

Effects of Nitrogen Application on Soil Nitrification and Denitrification Rates and N₂O Emissions in Greenhouse

Y. K. Li¹, B. Li¹, W. Z. Guo¹, and X. P. Wu^{2*}

ABSTRACT

Nitrous oxide (N₂O) 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 N₂O emissions. In recent years, greenhouse grown vegetables have rapidly developed in China. Although excessive fertilizer application in greenhouse vegetable production can result in increased N₂O 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 (N₁₂₀₀, traditional N amount), 900 (N₉₀₀), and 600 kg N ha⁻¹ (N₆₀₀) and the control (N₀) were carried out on cucumber in a greenhouse in the North China Plain. Results showed that N₂O emissions mainly occurred in the first five days after topdressing, and accounted for 75.8%-95.2% of total N₂O emissions produced in the whole interval (10 days). Significant exponential correlations were observed between N₂O flux and nitrification or denitrification rates ($P < 0.01$). The results also indicated that nitrification dominated and played a more important role in N₂O emissions than denitrification under the irrigation conditions of the study (water-filled pore space was 40.0 to 66.6%). Cumulative N₂O emissions were 0.48-5.01 kg N ha⁻¹ in the cucumber growing season, accounting for 0.28-0.38% of nitrogen input. Compared to N₁₂₀₀, treatment N₆₀₀ significantly reduced the rate of N₂O emissions by 53.4%, and also maintained cucumber yield. Based on this study, 50% of the traditional N fertilizer rate (N₆₀₀) was considered sustainable for greenhouse cucumber production in the North China Plain.

Keywords: Cucumber, Environmental factor, Nitrogen fertilizer, N₂O flux. Soil NO₃-N.

INTRODUCTION

Nitrous oxide (N₂O) 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 N₂O emissions has increased by 17% from 1990 to 2005 (Kroeze *et al.*, 1999; IPCC, 2007). Agricultural soil is a major source of N₂O emissions, releasing 6.3 Tg N₂O-N yr⁻¹ into the atmosphere, accounting for 58% of total N₂O emissions (Mosier *et al.*, 1998; IPCC,

2007). Nitrification and denitrification are two major processes producing N₂O, representing approximately 70% of total global N₂O 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 N₂O emissions. Nitrogen fertilizer application and irrigation are regarded as two of the most important

¹ Beijing Research Center of Intelligent Equipment for Agriculture, Beijing Academy of Agriculture and Forestry Sciences, Beijing 100097, People's Republic of China.

² Institute of Agricultural Resource and Regional Planning, Chinese Academy of Agriculture Sciences, Beijing 100081, People's Republic of China.

*Corresponding author; e-mail: xpwu@caas.ac.cn



elements influencing N₂O emissions (Zhang *et al.*, 2008). Wang *et al.* (2011) and He *et al.* (2009) reported that seasonal N₂O 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 N₂O emissions (Liu *et al.*, 2011). In China, the rate of fertilizer-induced N₂O emissions from agricultural soils was 198.9 Gg N₂O–N in 1997, with 66.9 Gg N₂O–N produced by vegetable fields in 2009 (Lu *et al.*, 2006; Wang *et al.*, 2011). Additionally, the N₂O 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⁻¹, 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⁻¹ 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 N₂O emissions (Zhang *et al.*, 2002; Xiong *et al.*, 2006; He *et al.*, 2009; Alomran *et al.*, 2013). The N₂O emissions from China crop fields varied from 275 to 292 Gg N₂O–N yr⁻¹ 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 N₂O emissions (emissions induced by factors other than fertilization) from vegetable fields increased from 6.76 Gg N₂O–N in 1990 to 19.6 Gg N₂O–N in 2009 (He *et al.*, 2009; Wang *et al.*, 2011).

A number of studies have been carried out on N₂O 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 N₂O 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 N₂O flux during the cucumber growing season, (iii) determine the factors impacting N₂O 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⁻¹ of organic carbon (by H₂SO₄–K₂Cr₂O₇ oxidation), 1.55 g kg⁻¹ of total nitrogen (by Kjeldahl digestion), 32.4 mg kg⁻¹ of available phosphorus (Olsen-P method), 165.3 mg kg⁻¹ of available potassium (with NH₄OAc 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⁻³ (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⁻¹ (N₁₂₀₀); (2) 900 kg N ha⁻¹ (N₉₀₀); (3) 600 kg N ha⁻¹ (N₆₀₀), and (4) the

control, no nitrogen input (N₀). Traditional nitrogen amount was determined as per previous research in Hebei Province (Zhang *et al.*, 2005). Triple superphosphate (300 kg P₂O₅ ha⁻¹) and potassium sulfate (525 kg K₂O ha⁻¹) were applied for each treatment. Furrow irrigation (5,190 m³ ha⁻¹ 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.

