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Nitrous oxide emissions from a maize field during two consecutive growing seasons in the North China Plain

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Abstract

Nitrous oxide (N_2O) emissions from a maize field in the North China Plain (Wangdu County, Hebei Province, China) were investigated using static chambers during two consecutive maize growing seasons in the 2008 and 2009. The N_2O pulse emissions occurred with duration of about 10 days after basal and additional fertilizer applications in the both years. The average N_2O fluxes from the CK (control plot, without crop, fertilization and irrigation), NP (chemical N fertilizer), SN (wheat straw returning plus chemical N fertilizer), OM-1/2N (chicken manure plus half chemical N fertilizer) and OMN (chicken manure plus chemical N fertilizer) plots in 2008 were 8.51, 72.1, 76.6, 101, 107 ng N/(m^2·sec), respectively, and in 2009 were 33.7, 30.0 and 35.0 ng N/(m^2·sec) from CK, NP and SN plots, respectively. The emission factors of the applied fertilizer as N_2O-N (EFs) were 3.8% (2008) and 1.1% (2009) for the NP plot, 3.2% (2008) and 1.2% (2009) for the SN plot, and 2.8% and 2.2% in 2008 for the OM-1/2N and OMN plots, respectively. Hydromorphic properties of the investigated soil (with gley) are in favor of denitrification. The large differences of the soil temperature and water-filled pore space (WFPS) between the two maize seasons were suspected to be responsible for the significant yearly variations. Compared with the treatments of NP and SN, chicken manure coupled with compound fertilizer application significantly reduced fertilizer loss rate as N_2O-N.

Key words: nitrous oxide; fertilizers; wheat straw; manure; maize field; North China Plain

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Introduction

N_2O has been recognized as one of the most important trace gases in the atmosphere due to its significance for greenhouse effect and depletion of stratospheric ozone (Crutzen, 1981; Cicerone, 1987; IPCC, 2001). Atmospheric N_2O concentration at present is about 319 ppbV, still increasing at a rate of approximately 0.26% per year (IPCC, 2007). The main sources of atmospheric N_2O include fossil fuel combustion, biomass burning, arable land, animal excreta, soils under natural vegetation and oceans (Bouwman et al., 1995; Olivier et al., 1998). As reviewed by Mosier et al. (1998) and Kroeze et al. (1999), agriculture activities contributed about 78% of global anthropogenic N_2O emission, 67% of which is from agricultural soil. Therefore, a great number of studies have been conducted on N_2O flux measurements over agricultural fields (e.g., Sehy et al., 2003; Venterea et al., 2005; Stehfest and Bouwman, 2006; Phillips, 2007; Halvorson et al., 2008; Ussiri et al., 2009; Zaman and Nguyen, 2010). These measurements greatly extended the database for evaluating the influence of agricultural activities on atmospheric N_2O. However, the current estimation of N_2O emission from arable lands to the global budget is still with great uncertainty (ranged from 0.11 to 6.3 Tg N/yr) because of the large temporal-spatial variations of N_2O fluxes (Mosier et al., 1998; Bouwman et al., 2002; Yan et al., 2003).

The North China Plain (NCP) is one of the most important grain production regions in China. It accounts for 23% of Chinese cropland area while provides 39% of the total food in China (Ding et al., 2007). According to the statistical information (Ye and Guo, 2007), the current chemical fertilizer application rate (ca. 866 kg/(ha·yr)) has increased more than three times since 1980 in China to meet the increasing food demand. The N fertilizer application greatly enhances the crop yield in the NCP, but also stimulates N_2O emission (Meng et al., 2005; Ding et al., 2007). Organic manure from the livestock is also applied to the agricultural field as additional fertilizer by farmers, and the influence of applied organic manure on N_2O emission is still unclear. van Groenigen et al. (2004) pointed out that organic manure (slurry) stimulated N_2O

