and covered with transparent plastic films. The plastic sheet was used all year long. Ventilations were opened on top and bottom of the greenhouse to control the temperature and moisture inside the greenhouse. Ventilations also can be closed to prevent the precipitation and snow coming into the greenhouse. Felts were covered on the plastic films. They were opened around 9:00 AM and closed around 17:00 PM during spring and winter, and were continuously opened during summer and early autumn by following local conventional FMPs. During the tomato growing periods, the soil was covered by black plastic mulch. There was no mulch covering during other growing seasons.

The study was conducted from April 28, 2011 to November 19, 2013, and included 7 vegetable growing periods (Table 2). The vegetables cultivated included tomato (*Solanum lycopersicum*), cabbage (*Brassica oleracea* L. var. *capitata* L.), pakchoi (*Brassica rapa chinensis*), and lettuce (*Lactuca sativa* var. *augustana*). Seeds of tomato, lettuce, and cabbage were planted in small plots, then they were transplanted into the fields, and pakchois seeds were directly sown into the fields. We divided the entire study period into three rotational periods based on the local conventional managements in which a rotation span is comprised of a tomato growing season in spring and summer and one or two leaf vegetables growing seasons in rest of the year. Specifically, we defined the first, second, and third rotation period as the span from April 28, 2011 to February 21, 2012 (tomato-cabbage), February 22, 2012 to

**Table 1**
Soil properties of the study fields.

| Depth cm | Bulk density g cm$^{-3}$ | Particle size distribution % | | | Total nitrogen g kg$^{-1}$ | Total potassium g kg$^{-1}$ | Total phosphorus g kg$^{-1}$ | Mineral nitrogen mg kg$^{-1}$ | Available phosphorus mg kg$^{-1}$ | Available potassium mg kg$^{-1}$ | Soil organic matter g kg$^{-1}$ | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sand | Silt | Clay | | | | | | | | |
| 0–20 | 1.4 | 13.7 | 63.3 | 22.9 | 1.9 | 1.1 | 2.3 | 168.1 | 193.0 | 703.0 | 34.0 | 8.0 |
| 20–40 | 1.6 | 7.4 | 76.2 | 16.4 | 1.0 | 0.6 | 2.2 | 77.8 | 26.6 | 92.0 | 17.4 | 8.1 |
| 40–60 | 1.4 | 13.4 | 60.8 | 16.8 | 0.8 | 0.5 | 2.2 | 56.0 | 9.0 | 49.7 | 14.0 | 8.1 |
| 60–80 | 1.5 | 9.8 | 75.5 | 14.8 | 0.7 | 0.5 | 2.1 | 50.1 | 8.5 | 46.0 | 11.9 | 8.2 |
| 80–100 | 1.5 | 16.5 | 67.1 | 16.4 | 0.6 | 0.5 | 2.0 | 52.0 | 6.4 | 53.3 | 11.2 | 8.2 |

February 27, 2013 (tomato-pakchoi-cabbage), and February 28, 2013 to November 19, 2013 (tomato-cabbage), respectively. We set four treatments, including no N fertilizer use (CK), farmers' conventional N fertilizer application (FP), reduced N fertilizer rate (R), and reduced N fertilizer rate combined with nitrification inhibitor “dicyandiamide (DCD)” (R + DCD). Three replicates were set for each treatment and totally 12 plots (plot size: 9 m × 6.8 m) were fully randomized in the field. There was no N application in the CK plots. The rate of N application under the FP treatment was around 2400 kg N yr$^{-1}$ by following the local conventional FMPs. The rate of N application was around 1700 kg N yr$^{-1}$ for the R treatment, which was set based on the recommendation for agricultural areas in Beijing (Zhao and He, 2009). We kept the N fertilization rate the same as the R treatment for R + DCD, but applied DCD additionally in this treatment (Table 2). The DCD rate was 1% of total Urea N for the first rotation period, and 5% for the second and third rotation periods. During the study period, we applied urea (46.4% N) for both basal fertilizer application and topdressing, and applied cow manure for each basal fertilizer applications (Table 2). The water and total N contents in the manure were measured before each amendment to ensure that the manure-N applied was accurate. Details of N fertilization in each vegetable growing season are listed in Table 2. Superphosphate (in 12% $P_2O_5$) was added in each basal fertilizer application while potassium sulfate (in 51% $K_2O$) was added in both basal fertilizer application and topdressing for all the plots. All other FMPs, such as tillage, irrigation, sowing, transplanting, and harvest were kept the same for all the treatments. The soil was usually tilled into 10 cm depth after the applications of basal fertilizers, then the vegetables were sowed or transplanted in accompany with flood irrigations. All the plots were irrigated by the underground water nearby.

### 2.2. Nitrous oxide measurements

We used the static chamber-gas chromatograph (GC) method to measure the $N_2O$ fluxes (Wang and Wang, 2003; Zheng et al., 2008). Stainless steel base collars (0.7 m × 0.8 m) with narrow flat surface on top were inserted into 10 cm depth below the soil surface following the tillage, and were kept there until the next tillage. Portable stainless steel chambers (0.6 m high) with sealing strips on the bottom were used to cover the collars during each sampling. The heat-insulating foams were used to cover the surface of the chambers to prevent the changing of the inside temperature. When the height of tomatoes was higher than the chamber's height, we added an additional chamber without a top lid to ensure that the tomatoes were covered.

As soon as the chamber was closed, we used 100-mL plastic syringes to collect the gas samples at 0, 6, 12, 18 and 24 min. The gas samples were stored in air bags and all the samples were measured within 24 h. By following Zheng et al. (2008), a GC (Agilent 7890A, Agilent Technologies Inc., USA) equipped with an electron capture detector (ECD) was used to measure the $N_2O$ concentration. $N_2O$ flux was calculated by using a linear method based on the $N_2O$ concentrations at different sampling time. Only when the correlation of the measured $N_2O$ concentrations with sampling time was statistically significant at $P < 0.05$, the initial change rate was accepted as a valid flux (Zheng et al., 2008).