N₂O 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). N₂O 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).^a

Date	Growth stage		N rate (kg ha ⁻¹) ^b			Irrigation (m ³ ha ⁻¹)	Dates of N ₂ O sampling
			N ₆₀₀	N ₉₀₀	N ₁₂₀₀		
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							

^a Day of fertilization was "the first day of N₂O sampling". ^b N₆₀₀, N₉₀₀ and N₁₂₀₀ representing 600, 900 and 1,200 kg ha⁻¹ of N application amount, respectively.

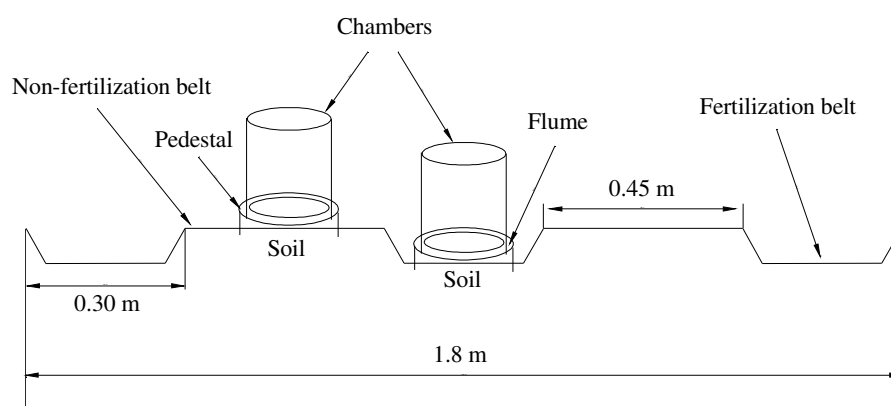


Figure 1. Schematic of experimental plot (fertilization and non-fertilization belts) and location of the chambers.



for each plot.

N₂O 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). N₂O 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 N₂O 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⁻¹. Details for this method were described by Zhang *et al.* (2011). N₂O 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 O₂, CO₂, and total gas balances inside an isothermal and gas-tight soil system. Nitrification (consumption of O₂ by ammonia oxidizing bacteria and archaea bacteria), denitrification (production of nitrogen containing gases such as NO, N₂O, and N₂), and soil respiration (consumption of O₂ and generation of equivalent volume of CO₂) 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 ¹⁵N-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, N₂O 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 N₂O sampling. Analysis of NO₃⁻-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 N₂O 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

N₂O fluxes with WFPS, mineral N content, soil temperature, and air temperature.

RESULTS AND DISCUSSION

N₂O 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 N₂O fluxes for the fertilized and non-fertilized belts were observed for each treatment during the growing season [Figure 2 (b and c)]. The N₂O 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 N₂O flux (Castaldi, 2000; Smith *et al.*, 2003). He *et al.* (2009) also reported that no N₂O emission peak occurred, even after fertilization, when soil temperatures were below 15°C.

N₂O flux peaks in the fertilized (Figure 2-b) and non-fertilized (Figure 2-c) belts appeared after topdressing. The N₂O fluxes decreased notably over a week and gradually tended to be stable after the peak appeared. Similar peaks in N₂O fluxes were observed by Malla *et al.* (2005) on application of nitrogen fertilizer. For different nitrogen treatments in the present study, N₂O emissions on the first five days were higher than that of the non-fertilized belts after topdressing. N₂O 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 N₂O emissions over the 10 days, respectively, while the corresponding

