

## Effects of Nitrogen Application on Soil Nitrification and Denitrification Rates and N<sub>2</sub>O Emissions in Greenhouse

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### ABSTRACT

Nitrous oxide (N<sub>2</sub>O) has significant impact on global warming and leads to the depletion of ozone in the stratosphere. Agricultural soil is regarded as a major source of N<sub>2</sub>O emissions. In recent years, greenhouse grown vegetables have rapidly developed in China. Although excessive fertilizer application in greenhouse vegetable production can result in increased N<sub>2</sub>O emissions, research data on such emissions from greenhouse vegetables, such as cucumber, remains limited. In this study, four nitrogen (N) fertilizer treatments including 1,200 (N<sub>1200</sub>, traditional N amount), 900 (N<sub>900</sub>), and 600 kg N ha<sup>-1</sup> (N<sub>600</sub>) and the control (N<sub>0</sub>) were carried out on cucumber in a greenhouse in the North China Plain. Results showed that N<sub>2</sub>O emissions mainly occurred in the first five days after topdressing, and accounted for 75.8%-95.2% of total N<sub>2</sub>O emissions produced in the whole interval (10 days). Significant exponential correlations were observed between N<sub>2</sub>O flux and nitrification or denitrification rates ( $P < 0.01$ ). The results also indicated that nitrification dominated and played a more important role in N<sub>2</sub>O emissions than denitrification under the irrigation conditions of the study (water-filled pore space was 40.0 to 66.6%). Cumulative N<sub>2</sub>O emissions were 0.48-5.01 kg N ha<sup>-1</sup> in the cucumber growing season, accounting for 0.28-0.38% of nitrogen input. Compared to N<sub>1200</sub>, treatment N<sub>600</sub> significantly reduced the rate of N<sub>2</sub>O emissions by 53.4%, and also maintained cucumber yield. Based on this study, 50% of the traditional N fertilizer rate (N<sub>600</sub>) was considered sustainable for greenhouse cucumber production in the North China Plain.

**Keywords:** Cucumber, Environmental factor, Nitrogen fertilizer, N<sub>2</sub>O flux. Soil NO<sub>3</sub>-N.

### INTRODUCTION

Nitrous oxide (N<sub>2</sub>O) emissions significantly impact global warming and the depletion of ozone in the stratosphere (Akimoto *et al.*, 2005; Meade *et al.*, 2011). Over recent years, due to intensive human practices, the rate of global N<sub>2</sub>O emissions has increased by 17% from 1990 to 2005 (Kroeze *et al.*, 1999; IPCC, 2007). Agricultural soil is a major source of N<sub>2</sub>O emissions, releasing 6.3 Tg N<sub>2</sub>O-N yr<sup>-1</sup> into the atmosphere, accounting for 58% of total N<sub>2</sub>O emissions (Mosier *et al.*, 1998; IPCC,

2007). Nitrification and denitrification are two major processes producing N<sub>2</sub>O, representing approximately 70% of total global N<sub>2</sub>O emissions (Moiser *et al.*, 1996; Malla *et al.*, 2005). Therefore, environmental factors (e.g. soil moisture, temperature, pH, and rainfall) and human factors (e.g. irrigation and nitrogen fertilization) (Smith *et al.*, 2003; He *et al.*, 2007; Baggs *et al.*, 2010; Sanchez-Marti *et al.*, 2010) related to nitrification and denitrification can affect N<sub>2</sub>O emissions. Nitrogen fertilizer application and irrigation are regarded as two of the most important

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elements influencing N<sub>2</sub>O emissions (Zhang *et al.*, 2008). Wang *et al.* (2011) and He *et al.* (2009) reported that seasonal N<sub>2</sub>O emissions from vegetable fields increased significantly with nitrogen fertilizer application ( $P < 0.0001$ ). Increased N availability can increase microbial nitrification and denitrification rates, thereby escalating N<sub>2</sub>O emissions (Liu *et al.*, 2011). In China, the rate of fertilizer-induced N<sub>2</sub>O emissions from agricultural soils was 198.9 Gg N<sub>2</sub>O–N in 1997, with 66.9 Gg N<sub>2</sub>O–N produced by vegetable fields in 2009 (Lu *et al.*, 2006; Wang *et al.*, 2011). Additionally, the N<sub>2</sub>O flux from irrigation was 1.17 times more than that without irrigation in greenhouse conditions (Zhang *et al.*, 2002).