We measured the $N_2O$ fluxes once a week, and the sampling time was fixed between 8:00 AM to 10:00 AM in each day by assuming that the data of that period can represent the mean $N_2O$ flux of whole day. Following each event of FMPs, such as irrigation, fertilization, and tillage, the $N_2O$ fluxes were measured daily until the fluxes returned

**Table 2**
Vegetable species and fertilization events.

| Rotation period | Vegetable Species (period) | Periods Month/day/year | Application amount of N fertilizers, kg N ha$^{-1}$ | | | | |
|---|---|---|---|---|---|---|---|
| | | | Treatments | Total | Basal fertilizer application | | Topdressing |
| | | | | | Urea | Organic manures | |
| First rotation | Tomato (P1) | 4/28/2011–8/13/2011 | FP | 1550 | 150 | 800 | 150:150:150:150 |
| | | | R | 1100 | 50 | 800 | 50:50:50:50:50 |
| First rotation | Cabbage (P2) | 9/12/2011–1/12/2012 | FP | 800 | 80 | 400 | 160:160 |
| | | | R | 665 | 45 | 400 | 90:90 |
| Second rotation | Tomato (P3) | 2/22/2012–7/27/2012 | FP | 1550 | 150 | 800 | 150:150:150:150 |
| | | | R | 1100 | 50 | 800 | 50:50:50:50:50 |
| Second rotation | Pakchoi (P4) | 7/28/2012–10/26/2012 | FP | 120 | 0 | 0 | 120 |
| | | | R | 48 | 0 | 0 | 48 |
| Second rotation | Lettuce (P5) | 10/27/2012–2/23/2013 | FP | 800 | 80 | 400 | 160:160 |
| | | | R | 560 | 32 | 400 | 64:64 |
| Third rotation | Tomato (P6) | 2/28/2013–8/13/2013 | FP | 1550 | 150 | 800 | 150:150:150:150 |
| | | | R | 1100 | 50 | 800 | 50:50:50:50:50 |
| Third rotation | Cabbage (P7) | 8/24/2013–11/19/2013 | FP | 800 | 80 | 400 | 160:160 |
| | | | R | 560 | 32 | 400 | 64:64 |

1) There was no N fertilizer input in the CK treatment. 2) The N fertilization rates of R + DCD treatment were the same as R. The rates of DCD applied were 1% of total Urea N in the first rotation, and 5% in the second and third rotations. During the tomato growing seasons, 50% of DCD was applied in basal fertilization and 50% in the second topdressing; during the pakchoi growing season, all DCD was input followed by topdressing; during the lettuce and cabbage growing seasons, all DCD was input followed by basal fertilization. 3) During the tomato growing seasons, urea was dissolved in water then applied via flood irrigation as topdressing; during the cabbage, pakchoi and lettuce growing seasons, urea was hole-applied as topdressing followed by flood irrigation. 4) There were two short fallow periods (Aug 14, 2011 to Sep 11, 2011 and Jan 13, 2012 to Feb 21, 2012) without sampling after the final harvest of tomato in P1 and the harvest of cabbage in P2.

to the level before these events. $N_2O$ fluxes for the days without measurements were estimated as the arithmetic mean fluxes of the two closest days when observations were carried out. The daily estimates were then summed to obtain total $N_2O$ emissions for each vegetable growing season or rotation period.

### *2.3. Measurements of environmental factors and vegetable yields*

Soil temperature (0–5 cm depth; recorded using JM624, Jingming Instrument CO., LTD, Tianjin, China), soil moisture (0–16 cm depth; recorded using Trime-IPH, Imko, Germany), and air temperature inside the greenhouse were simultaneously measured when conducting the $N_2O$ measurements. Daily ambient air temperature was recorded at a local climate station. Soil moisture was expressed as soil water filled pore space (WFPS, %) by using the Eq. (1):

$$\mathrm{WFPS} = \frac{\theta_v}{1-\left({}^{\rho_b}/_{2.65}\right)} \times 100\% \tag{1}$$

where $\theta_v$ is the measured soil volumetric water content ($cm^3\ cm^{-3}$) and $\rho_b$ is soil bulk density ($g\ cm^{-3}$).

We also measured soil ammonium ($NH_4^+$) and nitrate ($NO_3^-$) concentrations by using a continuous flow analyzer (continuous flow analyzer, Skalar Analytical B.V., Netherlands). The soils (0–20 cm) for measuring $NH_4^+$ and $NO_3^-$ concentrations were taken once a week in each plot, and the sampling frequency was increased into three times a week (1, 3, 5 day(s) after these events) following the events of fertilizer and/or irrigation.

Fresh vegetable yields were measured for each growing season. For tomato, we weighted the fruits at each harvest (totally 12 times in P1 and P6, 22 times in P3), then calculated the total yields by summing the fruits of each harvest. For pakchoi, lettuce, and cabbage, we weighted the aboveground biomass at the harvest.

### *2.4. Data analysis and statistics*

We calculated direct Emission Factor ($EF_d$) for each vegetable season and rotation period. The $EF_d$ is defined as the loss rate of N fertilizers via $N_2O$ emission (Bouwman, 1996; Bouwman et al., 2002; IPCC, 2006), and was calculated as:

$$EF_d = \frac{100(E_F - E_C)}{N} \tag{2}$$

where $E_F$ are the cumulative $N_2O$ emissions ($kg\ N\ ha^{-1}$) for FP, R, or R + DCD, $E_c$ is the cumulative $N_2O$ emissions ($kg\ N\ ha^{-1}$) for the CK, and $N$ is the amount of N applied.

One-way ANOVA (SPSS 18.0, Beijing, China) was used to analysis the differences in vegetable yields and $N_2O$ emissions among different treatments. Liner analysis (Origin 8.0, OriginLab, Guangzhou, China) was used to identify the significance of the correlations between $N_2O$ fluxes and the environmental factors.

## **3. Results**

### *3.1. Daily $N_2O$ fluxes*

The $N_2O$ fluxes under each treatment are illustrated in Fig. 1. The temporal patterns of the $N_2O$ fluxes were similar among the FP, R, and R + DCD treatments, with frequent $N_2O$ peaks primarily induced by fertilization and/or irrigation events. For instance, the highest $N_2O$ fluxes were observed on June 15, 2012 in all these treatments, following an event of topdressing coupled with irrigation at the tomato growing period (Fig. 1). Application of N fertilizers clearly showed a positive impact on the $N_2O$ fluxes in this study. $N_2O$ fluxes remained at relatively low levels under CK, although several small peaks were observed following irrigation events (e.g., May 18, 2011, July 30, 2012, September 1, 2013; Fig. 1).

We observed different magnitudes for the $N_2O$ fluxes under FP, R, and R + DCD, although the seasonal patterns were similar among them (Fig. 1). Compared to the FP, the treatment of R or R + DCD usually reduced the $N_2O$ peaks induced by fertilization and/or irrigation events. For example, the highest $N_2O$ flux (occurred on June 15, 2012) under the FP treatment was reduced by 43.0% (195.12 vs. 342.13 mg $N_2O\ m^{-2}\ day^{-1}$) and 55.7% (151.47 vs. 342.13 mg $N_2O\ m^{-2}\ day^{-1}$), respectively, by R and R + DCD.