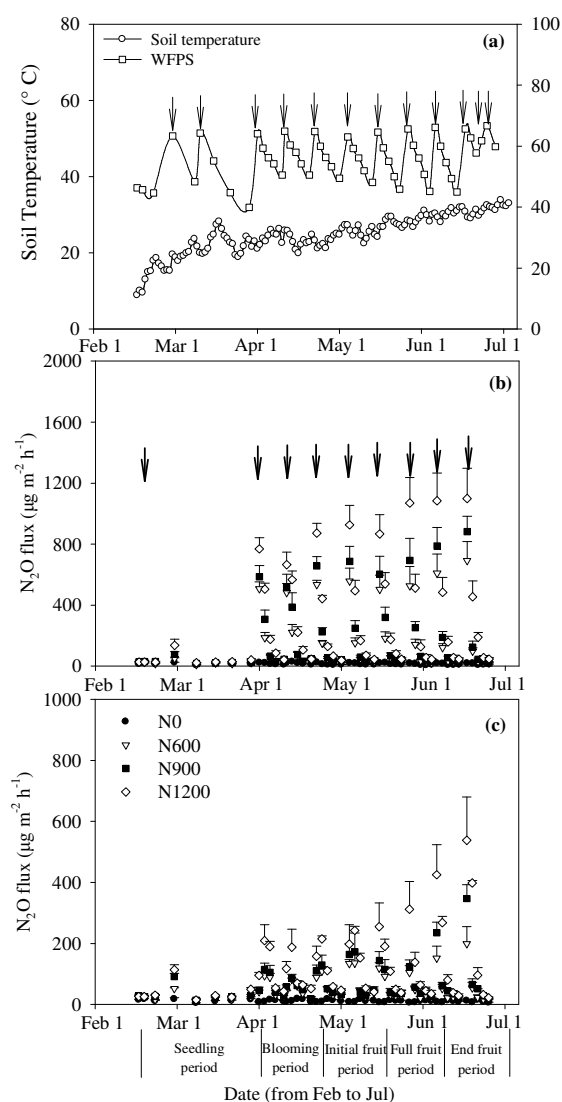


Figure 2. Temporal courses of soil temperature (5 cm depth), soil moisture (WFPS: Water-Filled Pore Space) (a), and N₂O fluxes for different N treatments in the fertilized (b) and non-fertilized belts (c) during cucumber growing seasons. Vertical bars denote the standard errors of the means (n= 3). Solid and bold arrows indicate irrigation and fertilizer N application, respectively. N₀, N₆₀₀, N₉₀₀, and N₁₂₀₀ are the treatments fertilized with 0, 600, 900, and 1,200 kg N ha⁻¹, 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 N₂O 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 N₂O 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 N₆₀₀ 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 N₁₂₀₀ 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 N₂O flux (Figure 4). Similar findings were observed by Chen and Huang (2006). The nitrification of treatments N₀, N₆₀₀, N₉₀₀, and N₁₂₀₀ 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

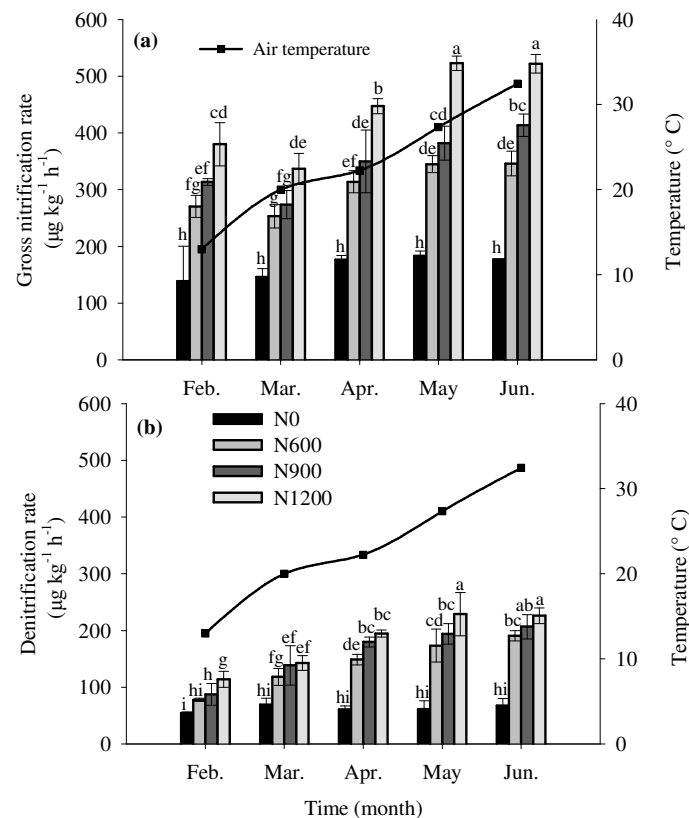


Figure 3. Monthly variation of gross nitrification rate (mean value±standard deviation) (a) and denitrification rate (mean value±standard deviation) (b) of greenhouse soil under different nitrogen conditions and the monthly temperature (curve with the square symbol). Different letters (a, b) denote significantly different between treatments at $P < 0.05$. N₀, N₆₀₀, N₉₀₀, and N₁₂₀₀ are the treatments fertilized with 0, 600, 900, and 1,200 kg N ha⁻¹, respectively.