Vegetable production has developed rapidly in recent years, but excessive fertilization has become a common phenomenon in China. In greenhouse vegetable cropping systems, nitrogen fertilization rates in Hebei Province are about 1,269 kg N ha<sup>-1</sup>, which are 2.8 times that of the recommended rate (Zhang *et al.*, 2005). In cucumber fields, the accumulated nitrogen in Shandong Province was above 1,500 kg ha<sup>-1</sup> after a growing season, which was sufficient for the occurrence of soil nitrification and denitrification (Ma *et al.*, 2000). In addition, the temperature inside greenhouses is always higher than that outside, and soil usually lacks plowing and insolation. All of these factors exacerbate N<sub>2</sub>O emissions (Zhang *et al.*, 2002; Xiong *et al.*, 2006; He *et al.*, 2009; Alomran *et al.*, 2013). The N<sub>2</sub>O emissions from China crop fields varied from 275 to 292 Gg N<sub>2</sub>O–N yr<sup>-1</sup> during the 1990s, with vegetable crops accounting for about 20% of that amount (Zheng *et al.*, 2004; Lu *et al.*, 2006; Wang *et al.*, 2011). Further, the background N<sub>2</sub>O emissions (emissions induced by factors other than fertilization) from vegetable fields increased from 6.76 Gg N<sub>2</sub>O–N in 1990 to 19.6 Gg N<sub>2</sub>O–N in 2009 (He *et al.*, 2009; Wang *et al.*, 2011).

A number of studies have been carried out on N<sub>2</sub>O emissions in wheat fields (Meade *et al.*, 2011), maize fields (Liu *et al.*, 2011),

rice paddies (Pramanik *et al.*, 2013) and grasslands (Liu *et al.*, 2010); however, no studies have reported on N<sub>2</sub>O emissions from greenhouse cucumber crops. In this study, four N fertilization levels under the same irrigation conditions in a greenhouse in the North China Plain were established. The aims of this study were to: (i) monitor the nitrification and denitrification rates, (ii) compare the effects of different N rates on N<sub>2</sub>O flux during the cucumber growing season, (iii) determine the factors impacting N<sub>2</sub>O emissions, and (iv) identify reasonable nitrogen fertilizer application rate.

## MATERIALS AND METHODS

### Study Site

The study site was located at Mazhuang Experimental Station in Xinji County of Hebei Province (115°17'37"E, 37°47'53"N) in the North China Plain. The selected greenhouse was 39 m long and 7.5 m wide, with a wall made of brick-concrete, and brackets constructed with welded metal wires. The soil texture was sandy loam, containing 8.93 g kg<sup>-1</sup> of organic carbon (by H<sub>2</sub>SO<sub>4</sub>–K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub> oxidation), 1.55 g kg<sup>-1</sup> of total nitrogen (by Kjeldahl digestion), 32.4 mg kg<sup>-1</sup> of available phosphorus (Olsen-P method), 165.3 mg kg<sup>-1</sup> of available potassium (with NH<sub>4</sub>OAc extraction), at a pH of 6.6 (1:2.5 soil-water ratios) and bulk density of the 0–20 cm topsoil of 1.35 g cm<sup>-3</sup> (average fertilization and non-fertilization belts) (Lu, 2000). The cucumber variety used in the experiment was Bomei 11, and the cucumbers were planted on 18 February, 2009, and harvested on 3 July, 2009.

### Experimental Design and Management

Four nitrogen treatments with three replications (Plot size: 6×1.8 m) were applied as urea: (1) traditional, nitrogen fertilizer input 1,200 kg N ha<sup>-1</sup> (N<sub>1200</sub>); (2) 900 kg N ha<sup>-1</sup> (N<sub>900</sub>); (3) 600 kg N ha<sup>-1</sup> (N<sub>600</sub>), and (4) the

control, no nitrogen input (N<sub>0</sub>). Traditional nitrogen amount was determined as per previous research in Hebei Province (Zhang *et al.*, 2005). Triple superphosphate (300 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>) and potassium sulfate (525 kg K<sub>2</sub>O ha<sup>-1</sup>) were applied for each treatment. Furrow irrigation (5,190 m<sup>3</sup> ha<sup>-1</sup> in total) was applied, and the irrigation frequency was consistent with the schedule of local farmers (Table 1). The plot was isolated by 1 m deep polyvinyl chloride (PVC) boards. Three rows of cucumbers were planted in each plot, with a row space of 60 cm and an interplant distance of 30 cm.

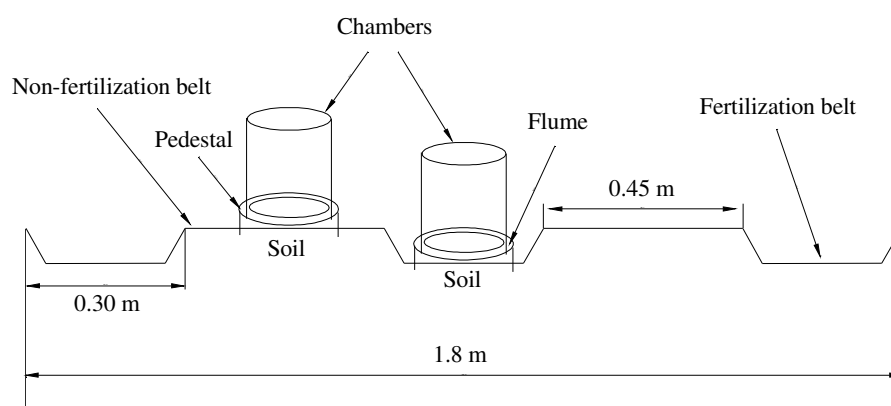
## N<sub>2</sub>O Flux Measurements

The width of the experimental plot was 1.8 m, with three fertilized furrows (fertilized belts). Each furrow was 0.30 m wide, and cucumbers were planted in the furrows. The areas (0.45 m wide) between fertilized furrows were regarded as the non-fertilization belts (Figure 1). N<sub>2</sub>O flux of the fertilized and non-fertilized belts were monitored synchronously (plants were not included in chambers). The average flux emitted from the fertilized and non-fertilized belts was considered as the statistical value