During the study period from April 2011 to Nov 2013, the daily $N_2O$ fluxes ranged from −2.97 to 342.13, −4.07 to 195.12, −3.84 to 151.47, and −8.55 to 50.30 mg $N_2O\ m^{-2}\ day^{-1}$, respectively, for the FP, R, R + DCD and CK treatments. The average daily $N_2O$ fluxes through P1 to P7 ranged from 8.02 to 42.74, 3.73 to 22.21, 3.50 to 19.49, and 0.79 to 6.53 mg $N_2O\ m^{-2}\ day^{-1}$, respectively, for FP, R, R + DCD, and CK (Table 3). In comparisons with the FP treatment, the R significantly reduced the seasonal average $N_2O$ fluxes for P3, P4 and P6, and the R + DCD significantly reduced the seasonal average $N_2O$ fluxes for all the growing seasons ($P < 0.05$). Compared to the FP, the treatment of R or R + DCD also mitigated the mean $N_2O$ flux for each rotational period although the decreases were only significant ($P < 0.05$) for the second and third rotations (Table 3).

### *3.2. Cumulative $N_2O$ emissions for vegetable growing seasons and rotational periods*

The seasonal cumulative $N_2O$ emissions through P1 to P7 ranged from 0.15 to 3.27, 2.09 to 19.66, 1.13 to 11.33, and 0.94 to 9.46 kg N $ha^{-1}$, respectively, for the CK, FP, R, and R + DCD plots (Table 3). The total $N_2O$ emissions during the three rotational periods varied from 1.66 to 3.73, 18.71 to 26.58, 9.58 to 15.96, and 7.11 to 13.42 kg N $ha^{-1}$, respectively, for CK, FP, R, and R + DCD (Table 3). We observed both seasonal and inter-rotational variations in total cumulative $N_2O$ emissions. For example, the cumulative $N_2O$ emissions during the tomato growing seasons were higher than those during other vegetable growing periods for all the treatments with N applications. The total $N_2O$ emissions of the first rotational period were higher than those of the second and third rotational periods across all the treatments.

As Table 3 lists, the seasonal total $N_2O$ emissions under the R treatment were significantly lower than those under the FP for all the vegetable growing seasons excepting P5 and P7 ($P < 0.05$), indicating that reducing synthetic N application rate by around 60% (300 vs. 750 kg N $ha^{-1}$ for tomato, 225 or 160 vs. 400 kg N $ha^{-1}$ for cabbage, 48 vs. 120 kg N $ha^{-1}$ for pakchoi, and 160 vs. 400 kg N $ha^{-1}$ for lettuce) effectively decreased the $N_2O$ emissions. Compared with FP, the $N_2O$ mitigation efficacy of the R treatment ranged from 10.5% to 61.4% through P1 to P7. The seasonal cumulative $N_2O$ emissions from the R + DCD plots were lower than those from the FP or R plots for all the vegetable growing seasons. The difference being significant ($P < 0.05$) through P1 to P7 and in P3, respectively, for the comparisons between R + DCD and FP and between R + DCD and R. Compared with FP, the $N_2O$ mitigation efficacy of the R + DCD treatment ranged from 42.8% to 65.4% through P1 to P7. Compared to FP, R or R + DCD also significantly ($P < 0.05$) reduced $N_2O$ emissions for each rotational period. R reduced the cumulative $N_2O$ emissions from the FP plots by 40.0%, 38.1% and 48.8% for the three rotation periods. R + DCD reduced the cumulative $N_2O$ emissions by 49.5%, 61.1% and 62.0% compared with FP. Compared with R, the R + DCD treatment reduced the cumulative $N_2O$ emissions by 15.9% to 37.2% across the three rotation periods. However, the differences were only significant for the second rotation period ($P < 0.05$). These results indicate that reducing N application rates clearly mitigated the $N_2O$ emissions for the study fields. Although applying DCD reduced the $N_2O$ emissions, the $N_2O$ reductions were not consistent.