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emission via developing an optimum condition for denitrification due to the input of both available N and organic C. However, Meijide et al. (2007) found that organic manure reduced N_2O emission in comparison with application of mineral N fertilizer. Recently, crop straw is being returned to agricultural field according to a regulation of Chinese government. Returning straw to the field can increase soil fertility as addition of C and N into the soil (Tirol-Padre et al., 2005), but also improve the physical properties of soil, such as water content, aeration etc. (Mackenzie et al., 1997; Malhi et al., 2006). Such changes of soil micro-environment would have effect on N_2O emission. For instance, Zou et al. (2005a) presented that the wheat straw returning could slightly reduce N_2O emission from rice paddies, while Zhao et al. (2008) indicated that maize straw returning increased N_2O emission from a wheat field. To our knowledge, only few studies with limited sites have conducted N_2O flux measurements under above changes for agriculture activities in this region (Dong et al., 2001, 2007; Pan et al., 2004; Meng et al., 2005; Ding et al., 2007; Wan et al., 2008; Zhao et al., 2008). In addition, the large differences of fertilizer-induced N_2O-N emission factors (EFs, ranging from 0.006% to 1.9%) and average fluxes (ranging from 4.21 to 74.6 ng N/(m^2·sec)) from the agricultural field in the NCP indicate that further field measurements are still needed.

In this study, we set up experiments to continuously investigate N_2O fluxes and EFs under different managements of agricultural activities from a maize field in the NCP during two maize growing seasons.

1 Materials and methods

1.1 Site description

The field experiment was performed in an agricultural field where winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) have been cultivated by the way of rotation for several decades. The field is located in a village called Dongbaituo, Wangdu County, Hebei Province, China (38°71′N, 115°15′E), and it belongs to a typical region of the NCP. Organic manure (a kind of mixture of pig urine, manure, leaves and grass in hogpen after fermentation) was the main fertilizer applied to the field before 1980s, and then it was gradually replaced by chemical fertilizer. Recently, straw incorporating with chemical fertilizer is the prevailing cultivated method in this region. It should be mentioned that there is a hennery near our investigated field. The experimental site lies to the southwest of henneries about 500 m, therefore the hennery will have little influence on the field as the prevailing wind direction is southeast in this region during summer season.

The field soil is classified as aquic inceptisol with a sandy loam texture, showing a soil pH (in a 1: 2.5 soil-to-water ratio) of 8.1, a soil organic C of 8.34–9.43 g/kg and total N of 1.02–1.09 g/kg. In this region, the annual mean temperature was about 12.3°C, the highest and lowest mean monthly values were 26.5°C in July and –4.1°C in January, and the annual mean rainfall is about 555 mm.

1.2 Experimental design

The study included five treatments: control (CK, without crop, fertilization and irrigation) plot; chemical N fertilizer (NP) plot; wheat straw returning plus chemical N fertilizer (SN) plot; chicken manure plus half-fertilizer N (OM-1/2N) plot and chicken manure plus chemical N fertilizer (OMN) plot. The CK plot had been controlled under no fertilizer application for at least half year before the experiment. As for CK plot, it may be more reasonable for the same designs as the treatment plots except for fertilization. However, the design of control treatments in the literature did not have uniform rule. For instance, Dusenbury et al. (2008) established uncultivated grass system as their control plot (no fertilizer, crop and irrigation) for deriving EFs of fertilizer crop fields in a wheat field, while others only mentioned unfertilized or without fertilization and crop residual as the control plots in agricultural fields (Zou et al., 2005b; Alluvione et al., 2010; Ma et al., 2010). Our incipient understanding about the control treatment was that the influence of human activities on the field was as small as possible, and thus, the field without crop and irrigation was designed as the control plot which was similar with the design of Dusenbury et al. (2008). The measurements of N_2O emission from OM-1/2N and OMN plots were only carried out in 2008. Each plot had an area of 6.5×3.5 m^2, and was separated by plastic boards that were inserted into the soil about 50 cm depth. Two (in 2008) and three (in 2009) replicate chambers for flux measurements were designed for each plot. Maize was sown on 25 June 2008 and 29 June 2009. According to the cultivating manner of local farmers, compound fertilizers (525 kg/ha, N: P_2O_5: K_2O = 17% : 20% : 8% in 2008 and 413 kg/ha, N : P_2O_5: K_2O = 24% : 12% : 6% in 2009) as basal fertilizer were evenly broadcast onto the soil surface by hand after sowing for all fertilization plots. Another kind of compound fertilizer (375 kg/ha, N : K_2O = 22% : 8%) was further applied to the NP, SN and OMN plots as additional fertilizer on 16 August 2008, and urea (150 kg/ha, N = 46.2%) as additional fertilizer was applied to the NP and SN plots on 1st August 2009. Wheat straws (9.5 ton/ha in 2008 and 4.3 ton/ha in 2009, N = 0.48%) were evenly broadcast onto the soil surface as basal fertilizer in the SN plot in both years. Organic manure (22 ton/ha, N = 1.34%) was also applied as basal fertilizers to the OM-1/2N and OMN plots in 2008. Flooding irrigations (ca. 40 mm) were carried out immediately after the applications of additional fertilizer in 2008 and basal fertilizer in 2009. The field was not irrigated for the fertilizer cases on 25 June 2008 and 1st August 2009, because strong rain events with cumulative rainfall of about 25 mm took place both before and after fertilizer applications. Additional field managements including herbicide and pesticide applications were also strictly according to the cultivating manner of local farmers. Maize was harvested in mid-October in both years.