**Table 1.** Nitrogen input rates, irrigation rates and date of sampling in greenhouse cucumber experiment (2009).<sup>a</sup>

Date	Growth stage		N rate (kg ha <sup>-1</sup> ) <sup>b</sup>			Irrigation (m <sup>3</sup> ha <sup>-1</sup> )	Dates of N <sub>2</sub> O sampling
			N <sub>600</sub>	N <sub>900</sub>	N <sub>1200</sub>		
16 Feb.	Seedling period	Basal fertilizer	120	180	240	270	16 Feb, 18 Feb, 22 Feb, 1 Mar, 9 Mar, 16 Mar, 22 Mar, 29 Mar,
28 Feb.							
9 Mar.							
1 Apr.	Blooming period	Topdressing	60	90	120	480	1 Apr, 3 Apr, 5 Apr, 7 Apr, 10 Apr,
11 Apr.							
22 Apr.	Initial fruit period		60	90	120	480	22 Apr, 24 Apr, 26 Apr, 28 Apr, 1 May,
4 May							
15 May							
26 May	Full fruit period		60	90	120	480	15 May, 17 May, 19 May, 21 May, 24 May,
5 Jun.							
16 Jun.							
21 Jun.	End fruit period		60	90	120	480	5 Jun, 7 Jun, 9 Jun, 11 Jun, 14 Jun,
25 Jun.							
Total							
			600	900	1200	5190	

<sup>a</sup> Day of fertilization was "the first day of N<sub>2</sub>O sampling". <sup>b</sup> N<sub>600</sub>, N<sub>900</sub> and N<sub>1200</sub> representing 600, 900 and 1,200 kg ha<sup>-1</sup> of N application amount, respectively.



**Figure 1.** Schematic of experimental plot (fertilization and non-fertilization belts) and location of the chambers.



for each plot.

N<sub>2</sub>O samples were collected using closed static chambers. Chambers (20 cm diameter×25 cm height) consisted of a chamber cap and a pedestal made of polyvinyl chloride (PVC) materials. The ring pedestal with a flume around the top was inserted to a depth of 5 cm into the soil before sampling to keep the chamber sealed (Figure 1). N<sub>2</sub>O samples were collected at 1 or 2 day (d) intervals in the first 10 days after fertilizer application, and then at 7 day intervals in the other periods (Table 1). Sampling was carried out from 10:00 to 12:00 every day. Gas samples were taken using a 50 mL airtight syringe attached to a three-way stop cork at fixed intervals of 0, 10, 20, and 30 min after chamber closure, and then stored in evacuated bags made of inert aluminum-coated plastic. The N<sub>2</sub>O samples were analyzed using a gas chromatograph (GC7890, Agilent Technologies Inc., USA) fitted with an electron capture detector (ECD) set at 300 °C. The column temperature was maintained at 40°C and the carrier gas was argon-methane (5%) at a flow rate of 30 mL min<sup>-1</sup>. Details for this method were described by Zhang *et al.* (2011). N<sub>2</sub>O fluxes were calculated according to Li *et al.* (2009).

#### Determination of Nitrification and Denitrification Rates Using BaPS System

The nitrification and denitrification rates were determined using Barometric Process-Separation (BaPS), which is based on measuring O<sub>2</sub>, CO<sub>2</sub>, and total gas balances inside an isothermal and gas-tight soil system. Nitrification (consumption of O<sub>2</sub> by ammonia oxidizing bacteria and archaea bacteria), denitrification (production of nitrogen containing gases such as NO, N<sub>2</sub>O, and N<sub>2</sub>), and soil respiration (consumption of O<sub>2</sub> and generation of equivalent volume of CO<sub>2</sub>) are the main biological processes responsible for gas pressure changes in this system. The gross nitrification and denitrification rates and respiration can be

calculated based on the gas and inverse balance. The basic principle of BaPS and relevant measuring processes are discussed in Muller *et al.* (2004) and Liu *et al.* (2005). Many studies have shown consistent gross nitrification and denitrification rates by BaPS and <sup>15</sup>N-pool dilution (Ingwersen *et al.*, 1999; Breuer *et al.*, 2002). In this study, undisturbed soil (10 cm depth) was sampled and sealed four times per month in the cucumber growing season, from February to June, by circular stainless rings equipped with the BaPS. At the same time, N<sub>2</sub>O samples were collected simultaneously. All soil and gas samples were transported to the laboratory for analysis.