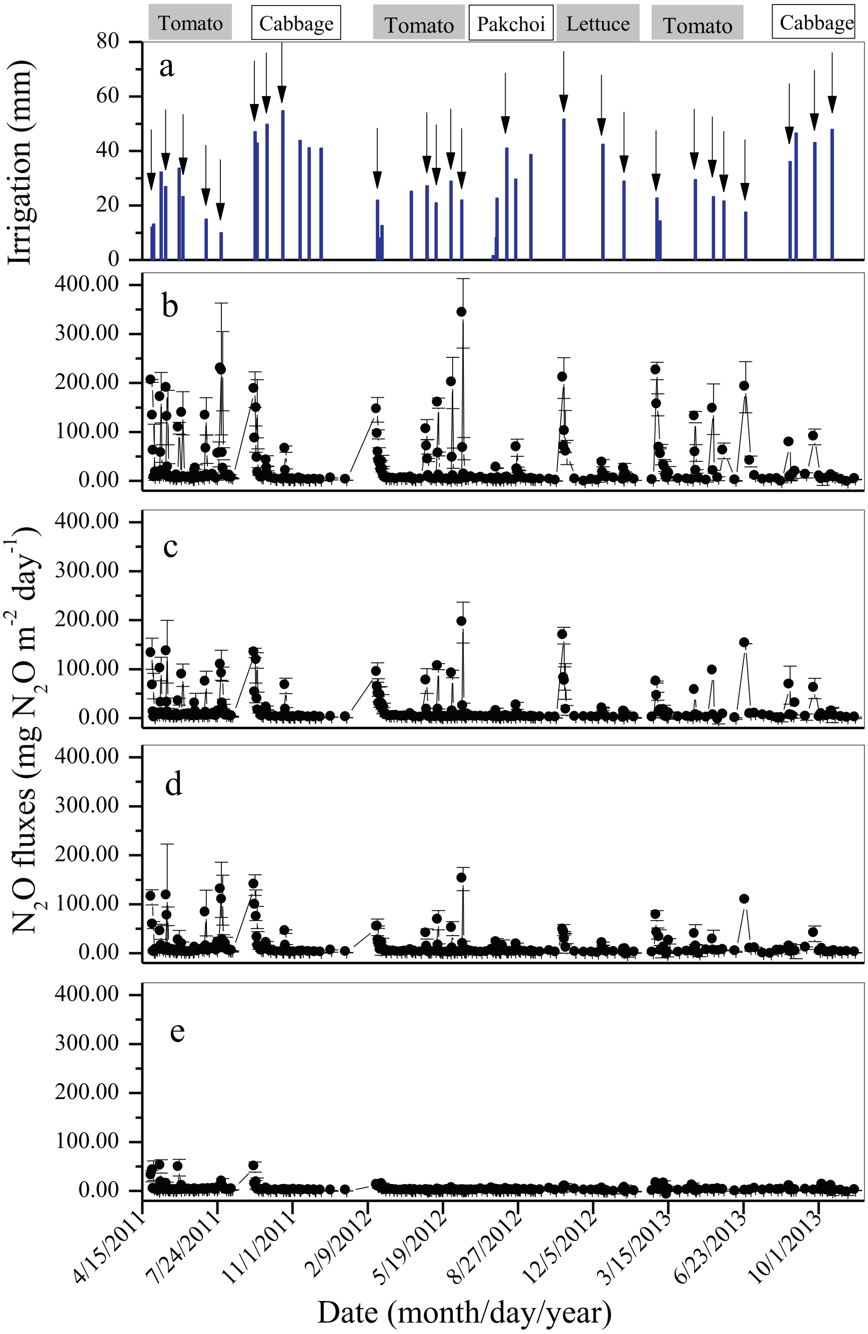

**Fig. 1.** Irrigation amounts (a), and nitrous oxide fluxes under the FP (b), R (c), R + DCD (d) and CK (e) treatments. Black arrows indicate fertilization events applied at the FP, R, and R + DCD plots. $N_2O$ flux data are means of three replicates and vertical bars indicate standard errors of replicates.

### 3.3. Emission factors

The $EF_d$s under the FP, R, and R + DCD treatments ranged from 0.46% to 1.44%, 0.41% to 1.37%, and 0.28% to 1.20%, respectively, through P1 to P7 (Table 3). The $EF_d$s varied between 0.72% and 0.97%, 0.46% and 0.71%, and 0.33% and 0.56%, respectively, for FP, R, and R + DCD across the three rotation periods (Table 3). We observed both seasonal and inter-rotational variations for the $EF_d$s. The $EF_d$s were different among different treatments and showed a trend of FP > R > R + DCD for all the vegetation growing periods, although the differences were not always significant. In addition, the $EF_d$s of the first rotation period were higher than that of the second and third rotation periods across all the treatments. These results suggest that reducing N-fertilizer application rate and/or applying nitrification inhibitor could mitigate the $N_2O$ emissions from the greenhouse vegetation systems. Again, we note that the differences in $EF_d$s between R and R + DCD were only significant in P3 and the second rotational period.

### 3.4. Fresh vegetable yields

Tomato fruit yields varied from 75.1 to 85.0, 80.5 to 95.6, 78.3 to 103.4, and 77.6 to 86.5 t $ha^{-1}$, respectively, under the CK, FP, R, and R + DCD treatments. There was no significant difference among different treatments for the tomato yields (Table 4). Cabbage yields in P2 and P7 were 36.9 and 39.7, 43.6 and 49.4, 43.2 and 42.2, and 43.0 and 42.3 t $ha^{-1}$, respectively, under CK, FP, R, and R + DCD (Table 4). The

**Table 3**
Average daily $N_2O$ fluxes, cumulative $N_2O$ emissions, and direct emission factors ($EF_d$s) for each vegetable growing season and rotation period.

| Period | Average daily $N_2O$ fluxes mg $N_2O$ $m^{-2}$ $day^{-1}$ | | | | Cumulative $N_2O$ emissions kg $N_2O$-N $ha^{-1}$ | | | | $EF_d$ % | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | CK | FP | R | R + DCD | CK | FP | R | R + DCD | FP | R | R + DCD |
| Tomato (P1) | 6.53b[1.56] | 37.61a[5.76] | 22.21ab[4.30] | 17.14b[6.32] | 3.27c[0.26] | 19.66a[2.61] | 11.33b[1.70] | 9.46b[2.88] | 1.06a[0.18] | 0.73a[0.18] | 0.56a[0.28] |
| Cabbage (P2) | 4.05b[1.43] | 21.99a[5.24] | 22.10a[3.84] | 19.49b[5.68] | 0.46c[0.11] | 6.92a[1.52] | 4.62b[0.79] | 3.96b[0.37] | 0.81a[0.18] | 0.67a[0.12] | 0.56a[0.04] |
| Tomato (P3) | 1.74c[0.07] | 30.96a[4.12] | 18.23b[2.46] | 10.59b[0.63] | 1.15d[0.18] | 12.99a[1.35] | 8.06b[1.22] | 4.85c[0.12] | 0.76a[0.10] | 0.63a[0.09] | 0.33b[0.01] |
| Pakchoi (P4) | 0.79c[0.13] | 8.02a[0.98] | 3.73b[0.21] | 3.50b[0.52] | 0.36c[0.04] | 2.09a[0.20] | 1.13b[0.17] | 0.94b[0.15] | 1.44a[0.15] | 1.37a[0.27] | 1.20a[0.26] |
| Lettuce (P5) | 1.28c[0.35] | 24.94a[1.74] | 19.95a[3.77] | 9.13b[1.95] | 0.15c[0.05] | 5.53a[1.21] | 3.55ab[0.27] | 2.33b[0.26] | 0.67a[0.15] | 0.61a[0.06] | 0.39a[0.04] |
| Tomato (P6) | 2.47c[1.02] | 42.74a[3.00] | 18.08b[0.28] | 14.37b[3.33] | 1.07c[0.36] | 14.43a[0.79] | 5.57b[0.74] | 5.00b[0.32] | 0.86a[0.07] | 0.43b[0.06] | 0.36b[0.06] |
| Cabbage (P7) | 2.43b[0.76] | 17.31a[3.12] | 15.79a[0.21] | 7.22b[1.02] | 0.59c[0.09] | 4.28a[0.54] | 3.83ab[0.84] | 2.17bc[0.45] | 0.46a[0.07] | 0.41a[0.00] | 0.28a[0.11] |
| First rotation | 5.74b[1.68] | 29.39a[4.54] | 22.35a[4.47] | 17.53ab[5.00] | 3.73c[0.20] | 26.58a[4.11] | 15.96b[2.35] | 13.42b[3.10] | 0.97a[0.18] | 0.71a[0.15] | 0.56a[0.19] |
| Second rotation | 1.41d[0.07] | 24.21a[2.86] | 15.06b[1.77] | 8.81c[0.87] | 1.69d[0.23] | 20.66a[0.91] | 12.79b[1.33] | 8.03c[0.37] | 0.77a[0.04] | 0.65a[0.07] | 0.37b[0.01] |
| Third rotation | 2.47c[0.93] | 34.72a[3.07] | 17.39b[0.14] | 12.31b[2.73] | 1.66c[0.28] | 18.71a[1.32] | 9.58b[1.27] | 7.11b[1.61] | 0.72a[0.06] | 0.46ab[0.06] | 0.33b[0.10] |

1) The data are means of three replicates with standard errors listed in '[ ]'. Different letters indicate significant differences among the four treatments during each vegetable growing season or each rotational period at $P < 0.05$ (LSD test). 2) The first, second, and third rotation period was defined as the period from April 28, 2011 to February 21, 2012 (tomato-cabbage), February 22, 2012 to February 27, 2013 (tomato-pakchoi-cabbage), and February 28, 2013 to November 19, 2013 (tomato-cabbage), respectively.

cabbage yields under the CK were significantly ($P < 0.05$) lower than those under the other treatments in P2. In P7, the cabbage yields of FP were significantly ($P < 0.05$) higher than those of the other treatments (Table 4). We also observed a lower lettuce yields under CK ($P < 0.05$) and no other significant difference was observed among different treatments. There was no significant difference among FP, R and R + DCD treatments for the pakchoi yields.