1.3 N_2O flux measurements

N_2O fluxes were measured by static chambers. In each plot, two or three stainless steel pedestals were inserted 10 cm into the soils of each plot during the whole maize growing season. Chambers made of Plexiglas (60×60×90 cm^3) were sealed to corresponding pedestals with water during flux measurements. The chambers were semitransparent (the top side and the sides towards south and east covered by aluminum foils) with two fans fixed at opposite position in the middle height of each chamber for mixing the air inside evenly. The measurements took place in 2008 across 116 days including 6 periods: 24–28 June, 9–12 July, 29 July–2 August, 15–24 August, 16–25 September and 17 October. The campaigns took place in 2009 across 106 days for 5 periods: 28 June–10 July, 30 July–6 August, 25 August–2 September, 10–21 September and 11 October. The daily fluxes were measured at 9:30 and 15:00 (Beijing time) in 2008 and 9:30 in 2009. Four samples were drawn from the headspace by a sampling mini-pump (NMP 830 KNDC, Germany) to aluminum combined polyester gas sampling bags (Delin, Dalian, China) at 10-min intervals after the chambers were deployed. The chambers were moved away after sampling so that crops could grow normally. For all fertilization treatments, four maize plants were kept in each pedestal. The maize distances between rows and between hills were 50 cm and 30 cm, respectively. The top parts of the maize in the pedestals were cut off on 15 August 2008 and 24 August 2009 for fitting the size of the chamber as well as permitting active N uptake (Haider et al., 1987). Air temperature and soil temperature at 10 cm depth were simultaneously recorded on each sampling occasion.

N_2O concentrations were analyzed by a gas chromatography (GC, Model SP3410, Beijing Analytical Instrument Factory, China) with an electron capture detector (ECD). The temperatures for GC oven, injector port and ECD were 72°C, 72°C and 390°C, respectively. Gas sample was loaded into a 2-mL loop connected with a 10-port valve that is used for injecting sample and back flushing a pre-column. The pre-column and an analytical column were made of stainless steel with the same size (2 m × 4 mm), and packed with Porapak Q (80–100 mesh). High purity of N_2 (99.999%) was used as carrier gas for both the columns with flow rates of 30 mL/min. In order to improve the instrument sensitivity, a makeup gas (979 ppmV CO_2 in N_2) was introduced into the downstream of the analytical column with a flow rate of 8 mL/min, and the N_2O signal increased at least 4 times. No influence of CO_2 concentration (200–2000 ppmV) in the air samples on N_2O quantification was found by our improved method. The variation coefficient for analyzing N_2O was less than 0.31% based on the reproducibility of a N_2O standard gas (358 ppbV, Center of Standard Reference Materials, Beijing, China) within 9 hours. The fluxes were calculated based on the change rates of linearly increased N_2O concentrations with times in the chambers (R^2 > 0.85).

1.4 Soil sampling and analysis

Soil samples from 0–5 cm depth were collected by a ring sampler (100 cm^3) for the water-filled pore space (WFPS) analysis and mixed soil samples from 0–10 cm topsoil of each plot gathered by a trowel were used for soil NH_4^+-N and NO_3^--N contents detection. Soil moisture was determined by drying the soil at 105°C for 12 hr. WFPS was calculated according to the general particle density (ρ_s), soil water content (WC) and the bulk density (ρ_b) (Hillel, 1980).

$$\text{WFPS} = \frac{\rho_s \times \text{WC}}{\rho_s - \rho_b} \tag{1}$$

where, ρ_s is typically taken as a constant for inorganic soils as 2.65 g/cm^3, WC and ρ_b were measured according to the conventional methods.