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

		WFPS	Air temperature in	Soil
		(%)	greenhouse (°C)	temperature (°C)
		n ^a = 33	n= 33	n= 33
Nitrification rate (μg kg ⁻¹ h ⁻¹)	N ₀	0.439*	0.388	0.443*
	N ₆₀₀	0.626**	0.359	0.657**
	N ₉₀₀	0.541**	0.386	0.645**
	N ₁₂₀₀	0.499*	0.683**	0.688**
Denitrification rate (μg kg ⁻¹ h ⁻¹)	N ₀	0.223	0.200	0.264
	N ₆₀₀	0.630**	0.359	0.857**
	N ₉₀₀	0.403	0.696**	0.726**
	N ₁₂₀₀	0.656**	0.555**	0.799**

^a Number of observations; * Significant at $P < 0.05$, ** Significant at $P < 0.01$.

the dominant process producing N₂O 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 N₂O compared with denitrification when WFPS was 56 to 75%.

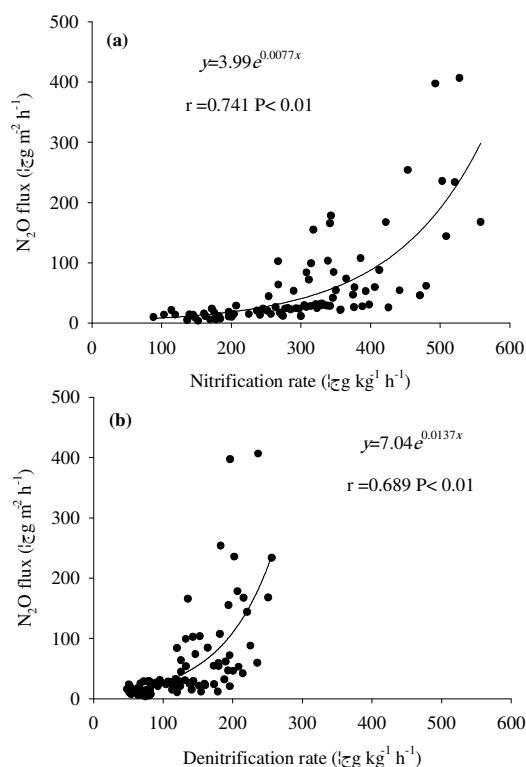


Figure 4. Relationship between the nitrification rate (a), denitrification rate (b) and N₂O flux.

N₂O Emissions and Environmental Factors

N₂O emissions are significantly influenced by farming activities such as nitrogen application and irrigation, which can alter the NO₃⁻-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 N₂O emissions. We observed significant correlations in soil NO₃⁻-N with N₂O emissions in the cucumber season (Figure 5), which is in agreement with other studies that

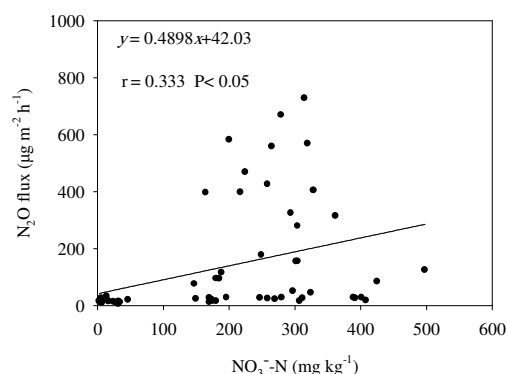


Figure 5. Relationship between N₂O fluxes and soil NO₃⁻-N content (average fertilization and non-fertilization belts).



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, N_2O emitted under 35 to 60% *WFPS* is produced during nitrification, while denitrification is the main process producing N_2O 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 N_2O emissions were probably masked by the effects of fertilization. When mineral N content of the soil is low, irrigation does not affect N_2O 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 N_2O 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 N_2O 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 N_2O 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 N_2O emissions showed a significant positive relationship with soil temperature, except for the control (Table 3).