### *3.5. Environmental factors*

Air temperature inside the greenhouse ranged from 5.0 to 42.5 °C (mean: 24.2 °C), which were higher than the ambient air temperature (range from −12.10 to 30.20 °C, mean: 15.4 °C; Fig. 2). Soil temperature (0–5 cm depth) varied from 6.4 to 32.9 °C (mean: 19.87 °C) and WFPS varied from 45.7% to 87.6% (mean: 61.1%) during the whole study period (Fig. 2). The increases in the WFPS were generally observed following irrigation, and there was no regular seasonal pattern for the WFPS.

High soil $NH_4^+$-N and $NO_3^-$-N concentrations appeared following each fertilization event (Fig. 3). However, it looks like the applications of organic manure did not obviously contribute to the abrupt increases in soil mineral N following fertilization, considering that the similar increases in soil mineral N were observed between the basal fertilizations and topdressings when the urea applied were exactly the same (e.g., in tomato growing seasons). Soil $NH_4^+$ contents ranged from 0.3 to 7.8 mg $kg^{-1}$ (mean: 2.2 mg $kg^{-1}$), 0.4 to 11.5 mg $kg^{-1}$ (mean: 2.4 mg $kg^{-1}$), 0.4 to 8.4 mg $kg^{-1}$ (mean: 2.4 mg $kg^{-1}$), and 0.6 to 9.9 mg $kg^{-1}$ (mean: 2.4 mg $kg^{-1}$) for the CK, FP, R and R + DCD treatments, respectively. Soil $NO_3^-$ contents varied between 7.4 and 136.0 (mean: 34.6 mg $kg^{-1}$), 24.1 and 328.9 (mean: 131.7 mg $kg^{-1}$), 15.6 and 176.0 (mean: 79.4 mg $kg^{-1}$), and 17.9 and 173.02 mg $kg^{-1}$ (mean: 77.5 mg $kg^{-1}$) for the CK, FP, R and R + DCD treatments, respectively. The soil $NO_3^-$-N contents in the CK were significantly lower than that in the other plots ($P < 0.05$). The soil $NO_3^-$-N contents under R and R + DCD was significantly ($P < 0.05$) lower than that under FP. We did not detect significant differences for $NO_3^-$-N between R and R + DCD treatments and for soil $NH_4^+$-N contents among the CK, F, R and R + DCD.

### *3.6. Relationship between seasonal cumulative $N_2O$ emissions and nitrogen input*

As Fig. 4 shows there exist significant linear correlations between seasonal cumulative $N_2O$ emissions and total N input for R + DCD ($P < 0.05$) and the other treatments ($P < 0.01$), indicating that N input rate was a key factor regulating seasonal total $N_2O$ emissions in the GV field. The slope of the linear correlation for the R + DCD was lower than that of the other treatments. This result also suggests that applying DCD could reduce the $N_2O$ emissions from GV fields.

## 4. Discussion

### *4.1. $N_2O$ emissions and impacting factors*

We identified GV fields as hot spots of $N_2O$ emissions through this study. The $N_2O$ emission rates (18.71 to 26.58 kg $N_2O$-N $ha^{-1}$ for the three rotational periods) observed under the conventional managements (FP) was higher than the $N_2O$ emissions from field crops in nearby regions (e.g., Liu et al., 2004; Cui et al., 2012). This conclusion is comparable with the studies conducted at Southeast China (Deng et al., 2012), North China Plain (Yan et al., 2014), and Southern China (Min et al., 2012) — all these studies reported higher $N_2O$ emissions from vegetable fields in comparison with field crops in nearby regions. The high $N_2O$ emission rates were primarily resulted from frequent fertilizations with high N application and/or irrigation (Fig. 1), which can be supported by the significant positive correlation between total $N_2O$ emissions and N application rate ($P < 0.01$, Fig. 4). However, we did not find any consistent relationship between daily $N_2O$ fluxes and mineral N.

The seasonal $EF_d$s under FP, R, and R + DCD varied from 0.46% to 1.44%, 0.41% to 1.37%, and 0.28% to 1.20%, respectively, through P1 to P7 (Table 3). The ranges of the $EF_d$s in our study were comparable with the estimations (0.03% to 1.55%) through compiling $N_2O$ flux data from vegetable fields in China (Wang et al., 2011). The coefficient

**Table 4**
The fresh vegetable yields (unit: t $ha^{-1}$) under different treatments.

| Treatments | First rotation | | Second rotation | | | Third rotation | |
|---|---|---|---|---|---|---|---|
| | Tomato (P1) | Cabbage (P2) | Tomato (P3) | Pakchoi (P4) | Lettuce (P5) | Tomato (P6) | Cabbage (P7) |
| CK | 75.1a[0.2] | 36.9b[1.2] | 85.0a[8.4] | 67.5a[3.4] | 13.8b[0.6] | 84.1a[6.1] | 39.7b[1.5] |
| FP | 80.5a[1.0] | 43.6a[0.8] | 95.6a[8.2] | 72.5a[1.6] | 20.4a[0.9] | 88.3a[0.8] | 49.4a[3.1] |
| R | 78.3a[0.4] | 43.2a[1.2] | 103.4a[9.0] | 70.3a[4.4] | 19.0a[1.9] | 86.3a[4.7] | 42.2b[2.2] |
| R + DCD | 77.6a[0.9] | 43.0a[1.2] | 86.5a[4.0] | 72.5a[3.7] | 16.6a[0.9] | 85.6a[5.8] | 42.3b[3.5] |

1) The data are means of three replicates with standard errors listed in '[ ]'. Different letters indicate significant differences among the four treatments at $P < 0.05$ (LSD test). 2) The first, second, and third rotation period was defined as the period from April 28, 2011 to February 21, 2012 (tomato-cabbage), February 22, 2012 to February 27, 2013 (tomato-pakchoi-cabbage), and February 28, 2013 to November 19, 2013 (tomato-cabbage), respectively.