#### Auxiliary Measurements

Topsoil samples (10 cm depth) were randomly collected on the same day as N<sub>2</sub>O sampling. Analysis of NO<sub>3</sub><sup>-</sup>-N concentrations in the soil was measured by extracting 10 g of mixed topsoil with 100 mL of 2 M KCl solution. The topsoil moisture content was determined gravimetrically by oven-drying samples at 105°C for > 12 hours. The water-filled pore space (WFPS) was calculated by  $WFPS (\%) = (\text{Soil bulk density} \times \text{Soil moisture content}) / (1 - \text{soil bulk density} / 2.65)$ . The topsoil (5 cm) and air temperatures in the chamber as well as in the greenhouse were measured simultaneously when N<sub>2</sub>O was sampled. Cucumber fruits were harvested and weighed by an electronic scale.

#### Statistical Analysis

Differences between treatments were determined by analysis of variance (ANOVA) and Tukey's multiple comparison tests using SPSS 18.0 statistical software. The significance levels for linear or non-linear regression curves were determined using *F*-test. Pearson correlation analysis was applied to investigate the associations of nitrification and denitrification rates and

N<sub>2</sub>O fluxes with WFPS, mineral N content, soil temperature, and air temperature.

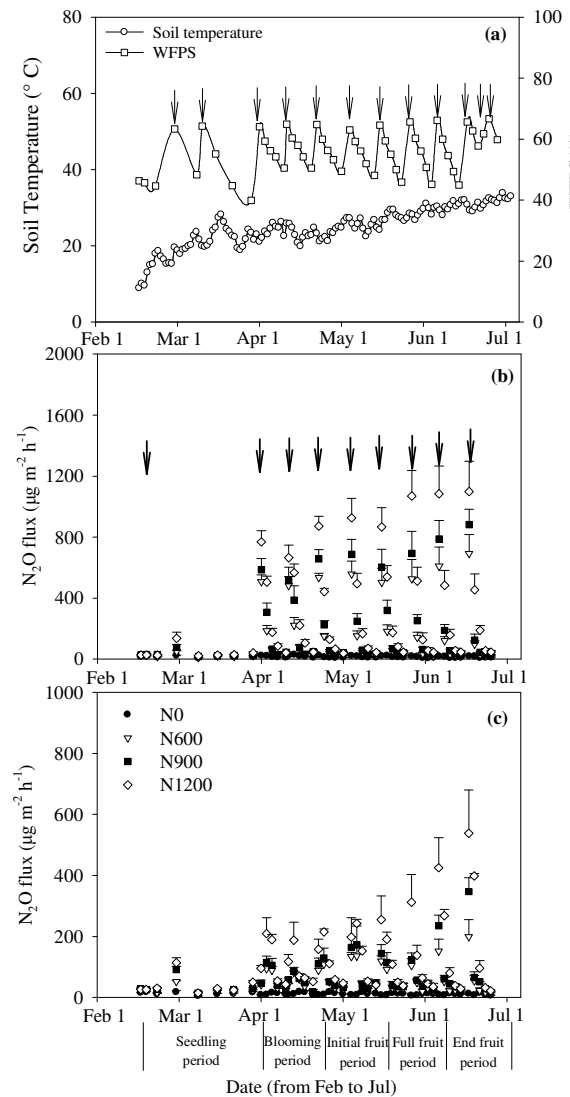
## RESULTS AND DISCUSSION

### N<sub>2</sub>O Flux of Fertilization and Non-fertilization Belts

Details of soil temperature and soil moisture content (WFPS) are outlined in Figure 2-a. Soil temperature ranged from 8.6 to 33.8°C, with a mean of 24.4°C. WFPS changed strongly with irrigation, and ranged from 40.0 to 66.6%, with a mean of 55.8%.

Similar temporal trends in N<sub>2</sub>O fluxes for the fertilized and non-fertilized belts were observed for each treatment during the growing season [Figure 2 (b and c)]. The N<sub>2</sub>O fluxes varied from 5.99 to 1,098.7  $\mu\text{g m}^{-2} \text{h}^{-1}$  and from 4.61 to 538.0  $\mu\text{g m}^{-2} \text{h}^{-1}$  for the fertilized and non-fertilized belts, respectively. The peaks mainly appeared following N fertilization and appeared on the fourteenth day after base nitrogen application, at first irrigation and when the soil temperature was high (19.6°C). The rise in both temperature and soil moisture led to the significant increase in N<sub>2</sub>O flux (Castaldi, 2000; Smith *et al.*, 2003). He *et al.* (2009) also reported that no N<sub>2</sub>O emission peak occurred, even after fertilization, when soil temperatures were below 15°C.