Cumulative N_2O Emissions and Cucumber Yield

The effects of nitrogen application on cumulative N_2O emissions and cucumber yield were significant (Table 4). N_2O emissions from the fertilized and non-fertilized belts were calculated by integrating the linearly interpolated data in the cucumber growing season, and the cumulative N_2O emissions ranged from 0.48 to 5.01 kg N ha⁻¹. Taking N_2O emissions from the N_0 treatment as the background emissions, the fertilizer-induced N_2O emission factors for N_{600} , N_{900} and N_{1200} were 0.30, 0.28 and 0.38% of nitrogen input, respectively. Less N_2O emissions were produced when less nitrogen fertilizer was used (Table 4). Compared to the N_{1200} treatment, cumulative N_2O emissions were reduced by 53.4% in the N_{600} treatment. At the same time, cucumber yield increased by 6.02%, which showed that an appropriate reduction in nitrogen application reduced cumulative N_2O emissions significantly without lowering the cucumber yield.

Table 3. Correlation between N_2O flux and environmental factors.

		WFPS (%)	Air temperature in greenhouse	Soil temperature
			(°C)	(°C)
		$n^a = 33$	$n = 33$	$n = 33$
N_2O flux ($\mu\text{g m}^{-2} \text{h}^{-1}$)	N_0	0.385*	-0.037	0.084
	N_{600}	0.667**	0.463**	0.497**
	N_{900}	0.707**	0.392*	0.428**
	N_{1200}	0.693**	0.765**	0.756**

^a Number of observations; * Significant at $P < 0.05$, ** Significant at $P < 0.01$.

Table 4. Cucumber yields, N₂O emission and emission factors under different nitrogen conditions.

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

^a N₀, N₆₀₀, N₉₀₀, and N₁₂₀₀ are the treatments fertilized with 0, 600, 900, and 1,200 kg N ha⁻¹, respectively; ^b Values with the same letter means no significant different among different treatments by Tukey with three replications ($P > 0.05$); ^c Emission factor induced by total applied N from chemical fertilizer.

CONCLUSIONS

We investigated the N₂O emissions and soil nitrification and denitrification rates under different nitrogen fertilization treatments including traditional nitrogen (N₁₂₀₀), 75% of traditional nitrogen (N₉₀₀), 50% of traditional nitrogen (N₆₀₀), and no nitrogen treatments (N₀) in a cucumber growing greenhouse in the North China Plain. N₂O emissions and nitrification and denitrification rates in the greenhouse soils were strongly related to fertilizer nitrogen inputs. Compared to the N₁₂₀₀ treatment, N₂O emissions and nitrification and denitrification rates of N₆₀₀ were reduced by 53.4, 30.2 and 22.5%, respectively. High N₂O 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 N₂O emissions, especially after nitrogen fertilizer application. The nitrification and denitrification rates presented an exponential relationship with N₂O emissions ($P < 0.01$), and nitrification was the main biological process producing N₂O under the traditional irrigation conditions in this experiment (WFPS of 40.0 to 66.6%). N₂O emissions ranged from 0.48 to 5.01 kg ha⁻¹ during the cucumber growing season, and 0.28-0.38% (average 0.32%) of the nitrogen application rate was emitted as N₂O-N. The improved N-fertilizer management reduced the

nitrogen application rate by 50% (N₆₀₀), increased cucumber yield by 6.02%, and significantly decreased N₂O 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 N₂O emissions without any negative effect on cucumber yield. Compared to the traditional nitrogen application rate i.e. 1,200 kg N ha⁻¹, a 50% reduction is suggested.

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REFERENCES

1. Akimoto, F., Matsunami, A., Kamata, Y., Kodama, I., Kitagawa, K., Arai, N., Higuchi, T., Itoh, A. and Haraguchi, H. 2005. Cross-correlation Analysis of Atmospheric Trace Concentrations of N₂O, CH₄ and CO₂ Determined by Continuous Gas-chromatographic Monitoring. *Energy*, **30**(2-4): 299–311.