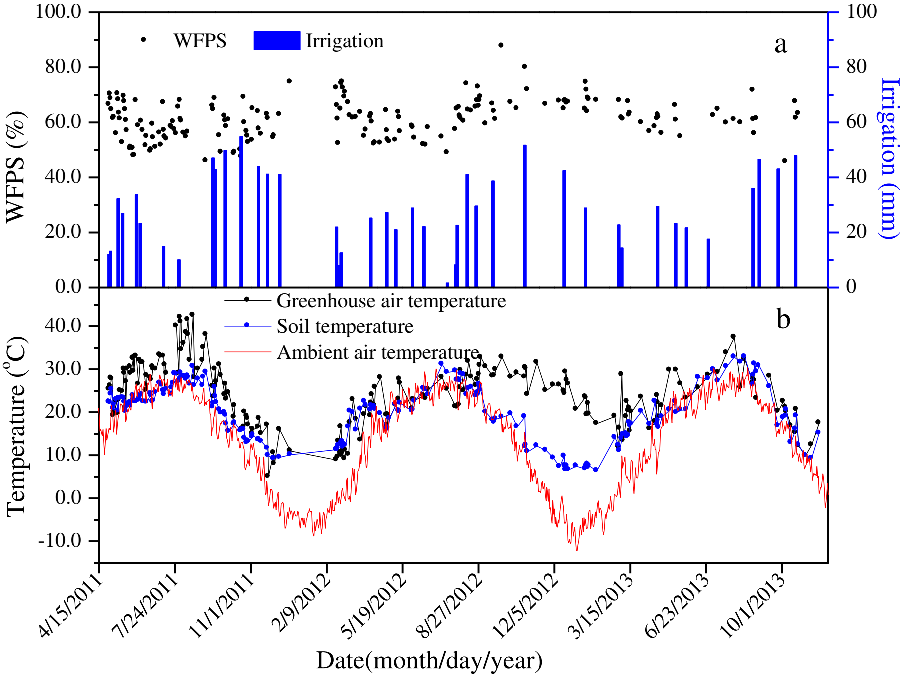

**Fig. 2.** Irrigation water amounts and soil moisture (in WFPS) (a), greenhouse air, ambient air, and soil temperature (0–5 cm) (b) during the entire investigation period.

of variations of the seasonal $EF_d$s were calculated as 33%, 43%, and 55%, respectively, for the FP, R, and R + DCD treatments, suggesting that short term measurements may not reliably quantify $EF_d$s and $N_2O$ emissions from GV fields. The seasonal $EF_d$s also varied across different vegetable species (Table 3). Therefore, measurements focusing on an individual vegetable species may not be reliably for quantifying $EF_d$s of multiple vegetable cropping rotations. It should be noted that large amounts (400 to 800 kg N) of dairy manure were applied in most of the growing seasons. Therefore the calculated seasonal $EF_d$s could not fully reflect the stimulation of manure-N on the seasonal $N_2O$ emissions,

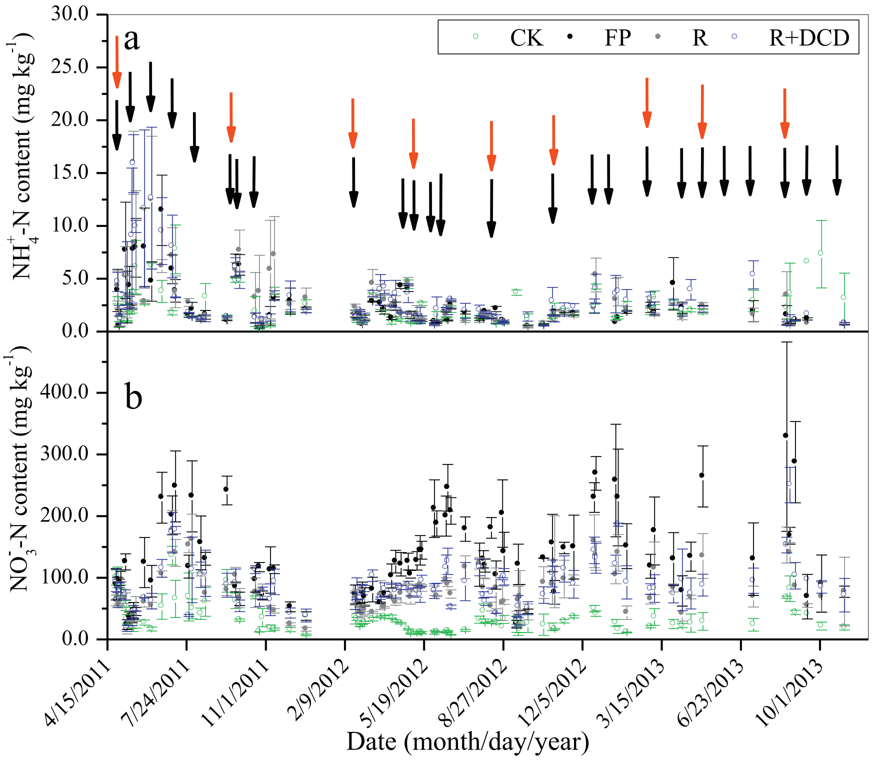

**Fig. 3.** Dynamics of $NH_4^+$ (a) and $NO_3^-$ (b) content during the entire investigation period. Data are means of three replicates and vertical bars are standard errors of the replicates. Black arrows indicate the events of N fertilization. Red arrows indicate the events of DCD application.

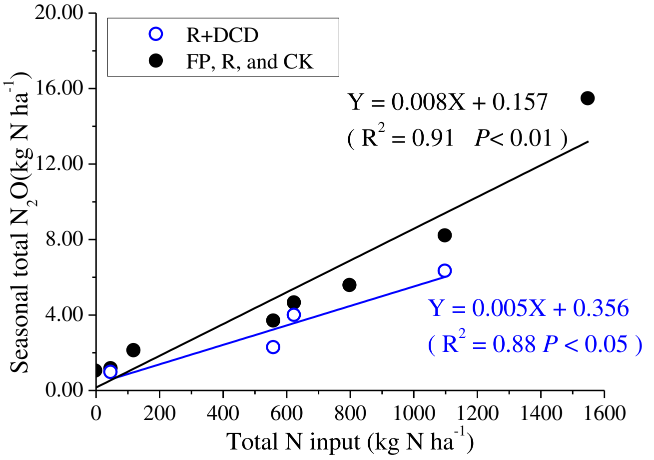

**Fig. 4.** The relationship between seasonal total $N_2O$ emissions and amounts of total N inputs (i.e., the sum of synthetic and organic N inputs).