N<sub>2</sub>O flux peaks in the fertilized (Figure 2-b) and non-fertilized (Figure 2-c) belts appeared after topdressing. The N<sub>2</sub>O fluxes decreased notably over a week and gradually tended to be stable after the peak appeared. Similar peaks in N<sub>2</sub>O fluxes were observed by Malla *et al.* (2005) on application of nitrogen fertilizer. For different nitrogen treatments in the present study, N<sub>2</sub>O emissions on the first five days were higher than that of the non-fertilized belts after topdressing. N<sub>2</sub>O emissions on the first day, the first three days, and the first five days in the fertilized belts accounted for 41.4 to 80.0%, 76.8 to 91.4%, and 90.6 to 95.2% of total N<sub>2</sub>O emissions over the 10 days, respectively, while the corresponding



**Figure 2.** Temporal courses of soil temperature (5 cm depth), soil moisture (WFPS: Water-Filled Pore Space) (a), and N<sub>2</sub>O fluxes for different N treatments in the fertilized (b) and non-fertilized belts (c) during cucumber growing seasons. Vertical bars denote the standard errors of the means (n= 3). Solid and bold arrows indicate irrigation and fertilizer N application, respectively. N<sub>0</sub>, N<sub>600</sub>, N<sub>900</sub>, and N<sub>1200</sub> are the treatments fertilized with 0, 600, 900, and 1,200 kg N ha<sup>-1</sup>, respectively.

proportions in the non-fertilized belts were 18.0 to 68.6%, 52.1 to 86.2%, and 75.8 to 95.0%, respectively. These results illustrated that N<sub>2</sub>O emissions were concentrated in the

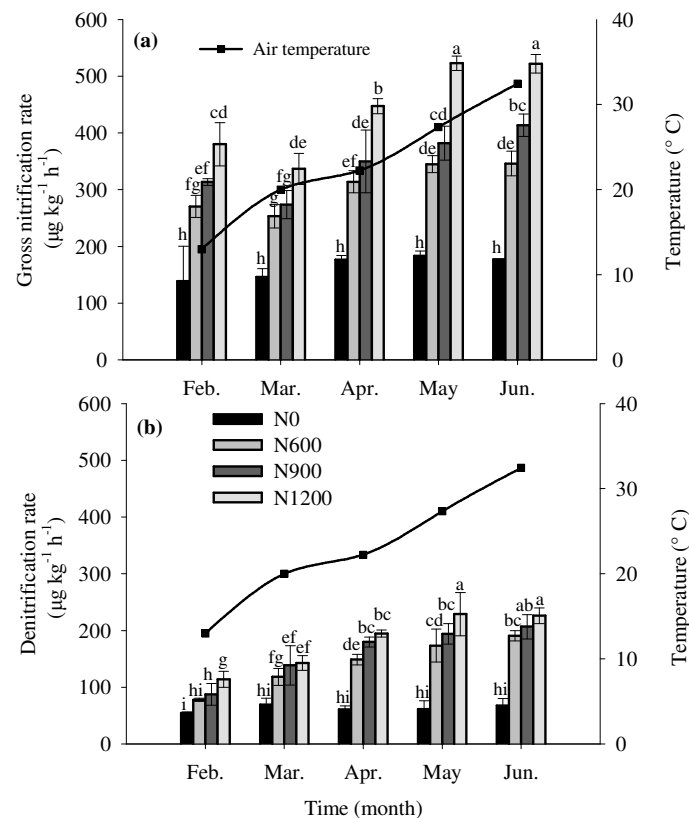


first five days for both the fertilized and non-fertilized belts, especially in the first three days after topdressing. These observations were consistent with He *et al.* (2007), who found a peak in N<sub>2</sub>O emissions on the first or second day after fertilizer application in greenhouse tomatoes.

### Nitrification and Denitrification Rates

The rates of nitrification and denitrification increased with the extension of the cucumber growing season and increase in air temperature; however, they decreased significantly with the decrease in N fertilizer application (Figure 3). The rates of nitrification and denitrification under N<sub>600</sub> treatment were reduced by 24.8 to 34.0% (average of 30.2%) and 15.7 to 31.8%

(average of 22.5%), respectively, compared to these under N<sub>1200</sub> treatment. Soil moisture, air temperature, and soil temperature were correlated positively with both nitrification and denitrification rates (Table 2). Increases in suitable soil moisture (WFPS of 40.0 to 66.6%) or temperature (8.6 to 33.8°C) improved the nitrification and denitrification rates (Breuer *et al.*, 2002; Cao *et al.*, 2006). Correlation analysis demonstrated significant exponential relationships between the rates of nitrification and denitrification and N<sub>2</sub>O flux (Figure 4). Similar findings were observed by Chen and Huang (2006). The nitrification of treatments N<sub>0</sub>, N<sub>600</sub>, N<sub>900</sub>, and N<sub>1200</sub> accounted for 72.3, 64.5, 66.7, and 69.8%, respectively, of total nitrification and denitrification, with an average value of 68.3%. This indicated that nitrification was