2. Alomran, A. M., Louki, I. I., Aly, A. A. and Nadeem, M. E. 2013. Impact of Deficit Irrigation on Soil Salinity and Cucumber Yield under Greenhouse Condition in an Arid Environment. *J. Agr. Sci. Tech.*, **15**: 1247–1259.
3. Baggs, E. M., Smales, C. L. and Bateman, E. J. 2010. Changing pH Shifts the Microbial Source as well as the Magnitude of N₂O Emission from Soil. *Biol. Fertil. Soils*, **46(8)**: 793–805.
4. Bateman, E. J. and Baggs, E. M. 2005. Contributions of Nitrification and Denitrification to N₂O Emissions from Soils at Different Water-filled Pore Space. *Biol. Fertil. Soils*, **41(6)**: 379–388.
5. Breuer, L., Kiese, R. and Butterbach-Bahl, K. 2002. Temperature and Moisture Effects on Nitrification Rates in Tropical Rain-forest Soils. *Soil Sci. Soc. Am J.*, **66(3)**: 834–844.
6. Cao, B., He, F. Y., Xu, Q. M., Yin, B and Cai, G. X. 2006. Denitrification Losses and N₂O Emissions from Nitrogen Fertilizer Applied to a Vegetable Field. *Pedosphere*, **16(3)**: 390–397.
7. Castaldi, S. 2000. Responses of Nitrous Oxide, Dinitrogen and Carbon Dioxide Production and Oxygen Consumption to Temperature in Forest and Agricultural Light-Textured Soils Determined by Model Experiment. *Biol. Fertil. Soils*, **32(1)**: 67–72.
8. Chen, S. T. and Huang, Y. 2006. Determination of Respiration, Gross Nitrification and Denitrification in Soil Profile Using BaPS System. *J. Environ. Sci.*, **18(5)**: 937–943.
9. Clemens, S., Reiner, W., Kirsten, K., Nazar, I. and Ruzimboy, E. 2008. Nitrous Oxide Emissions from Fertilized, Irrigated Cotton (*Gossypium hirsutum* L.) in the Aral Sea Basin, Uzbekistan: Influence of Nitrogen Applications and Irrigation Practices. *Soil Biol. Biochem.*, **40(2)**: 290–301.
10. He, F. F., Chen, Q., Jiang, R. F., Chen, X. P. and Zhang, F. S. 2007. Yield and Nitrogen Balance of Greenhouse Tomato (*Lycopersicon esculentum* Mill.) with Conventional and Site-Specific Nitrogen Management in Northern China. *Nutr. Cycl. Agroecosyst.*, **77(1)**: 1–14.
11. He, F. F., Jiang, R. F., Chen, Q., Zhang, F. S. and Su, F. 2009. Nitrous Oxide Emissions from an Intensively Managed Greenhouse Vegetable Cropping System in Northern China. *Environ. Pollut.*, **157(5)**: 1666–1672.
12. Ingwersen, J., Butterbach-Bahl, K., Gasche, R., Richter, O. and Papen, H. 1999. Barometric Process Separation: New Method for Quantifying Nitrification, Denitrification, and Nitrous Oxide Sources in Soils. *Soil Sci. Soc. Am. J.*, **63(1)**: 117–128.
13. IPCC. 2007. Climate Change 2007 Mitigation of Climate Changes. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Metz B, Davidson OR, Bosch PR, Dave R, Meyer L (Eds.), University Press, Cambridge, United Kingdom and New York, 499–532.
14. Kroeze, C., Mosier, A. R. and Bouwman, A. F. 1999. Closing the Global N₂O Budget: a Retrospective Analysis 1500–1994. *Global Biogeochem. Cycl.*, **13(1)**: 1–8.
15. Lan, T., Han, Y., Roelcke, M., Nieder, R. and Cai, Z. 2013. Processes Leading to N₂O and NO Emissions from Two Different Chinese Soils under Different Soil Moisture Contents. *Plant Soil*, **371(1-2)**: 611–627.
16. Laville, P., Lehuger, S., Loubet, B., Chaumartin, F. and Cellier, P. 2011. Effect of Management, Climate and Soil Conditions on N₂O and NO Emissions from an Arable Crop Rotation Using High Temporal Resolution Measurements. *Agric. Forest Meteorol.*, **151(2)**: 228–240.
17. Li, X. L., Zhang, X. Y., Xu, H., Cai, Z. C. and Yagi, K. 2009. Methane and Nitrous Oxide Emissions from Rice Paddy Soil as Influenced by Timing of Application of Hydroquinone and Dicyandiamide. *Nutr. Cycl. Agroecosyst.*, **85(1)**: 31–40.
18. Lin, S., Iqbal, J., Hu, R. G. and Feng M. L. 2010. N₂O Emissions from Different Land Uses in Mid-subtropical China. *Agric., Ecosyst. Environ.*, **136(1-2)**: 40–48.
19. Linn, D. M. and Doran, J. W. 1984. Effect of Water-filled Pore Space on Carbon Dioxide and Nitrous Oxide Production in Tilled and Nontilled Soils. *Soil Sci. Soc. Am. J.*, **48(6)**: 1267–1272.
20. Liu, Q. H., Huang, Y. and Zheng, X. H. 2005. Determination of Upland Soil Respiration and Its Components with BaPS System. *Acta Sci. Circum.*, **25(8)**: 1105–1111.
21. Liu, X. J., Mosier, A. R., Halvorson, A. D., Reule, C. A. and Zhang, F. S. 2007. Dinitrogen and N₂O Emissions in Arable Soils: Effect of Tillage, N Source and Soil Moisture. *Soil Biol. Biochem.*, **39(9)**: 2362–2370.