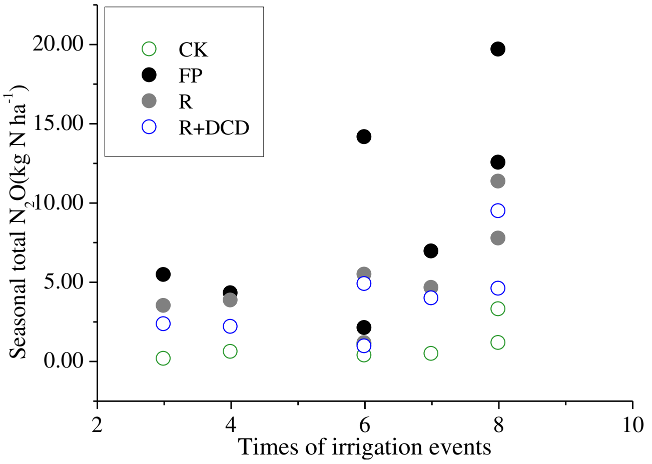

**Fig. 5.** The relationship between the seasonal total $N_2O$ emissions and times of irrigation events.

considering that some organic N in the manure could not been fully mineralized into inorganic N due to their relative slow rates of releasing and decomposition.

The organic manure used also regulated $N_2O$ fluxes in this study. Although the magnitudes of the mineral N contents and $N_2O$ peaks following the basal fertilizer applications with both synthetic fertilizers and organic manure inputs were similar with the corresponding magnitudes following the topdressing events with input of only synthetic fertilizers; the peaks of $N_2O$ fluxes usually lasted for 10 to 15 days following the basal fertilizer applications during the tomato growing periods (e.g., from April 28, 2011 to May 8, 2011; Fig. 1), while only lasted for 3 to 5 days following the topdressing events (e.g., from May 18, 2011 to May 21, 2011; Fig. 1). Therefore, the application of organic manure may also positively affect the $N_2O$ emissions from the studied vegetable fields. This result is consistent with other reports (Hosono et al., 2006; Yan et al., 2014; Min et al., 2012; Guo et al., 2012). Both nitrification and denitrification following manure application might have been accelerated and/or extended by continuous supplies of dissolved organic carbon (DOC) and $NH_4^+$ from the organic manure (e.g., Akiyama and Tsuruta, 2003a, 2003b; Snyder et al., 2009). In this study, the longer lasting of the $N_2O$ peak following manure application might be directly resulted from stimulation and/or extension of denitrification considering that the $N_2O$ peaks following manure applications may were primarily produced through denitrification because these peaks usually appeared following irrigation. However, the synthetic fertilizers may showed a stronger stimulation than the dairy manure for the $N_2O$ emissions from the studied GV fields considering that the largest $EF_d$ was observed in P4 when only synthetic fertilizer was applied for FP, R, and R + DCD.

Frequent surface flooding irrigations are probably another factor contributing to the high $N_2O$ emissions from the GV fields. Small spikes of $N_2O$ fluxes (e.g., May 18, 2011, July 30, 2012, September 1, 2013; Fig. 1) were often observed following irrigation events at the CK plots without N input. We also noticed positive trends between the seasonally cumulative $N_2O$ emissions and the times of irrigation events for all the treatments (Fig. 5), indicating that frequent application of surface irrigation was also a key factor regulating seasonally cumulative $N_2O$ emissions. Irrigation events might have stimulated $N_2O$ emissions by activating the microbial activities or facilitating anaerobic conditions for denitrification, whereby $N_2O$ is produced as an immediate product (Lou et al., 2012; He et al., 2009). In this study, the peaks of $N_2O$ fluxes following irrigations may were primarily resulted from denitrification because these peak fluxes usually coincided with relative high WFPS (>60%) that was reported as a range favorable for $N_2O$ production by denitrification (Davidson, 1991; Russow et al., 2000). However, we did not find any consistent relationship between daily $N_2O$ fluxes and WFPS, which could be partially explained by the relative high soil moistures throughout the whole investigation period due to the management practices of frequent irrigation, plastic film, and mulch cover. Because soil moisture may not be a limiting factor on $N_2O$ production during most of the periods, the relationship between the daily $N_2O$ fluxes and soil moisture could be confounded by the influences of other key factors, including the fertilization events and organic manure as discussed above. It should be noted that surface flooding irrigation was applied in this study, frequent low volume irrigation (e.g., drip irrigation) and mulch cover could mitigate $N_2O$ emissions from vegetable fields because low volume irrigation could limit water distribution in soil profiles (Evans and Sadler, 2008) and mulch could restrict $N_2O$ exchange between soil surface and atmosphere (Li et al., 2014). However, further studies are required to evaluate the impacts of low volume irrigation and mulch cover on the $N_2O$ emissions from GV croplands.

Soil temperature was also identified as a factor influenced the $N_2O$ emissions in this study. For example, $N_2O$ peaks during the cold periods (e.g., on December 18, 2012, $N_2O$ flux was 36.47 mg $N_2O$ $m^{-2}$ $day^{-1}$ after topdressing of 160 kg N $ha^{-1}$; Fig. 1) were smaller than the peaks during relative warm seasons (e.g., on April 28, 2012, $N_2O$ flux was 104.73 mg $N_2O$ $m^{-2}$ $day^{-1}$ after topdressing of 150 kg N $ha^{-1}$; Fig. 1) although similar amounts of fertilizers were applied. We also found a significant positive correlation between the cumulative peak $N_2O$ fluxes and average soil temperature in the CK plots ($P < 0.05$) when the cumulative peak $N_2O$ fluxes were relative high (e.g., >150 g N $ha^{-1}$). Again, this result is in line with other studies that reported positive impacts of soil temperature on $N_2O$ emissions (He et al., 2009; Rashti et al., 2015b; Yan et al., 2014). Both nitrification and denitrification positively respond to temperature increasing when it lower than 35 °C (Klemedtsson et al., 1987) and the increased nitrification and/or denitrification may be the main mechanisms responsible for the observed positive impacts of soil temperature on $N_2O$ emissions. Although high soil temperature could also increase $N_2O$ emission through affecting other processes, including acceleration of urea hydrolysis (Yadav et al., 1987), increasing N mineralization (He et al., 2007, 2009), and enhancing soil respiration that may increase soil anaerobic volume (Flessa et al., 2002). These mechanisms may not be primary factors functioned in our study considering that mineral N was high during the cold periods (Fig. 3) and soil moisture and anaerobic volume were not limiting factors, especially following each event of surface flooding irrigation (Fig. 2). Since the felts and plastic films obviously increased air temperature inside the greenhouse compared to the ambient air temperature (Fig. 2), the greenhouse covering is also a management that could stimulate $N_2O$ emissions from GV systems.