The soil NH_4^+-N and NO_3^--N contents were determined by extracting 20 g of the mixed fresh soil with 100 mL of 1 mol/L KCl solution and were stored frozen until analyzed by a colorimetric continuous flow analyzer (SANT^{++}, Skalar Company, the Netherlands).

1.5 Data calculation and analysis

Data analysis was performed using SPSS 13.0 software (SPSS Inc., Chicago, USA) and Origin 7.5 (Origin Lab Corporation, USA). Data were log-transformed as needed to normalize the distributions before statistical analysis. Spearman Rank Order Correlations were used to analyze the relationships between control factors and N_2O fluxes in the all treatments. Cumulative N_2O emissions from each plot were calculated by a linear interpolation based on sampling date. The relative standard deviations of the flux measurements for each plot were generally less than 37% when the N_2O emission rates were larger than 30 ng N/(m^2·sec), and only the average fluxes were presented in Fig. 1 and Fig. 3 which are shown by plotting the data in equal time span during each sampling campaign. The EFs were calculated as the following:

$$\text{EF} = \frac{A_{N_2O\text{-N-F}} - A_{N_2O\text{-N-C}}}{\text{TN}_{in}} \times 100\% \tag{2}$$

where, $A_{N_2O\text{-N-F}}$ and $A_{N_2O\text{-N-C}}$ are the amount of cumulative N_2O-N emission from fertilized plot and control plot, respectively, TN_{in} is total N input.

2 Results and discussion

2.1 N_2O emissions from the experimental field

2.1.1 N_2O emissions from the CK plot

N_2O emissions from the CK plot are shown in Fig. 1a. Large difference of N_2O emission from the CK plot between the two consecutive years was found (Table 1). Small pulse emissions of N_2O (from 19.7 to 57.0 ng N/(m^2·sec)) were only observed after the rain events on 24–28 June in 2008, whereas several pulse emissions occurred after corresponding rain events in 2009, especially the abruptly remarkable increase of N_2O emission (from 10 to 312 ng N/(m^2·sec)) after the rain event on 8 July. Compared with 2008, less frequent rainfall events occurred from June to mid-July in 2009 (Fig. 2). The influence of soil moisture on N_2O emission has been well recognized,

Table 1 Comparison of N_2O fluxes (means ± standard deviation) and fertilizer-induced N_2O-N emission factors (EFs) in different plots

Year	Treatment	Total N (kg N/ha)	Mean N_2O fluxes (ng N/(m^2·sec))	Cumulative N_2O emitted (kg N/ha)	EF (%)[a]
2008	CK	–	8.51 ± 11.0	0.85	–
	NP	172	72.1 ± 88.4	7.22	3.8
	SN	218	76.6 ± 109	7.66	3.2
	OM-1/2N	342	101 ± 247	10.2	2.8
	OMN	469	107 ± 217	10.8	2.2
2009	CK	–	33.7 ± 35.6	3.09	–
	NP	168	30.0 ± 33.2	2.75	1.1
	SN	189	35.0 ± 37.4	3.21	1.2
	OM-1/2N	108	16.3 ± 1.4	1.49	0.51

[a] EF was calculated without considering the pulse N_2O emissions due to the rainfall events in the CK plot.