22. Liu, X. R., Dong, Y. S., Qi, Y. C. and Li, S. G. 2010. N₂O Fluxes from the Native and Grazed Semi-arid Steppes and their Driving Factors in Inner Mongolia, China. *Nutr. Cycl. Agroecosyst.*, **86(2)**: 231–240.
23. Liu, C. Y., Wang, K., Meng, S. X., Zheng, X. H., Zhou, Z. X., Han, S. H., Chen, D. L. and Yang, Z. P. 2011. Effects of Irrigation, Fertilization and Crop Straw Management on Nitrous Oxide and Nitric Oxide Emissions from a Wheat–maize Rotation Field in Northern China. *Agric. Ecosyst. Environ.*, **140(1-2)**: 226–233.
24. Lu, R.K., 2000. Soil Agro-Chemical Analyses. Agricultural Technical Press of China, Beijing in Chinese.
25. Lu, Y. Y., Huang, Y., Zou, J. W. and Zheng, X. H. 2006. An Inventory of N₂O Emissions from Agriculture in China Using Precipitation Rectified Emission Factor and Background Emission. *Chemosphere* , **65(11)**: 1915–1924.
26. Ma, W. Q., Mao, D. R. and Zhang, F. S. 2000. Nutrients Accumulation with Vegetable Awning (Greenhouse) in Shangdong Province. *Phosphate Compound Fertil.*, **15(3)**: 65–67.
27. Malla, G., Bhatia, A., Pathak, H., Prasad, S., Jain, N. and Singh, J. 2005. Mitigating Nitrous Oxide and Methane Emissions from Soil in Rice–wheat System of the Indo-Gangetic Plain with Nitrification and Urease Inhibitors. *Chemosphere*, **58(2)**: 141–147.
28. Meade, G., Pierce, K., Doherty, J. V., Mueller, C., Lanigan, G. and Cabe, T. M. 2011. Ammonia and Nitrous Emissions Following Land Application of High and Low Nitrogen Pig Manures to Winter Wheat at Three Growth Stages. *Agric. Ecosyst. Environ.*, **140(1-2)**: 208–217.
29. Moiser, A. R., Duxbury, J. M., Freney, J. R., Heinemeyer, O. and Minami, K. 1996. Nitrous Oxide Emission from Agricultural Fields: Assessment, Measurement and Mitigation. *Plant Soil*, **18(1)**:95–108.
30. Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S. and Cleemput, O. 1998. Closing the Global N₂O Budget: Nitrous Oxide Emissions through the Agricultural Nitrogen Cycle. *Nutr. Cycl. Agroecosyst.*, **52(2-3)**: 225–248.
31. Muller, C., Abbasi, M. K., Kammann, C., Clough, T. J., Sherlock, R. R. and Stevens, R. J. 2004. Soil Respiration Quotient Determined *via* Barometric Process Separation Combined with Nitrogen-15 Labeling. *Soil Sci. Soc. Am. J.*, **68(5)**: 1610–1615.
32. Pramanik, P., Haque, Md. M. and Kim, P. J. 2013. Effect of Nodule Formation in Roots of Hairy Vetch (*Vicia villosa*) on Methane and Nitrous Oxide Emissions during Succeeding Rice Cultivation. *Agric. Ecosyst. Environ.*, **178**: 51-56.
33. Sanchez-Martin, L., Mejjide, A., Garcia-Torres, L., and Vallejo, A. 2010. Combination of Drip Irrigation and Organic Fertilizer for Mitigating Emissions of Nitrogen Oxides in Semiarid Climate. *Agric. Ecosyst. Environ.*, **137(1-2)**: 99–107.
34. Stevens, R. J., Laughlin, R. J. and Mosier, A. 1998. Measurement of Nitrous Oxide and Dinitrogen Emissions from Agricultural Soils, International Workshop on Dissipation of N from the Human N-cycle, and its Role in Present and Future N₂O Emissions to the Atmosphere. *Nutr. Cycl. Agroecosyst.*, **52(3)**:131–139.
35. Smith, K. A., Ball, T., Conen, F., Dobbie, K. E., Massheder, J. and Rey, A. 2003. Exchange of Greenhouse Gases between Soil and Atmosphere: Interactions of Soil Physical Factors and Biological Processes. *Eur. J. Soil Sci.*, **54(4)**: 779–791.
36. Wang, J. Y., Xiong, Z. Q. and Yan, X. Y. 2011. Fertilizer-induced Emission Factors and Background Emissions of N₂O from Vegetable Fields in China. *Atmos. Environ.*, **45(38)**: 6923–6929.
37. Xiong, Z. Q., Xie, Y. X., Xing, G. X., Zhu, Z. L. and Butenhoff, C. 2006. Measurements of Nitrous Oxide Emissions from Vegetable Production in China. *Atmos. Environ.*, **40(12)**: 2225–2234.
38. Zhang, G. Y., Chen, M. C., Min, H. and Chai, W. G. 2002. Research of N₂O Flux from Greenhouse and Nitrifier and Denitrifier Numbers. *Plant Nutr. Fertil. Sci.*, **8(2)**: 239–243.
39. Zhang, J. B., Cai, Z. C. and Zhu, T. B. 2011. N₂O Production Pathways in the Subtropical acid Forest Soils in China. *Environ. Res.*, **111(5)**: 643–649.
40. Zhang, Y. C., Li, Q. Y., Zhai, C. X., Chen, L. L., Wu, Y. S. and Kang, F. Z. 2005. The Condition and Appraisal of the Vegetable Apply Fertilizer in Greenhouse in Hebei Province. *J. Hebei Agric. Sci.*, **9(3)**: 61–67.
41. Zhang, W., Mo, J. M., Yu, G. R., Fang, Y. T., Li, D. J., Lu, X. K. and Wang, H. 2008.