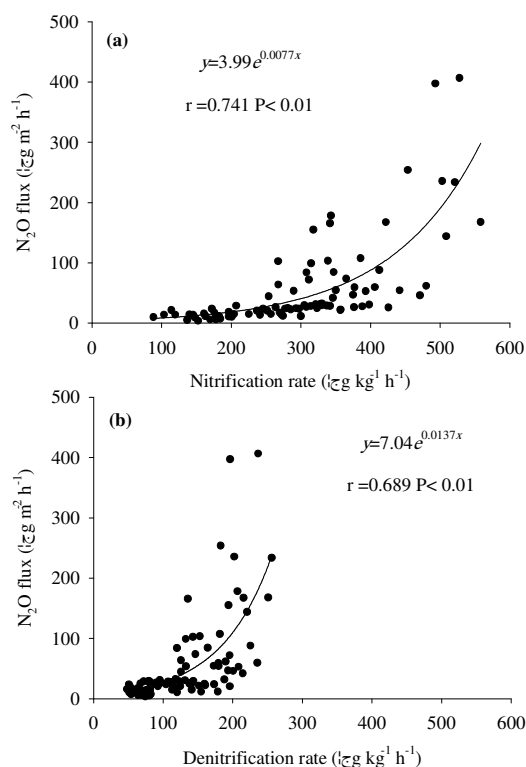
**Figure 3.** Monthly variation of gross nitrification rate (mean value±standard deviation) (a) and denitrification rate (mean value±standard deviation) (b) of greenhouse soil under different nitrogen conditions and the monthly temperature (curve with the square symbol). Different letters (a, b) denote significantly different between treatments at  $P < 0.05$ . N<sub>0</sub>, N<sub>600</sub>, N<sub>900</sub>, and N<sub>1200</sub> are the treatments fertilized with 0, 600, 900, and 1,200 kg N ha<sup>-1</sup>, respectively.

**Table 2.** Correlation between the rate of nitrification and denitrification and environmental factors.

		WFPS	Air temperature in	Soil
		(%)	greenhouse (°C)	temperature (°C)
		n <sup>a</sup> = 33	n= 33	n= 33
Nitrification rate ( $\mu\text{g kg}^{-1} \text{h}^{-1}$ )	N <sub>0</sub>	0.439*	0.388	0.443*
	N <sub>600</sub>	0.626**	0.359	0.657**
	N <sub>900</sub>	0.541**	0.386	0.645**
	N <sub>1200</sub>	0.499*	0.683**	0.688**
Denitrification rate ( $\mu\text{g kg}^{-1} \text{h}^{-1}$ )	N <sub>0</sub>	0.223	0.200	0.264
	N <sub>600</sub>	0.630**	0.359	0.857**
	N <sub>900</sub>	0.403	0.696**	0.726**
	N <sub>1200</sub>	0.656**	0.555**	0.799**

<sup>a</sup> Number of observations; \* Significant at  $P < 0.05$ , \*\* Significant at  $P < 0.01$ .

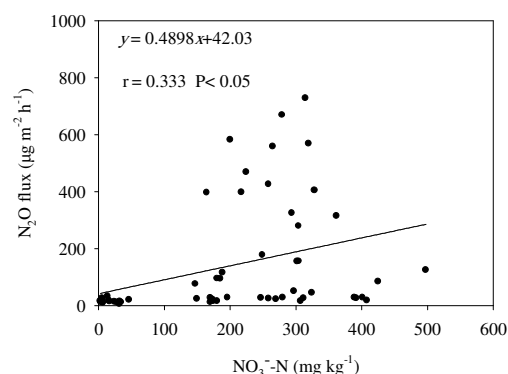
the dominant process producing N<sub>2</sub>O in soil (WFPS of 40.0 to 66.6%). This is in agreement with Sanchez-Martin *et al.* (2010), who found that nitrification was more important in the production of N<sub>2</sub>O compared with denitrification when WFPS was 56 to 75%.



**Figure 4.** Relationship between the nitrification rate (a), denitrification rate (b) and N<sub>2</sub>O flux.

### N<sub>2</sub>O Emissions and Environmental Factors

N<sub>2</sub>O emissions are significantly influenced by farming activities such as nitrogen application and irrigation, which can alter the NO<sub>3</sub><sup>-</sup>-N concentrations and moisture in the soil (Laville *et al.*, 2011). Compared to the control, nitrogen application increased the rates of nitrification and denitrification and, consequently, led to a significant increase in N<sub>2</sub>O emissions. We observed significant correlations in soil NO<sub>3</sub><sup>-</sup>-N with N<sub>2</sub>O emissions in the cucumber season (Figure 5), which is in agreement with other studies that



**Figure 5.** Relationship between N<sub>2</sub>O fluxes and soil NO<sub>3</sub><sup>-</sup>-N content (average fertilization and non-fertilization belts).



have reported increased emissions with increasing soil  $\text{NO}_3\text{-N}$  (Stevens *et al.*, 1998; Laville *et al.*, 2011).

Irrigation often causes the soil pores to fill with water, which aggravates the anaerobic environment and intensifies denitrification (Clemens *et al.*, 2008). Bateman and Baggs (2005) and Baggs *et al.* (2010) stated that the optimum *WFPS* for ammonia oxidation was around 65% *WFPS*. At a *WFPS* of between 30 and 70%, the relationship between aerobic microbial processes and *WFPS* appeared linear (Linn and Doran, 1984). Generally,  $\text{N}_2\text{O}$  emitted under 35 to 60% *WFPS* is produced during nitrification, while denitrification is the main process producing  $\text{N}_2\text{O}$  under 70-90% *WFPS* (Bateman and Baggs, 2005; Liu *et al.*, 2007; Zhang *et al.*, 2009; Laville *et al.*, 2011). According to Lan *et al.* (2013), the effects of moisture on  $\text{N}_2\text{O}$  emissions were probably masked by the effects of fertilization. When mineral N content of the soil is low, irrigation does not affect  $\text{N}_2\text{O}$  emissions significantly (He *et al.*, 2009). In this study, fertilizer was dissolved and flushed with furrow irrigation water during the topdressing period, and a significant positive relationship was found between  $\text{N}_2\text{O}$  flux and *WFPS* (Table 3). These findings are supported by a number of previous studies (Lin *et al.*, 2010; Laville *et al.*, 2011). Soil temperature also significantly affects  $\text{N}_2\text{O}$  emissions when soil nitrate content and soil moisture are relatively constant (He *et al.*, 2009). Cao *et al.* (2006) also found a highly significant positive correlation ( $r = 0.781$ )