### 4.2. Impacts of nitrification inhibitor application

The seasonal cumulative $N_2O$ emissions from the R + DCD plots were mitigated by 10.2% to 43.3% across P1 to P7 in comparison with those from the R plots (Table 3). The fresh vegetable yields between the R and R + DCD plots were similar without statistical differences (Table 4). These results suggest that applying DCD might be a potential option for mitigating $N_2O$ emissions from GV fields, in addition to reducing nitrogen input amount. Our results are comparable with other studies conducted at vegetable fields. For example, Guo et al. (2012) found that applying the DCD decreased $NO_3^-$-N, $NH_3$ and $N_2O$ losses in a tomato growing field. Yan et al. (2014) showed that applying DCD mitigated $N_2O$ emissions by 30.1% during a cucumber growth period and 21.1% during a cabbage growth period and did not significantly affect vegetable yields.

Nitrification inhibitors can block or control conversion from $NH_4^+$ to $NO_2^-$, and subsequently to $NO_3^-$. This function helps to keep N in the $NH_4^+$ form for a longer time, decrease soil $NO_3^-$ concentration during the retention period of nitrification inhibitors, enhance N uptake by crops, and mitigate $N_2O$ emission from both nitrification and denitrification (e.g., Ding et al., 2011; Shoji et al., 2001; Wolt, 2004; Pfab et al., 2012; Kleineidam et al., 2011). At the study vegetable fields, high $N_2O$ peaks usually appeared within several days following N fertilizations (Fig. 1) due to joint applications of N fertilizer(s) and irrigation. Although both the retention time and effectiveness of DCD on mitigating $N_2O$ emissions were variable across different crop fields depending on soil texture, soil temperature, soil moisture, and farming management (Akiyama et al., 2010), we anticipated that applying DCD is an effective option for mitigating $N_2O$ emissions from GV fields considering the fact that the high $N_2O$ peaks occurred immediately following N fertilization events and relative short retention time of DCD can also function for these peaks. The observations showed that the $N_2O$ peaks following the DCD applications were usually lower than the peaks without DCD in the R plots (Fig. 1). However, the $N_2O$ reductions by using DCD were only significant in P3 and the second rotational period. The inconsistent impacts of using DCD may were resulted from different rates (5% vs. 1% of total Urea N) and time of DCD applications, as well as the large spatial variations of the $N_2O$ emissions (Table 3). Anyhow, the inconsistent impacts of using DCD suggest that further studies are required to identify conditions and strategies favorable for exerting the inhibitory impacts of DCD in GV croplands.

### 4.3. Mitigation options for $N_2O$ emissions

N fertilization was considered as the most important management affecting $N_2O$ emissions from cropping systems (Mosier, 1994). Numerous studies have demonstrated that $N_2O$ emissions can be reduced by improving application of N fertilizers and increasing N use efficiency of crops, although the mitigation efficiency is highly variable across different cropping systems or regions (e.g., Eagle and Olander, 2012; Snyder et al., 2009). We identified that reducing the N application rate based on the recommendations is an option for lowing $N_2O$ emissions from GV fields considering that 10.5% to 61.4% of the seasonal total $N_2O$ emissions under FP were decreased by reducing the N application rate and the vegetable yields were not significantly declined under R for P1 to P6. However, we observed a significant reduction in the cabbage yield, suggesting that the adequate fertilizer dose for vegetable productions may be variable across the crop species that grow in different seasons, therefore setting recommendations of N application rates should considering cultivar, crop demands, soil N contents, and climate conditions. The variations in the $N_2O$ mitigation efficiency of reducing N across different vegetable growing seasons and rotational periods and different responses of vegetable yields to N reduction also stress the necessity of multi-year observations for reliably quantifying $N_2O$ mitigation efficiency and assessing optimum N managements for GV systems.

The impacts of applying DCD on $N_2O$ emissions were discussed in the Section 4.2, and we concluded applying DCD is a potential option for mitigating $N_2O$ emissions from GV systems. The application rate of DCD seems to have also regulated the mitigation efficiency in this study. Applying DCD at a rate of 5% of the total urea showed a higher mitigation efficiency than that at a rate of 1% of the total urea N in this study (e.g., 61.1% vs. 49.5% for the second and first rotation period). However, we only observed the significant impacts of using DCD in P3 and the second rotation period, suggesting that further studies are required to identify optimum strategies of applying DCD in GV croplands.

Another mitigation option would be improving irrigation methods. Although treatments were not set to quantify the impacts of different irrigation managements on $N_2O$ emissions from GV fields in this study, we observed that the impulse $N_2O$ fluxes occurred when nitrogen fertilizations were coupled with irrigation. Other conditions did not induce high $N_2O$ fluxes. Yan et al. (2014) also suggested that the fertilization along with immediate irrigation is the most critical factor affecting $N_2O$ emissions from vegetable fields. These results suggest an important role of irrigation on controlling $N_2O$ emissions. Applying low-volume irrigation (e.g., drip irrigation) in GV fields might be a potential practice for mitigating $N_2O$ emissions due to a relatively drier soil conditions associated with low amount of water applied and limited water distribution in soil profiles in each irrigation event, which could restrict $N_2O$ production through denitrification. However, a quantitative comparison should be conducted to evaluate the impacts of different irrigation managements on $N_2O$ emissions.

## 5. Conclusion

We measured $N_2O$ emissions from a GV system under four treatments, including CK, FP, R, and R + DCD. The cumulative $N_2O$ emissions varied from 18.71 to 26.58, 9.58 to 15.96, 8.03 to 13.42, and 1.66 to 3.73 kg N $ha^{-1}$, respectively, under FP, R, R + DCD, and CK for the three investigated rotation periods. The $N_2O$ $EF_d$s of the FP, R, and R + DCD treatments ranged between 0.46% and 1.44%, 0.41% and 1.37%, and 0.28% and 1.20%, respectively, among different vegetable growing seasons, and varied from 0.72% to 0.97%, 0.46% to 0.71%, and 0.33% to 0.56%, respectively, for the three rotation periods. In comparison with FP, the R and R + DCD treatments significantly ($P < 0.05$) reduced the $N_2O$ emissions by 38.1% to 48.8% and 49.5% to 62.0%, respectively, across the three rotational periods, while vegetable yields were not significantly reduced for most of the growing seasons. The $N_2O$ mitigation efficiencies of R and R + DCD varied from 10.5% to 61.4% and 42.8% to 62.7%, among different vegetable growing seasons. This study suggests that GV fields associated with intensive N application and frequent flooding irrigation may substantially contribute to the $N_2O$ emissions from metropolis. Reducing N-fertilizer application rate reasonably and applying nitrification inhibitor can greatly mitigate $N_2O$ mitigations from GV systems. The large variations in the $N_2O$ emission and mitigation efficiency of alternative N managements across different vegetable growing seasons and rotational periods required multi-year observations for reliably quantifying $N_2O$ emissions and its mitigation efficiency for GV systems.

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