- Emissions of Nitrous Oxide from Three Tropical Forests in Southern China in Response to Simulated Nitrogen Deposition. *Plant Soil*, **306(1-2)**: 221–236.
42. Zhang, H. H., He, P. J., Shao, L. M. and Yuan, L. 2009. Minimisation of N₂O Emissions from a Plant-soil System under Landfill Leachate Irrigation. *Waste Manage.*, **29(3)**: 1012–1017.
43. Zheng, X. H., Han, S. H., Huang, Y., Wang, Y. S. and Wang, M. M. 2004. Re-quantifying the Emission Factors Based on Field Measurements and Estimating the Direct N₂O Emission from Chinese Croplands. *Global Biogeochem. Cycl.*, **18**: GB2018.

اثر کار برد نیتروژن روی نیترات سازی و نیترات زدایی و تصعید N₂O در گلخانه

ی. ک. لی، ب. لی، و. ز. گوو، و. ز. پ. وو

چکیده

اکسید نیتروژن (N₂O) اثر مهمی روی گرم 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 N₂O 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 (N₁₂₀₀، مقدار رایج و سنتی)، ۹۰۰ (N₉₀₀)، ۶۰۰ کیلو گرم در هکتار (N₆₀₀)، و شاهد (N₀) روی محصول خیار در دشت شمالی چین بررسی شد. نتایج نشان داد که بیشتر تصاعد گاز N₂O 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 N₂O 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 N₂O 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 N₁₂₀₀، تیمار N₆₀₀ به طور معنی داری نرخ انتشار N₂O را در حدود ۵۳/۴٪ کاهش داد و سطح عملکرد خیار را حفظ کرد. بر پایه این پژوهش، مصرف نیتروژن در حد (N₆₀₀) 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.