between soil temperature (from 5 to 32°C) and  $\text{N}_2\text{O}$  emissions during the growing season of Chinese cabbages. In this study, soil temperature during the cucumber growing season ranged from 8.6 to 33.8°C, and  $\text{N}_2\text{O}$  emissions showed a significant positive relationship with soil temperature, except for the control (Table 3).

### Cumulative $\text{N}_2\text{O}$ Emissions and Cucumber Yield

The effects of nitrogen application on cumulative  $\text{N}_2\text{O}$  emissions and cucumber yield were significant (Table 4).  $\text{N}_2\text{O}$  emissions from the fertilized and non-fertilized belts were calculated by integrating the linearly interpolated data in the cucumber growing season, and the cumulative  $\text{N}_2\text{O}$  emissions ranged from 0.48 to 5.01 kg N ha<sup>-1</sup>. Taking  $\text{N}_2\text{O}$  emissions from the  $\text{N}_0$  treatment as the background emissions, the fertilizer-induced  $\text{N}_2\text{O}$  emission factors for  $\text{N}_{600}$ ,  $\text{N}_{900}$  and  $\text{N}_{1200}$  were 0.30, 0.28 and 0.38% of nitrogen input, respectively. Less  $\text{N}_2\text{O}$  emissions were produced when less nitrogen fertilizer was used (Table 4). Compared to the  $\text{N}_{1200}$  treatment, cumulative  $\text{N}_2\text{O}$  emissions were reduced by 53.4% in the  $\text{N}_{600}$  treatment. At the same time, cucumber yield increased by 6.02%, which showed that an appropriate reduction in nitrogen application reduced cumulative  $\text{N}_2\text{O}$  emissions significantly without lowering the cucumber yield.

**Table 3.** Correlation between  $\text{N}_2\text{O}$  flux and environmental factors.

		WFPS (%)	Air temperature in greenhouse	Soil temperature
			(°C)	(°C)
		n <sup>a</sup> = 33	n = 33	n = 33
$\text{N}_2\text{O}$ flux ( $\mu\text{g m}^{-2} \text{h}^{-1}$ )	$\text{N}_0$	0.385*	-0.037	0.084
	$\text{N}_{600}$	0.667**	0.463**	0.497**
	$\text{N}_{900}$	0.707**	0.392*	0.428**
	$\text{N}_{1200}$	0.693**	0.765**	0.756**

<sup>a</sup> Number of observations; \* Significant at  $P < 0.05$ , \*\* Significant at  $P < 0.01$ .



**Table 4.** Cucumber yields, N<sub>2</sub>O emission and emission factors under different nitrogen conditions.

Treatments <sup>a</sup>	Yield (10 <sup>4</sup> kg ha <sup>-1</sup> )	Increasing ratio (%)	N <sub>2</sub> O emissions		Cumulative N <sub>2</sub> O emissions (135 d) (kg N ha <sup>-1</sup> )	Emission factor (%) <sup>c</sup>
			Fertilizer belts	Non-fertilizer belts		
N <sub>0</sub>	11.9 b <sup>b</sup>	—	0.28 d	0.20 d	0.48 d	—
N <sub>600</sub>	16.5 a	22.9	1.56 c	0.74 c	2.30 c	0.30
N <sub>900</sub>	15.5 a	18.8	2.06 b	0.95 b	3.01 b	0.28
N <sub>1200</sub>	15.4 a	15.9	3.37 a	1.64 a	5.01 a	0.38

<sup>a</sup> N<sub>0</sub>, N<sub>600</sub>, N<sub>900</sub>, and N<sub>1200</sub> are the treatments fertilized with 0, 600, 900, and 1,200 kg N ha<sup>-1</sup>, respectively; <sup>b</sup> Values with the same letter means no significant different among different treatments by Tukey with three replications ( $P > 0.05$ ); <sup>c</sup> Emission factor induced by total applied N from chemical fertilizer.