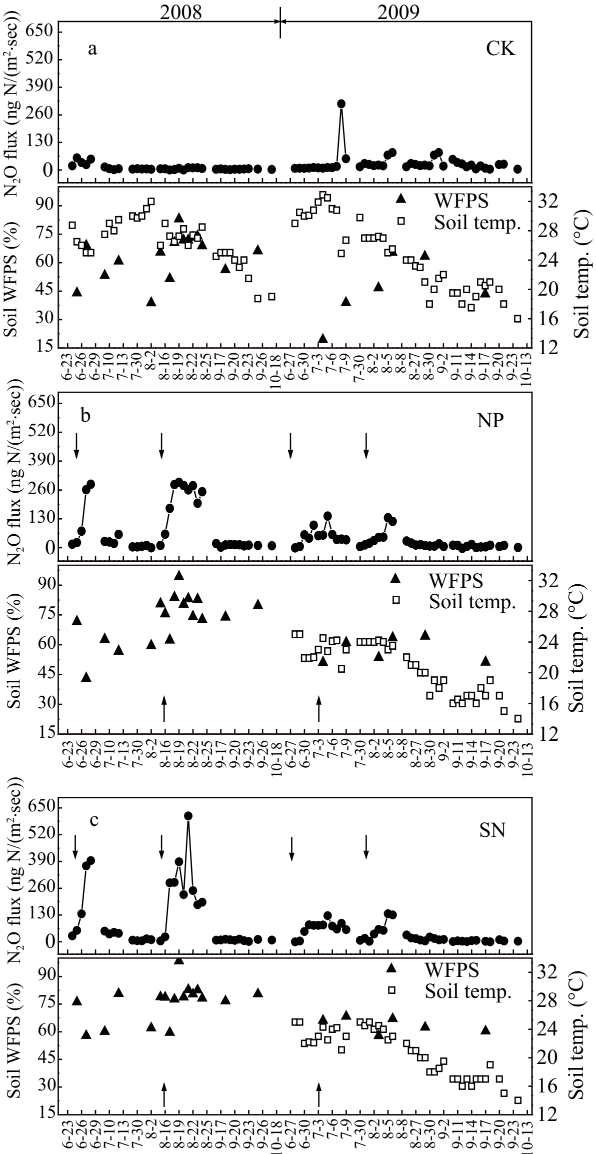

Fig. 1 Variations of N_2O flux, soil water-filled pore space (WFPS) and soil temperature from CK (a), NP (b) and SN (c) plots during the two maize growing periods. Downward facing solid arrows show fertilizer applications; upward facing solid arrows show irrigation events.

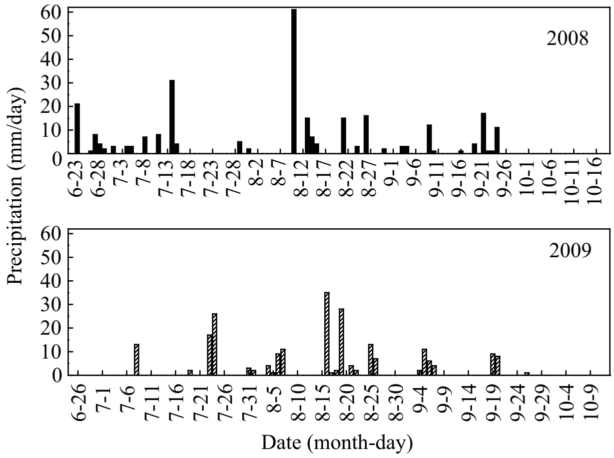

Fig. 2 Precipitation pattern during the maize growing periods in 2008 and 2009.

and is more prominent after rewetting of extremely dry soil (Jørgensen et al., 1998). Therefore, the sharp increase of N_2O emission was ascribed to the rewetting of the extremely dry soil (WFPS < 20%, Fig. 1a) by the light rainfall event (ca. 13 mm) on 8 July 2009. Compared with the rainfall episode on 8 July 2009, the pulse N_2O emissions from the CK plot due to other rainfall events in both years were relatively weak (in the range of 19.4–82.2 ng N/(m^2·sec)). This was probably ascribed to the relatively high soil moisture (usually greater than 35%, Fig. 1a) before other rainfall events. Lu et al. (2006) found that precipitation was the key factor for stimulating background N_2O emission from upland agricultural soils by an empirical model. Our results provided further evidence for their conclusion, while more exact prediction about the influence of rainfall on N_2O emission from background agricultural soil is still needed by considering the status of soil moisture.

The average N_2O fluxes in 2008 and 2009 were 8.51 and 33.7 ng N/(m^2·sec), respectively (Table 1), which were much higher, especially in 2009, than the reported range (0.317–8.02 ng N/(m^2·sec)) for the background N_2O emissions from croplands in China (summarized by Gu et al., 2009). Without considering the pulse N_2O emissions due to the rainfall events, the average N_2O fluxes in 2008 and 2009 were 7.20 and 10.3 ng N/(m^2·sec), respectively, which were still at the upper limit of the reported range.