## CONCLUSIONS

We investigated the N<sub>2</sub>O emissions and soil nitrification and denitrification rates under different nitrogen fertilization treatments including traditional nitrogen (N<sub>1200</sub>), 75% of traditional nitrogen (N<sub>900</sub>), 50% of traditional nitrogen (N<sub>600</sub>), and no nitrogen treatments (N<sub>0</sub>) in a cucumber growing greenhouse in the North China Plain. N<sub>2</sub>O emissions and nitrification and denitrification rates in the greenhouse soils were strongly related to fertilizer nitrogen inputs. Compared to the N<sub>1200</sub> treatment, N<sub>2</sub>O emissions and nitrification and denitrification rates of N<sub>600</sub> were reduced by 53.4, 30.2 and 22.5%, respectively. High N<sub>2</sub>O emissions occurred in the first five days after topdressing, which accounted for more than 75.8% of total emissions during the 10-day study period. Water-filled pore space (WFPS), air temperature, and soil temperature affected the nitrification rate, denitrification rate, and N<sub>2</sub>O emissions, especially after nitrogen fertilizer application. The nitrification and denitrification rates presented an exponential relationship with N<sub>2</sub>O emissions ( $P < 0.01$ ), and nitrification was the main biological process producing N<sub>2</sub>O under the traditional irrigation conditions in this experiment (WFPS of 40.0 to 66.6%). N<sub>2</sub>O emissions ranged from 0.48 to 5.01 kg ha<sup>-1</sup> during the cucumber growing season, and 0.28-0.38% (average 0.32%) of the nitrogen application rate was emitted as N<sub>2</sub>O-N. The improved N-fertilizer management reduced the

nitrogen application rate by 50% (N<sub>600</sub>), increased cucumber yield by 6.02%, and significantly decreased N<sub>2</sub>O emissions ( $P < 0.01$ ).

Based on this study, for the present greenhouse cucumber production in Hebei Province in the North China Plain, appropriate reduction in nitrogen fertilizer application significantly reduced N<sub>2</sub>O emissions without any negative effect on cucumber yield. Compared to the traditional nitrogen application rate i.e. 1,200 kg N ha<sup>-1</sup>, a 50% reduction is suggested.

## ACKNOWLEDGEMENTS

The study was supported by the National Basic Research Program of China (973 Program, 2011CB100501), National 863 Program of China (2013AA102901), Special Fund for Agro-scientific Research in the Public Interest (201203077), and the Technology Innovation Ability Construction Projects, Beijing Academy of Agriculture and Forestry Sciences (KJCX20140415).

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## اثر کار برد نیتروژن روی نیترات سازی و نیترات زدایی و تصعید N<sub>2</sub>O در گلخانه

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### چکیده

اکسید نیتروژن (N<sub>2</sub>O) اثر مهمی روی شدن زمین دارد و به تخلیه اوزن در استراسفر منجر می شود. زمین های کشاورزی به عنوان منبع اصلی تصعید و انتشار این گاز شناخته می شوند. در سال های اخیر، کاشت گلخانه ای سبزیجات به سرعت در چین توسعه یافته است. با وجود مصرف بیش از حد کودهای شیمیایی در گلخانه ها برای تولید سبزی های مختلف که می تواند تصعید N<sub>2</sub>O را افزایش دهد، داده های پژوهشی در زمینه انتشار این گاز در فرایند تولید سبزیجاتی مانند خیار همچنان محدود است. در این رابطه، در پژوهش حاضر، چهار تیمار کود نیتروژن شامل ۱۲۰۰ کیلو گرم در هکتار (N<sub>1200</sub>، مقدار رایج و سنتی)، ۹۰۰ (N<sub>900</sub>)، ۶۰۰ کیلو گرم در هکتار (N<sub>600</sub>)، و شاهد (N<sub>0</sub>) روی محصول خیار در دشت شمالی چین بررسی شد. نتایج نشان داد که بیشتر تصاعد گاز N<sub>2</sub>O که نزدیک به ۹۵/۲٪ - ۷۵/۸٪ کل تصاعد گاز طی دوره اندازه گیری (۱۰ روز) بود طی پنج روز اول بعد از کودپاشی سرک رخ داد. از تحلیل داده ها، رابطه های معنی دار نمایی (P < 0.01) بین جریان انتشار N<sub>2</sub>O و نرخ نیترات سازی و نیترات زدایی به دست آمد. همچنین، نتایج نشان داد که در انتشار و تصاعد گاز مزبور در شرایط آبیاری (تخلخل پر شده از آب در خاک بین ۴۰٪ تا ۶۶/۶٪) فرایند نیترات سازی غالب بود و نقش مهم تری از نیترات زدایی در این مطالعه داشت. انتشار تجمعی N<sub>2</sub>O طی فصل رشد خیار بین ۵/۰۱ - ۰/۴۸ کیلو گرم در هکتار بود که معادل ۰/۳۸٪ - ۰/۲۸٪ از نیتروژن افزوده شد به خاک را شامل می شد. در مقایسه با تیمار N<sub>1200</sub>، تیمار N<sub>600</sub> به طور معنی داری نرخ انتشار N<sub>2</sub>O را در حدود ۵۳/۴٪ کاهش داد و سطح عملکرد خیار را حفظ کرد. بر پایه این پژوهش، مصرف نیتروژن در حد (N<sub>600</sub>) معادل ۵۰٪ مقدار رایج و سنتی در دشت شمالی چین میتواند به عنوان مصرف پایدار برای تولید خیار گلخانه ای در این منطقه تلقی شود.