In addition to the influence rain events, the much higher N_2O emission in 2009 than 2008 was partially ascribed to the higher NO_3^--N and NH_4^+-N contents in 2009 (32 mg N/kg) than 2008 (24 mg N/kg). It is unexpected that the N content in the CK plot increased from 2008 to 2009, and the dry and wet depositions of ammonia emitted from the

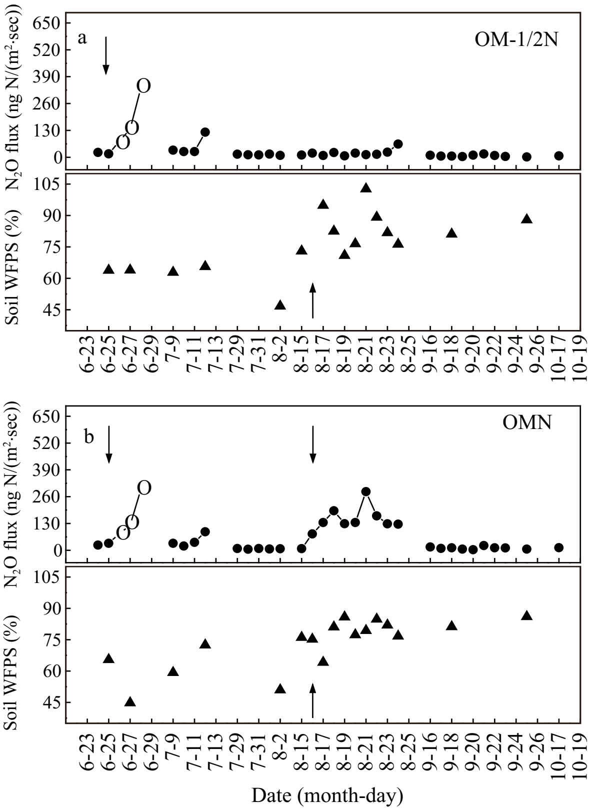

Fig. 3 Variations of N_2O flux, soil water-filled pore space (WFPS) and soil temperature from OM-1/2N (a) and OMN (b) in 2008. Open circles represent a quarter of the actual fluxes. Downward facing solid arrows show fertilizer applications; upward facing solid arrows show irrigation events.

hennery were suspected to be responsible.

2.1.2 N_2O emissions from fertilized soil

N_2O emissions from the NP, SN, OM-1/2N and OMN plots are presented in Fig. 1b, c and Fig. 3. In general, fertilizer application combined with irrigation (or rainfall event) greatly stimulated N_2O emission with duration of about 10 days. The N_2O emission rates in the fertilization plots always remained at the background level before fertilization and after 10 days of fertilization. The cumulative N_2O emissions during the periods of the pulse emission accounted for 70%–90% of the total emission from each fertilization plot during the two maize growing period.

Large yearly variations were found both in NP and SN plots (Fig. 1b, c). The average N_2O fluxes from NP and SN plots were 72.1 and 76.6 ng N/(m^2·sec) in 2008, and 30.0 and 35.0 ng N/(m^2·sec) in 2009, respectively (Table 1). It should be mentioned that the average N_2O fluxes from the two fertilization plots in 2009 were almost at the same level as that from the control plot. As mentioned in Section 2.1.1, N_2O emission from the control plot was strongly affected by rain events due to no shield of crop canopy, and thus, it is unreasonable for using the average N_2O flux from the control plot to calculate the EFs from the fertilization plots. The pulse N_2O emissions from the two fertilization plots induced by fertilization only focused on short duration, and the average N_2O fluxes (e.g., NP: 8.16 ng N/(m^2·sec) in 2008 and 8.13 ng N/(m^2·sec) in 2009) from the two fertilization plots during the whole maize growing period except for the pulse emission period induced by fertilization were close to those (7.20 ng N/(m^2·sec) in 2008 and 10.3 ng N/(m^2·sec) in 2009) from the control plot without considering the pulse emission induced by rain events. Therefore, the average N_2O fluxes from the control plot without considering the pulse emissions due to rain events were adopted for estimating the EFs, and the EFs from the NP and SN plots were 3.8% and 3.2% in 2008, and 1.1% and 1.2% in 2009, respectively.

The basal compound fertilizer applied to NP and SN plots was about 10 kg N/ha (11.2%) more in 2009 than in 2008, and the emission peaks from the two plots after the basal fertilizer application in 2009 were lower than those in 2008 by a factor of 2–3. Although the additional fertilizer applied to the NP and SN plots in 2009 was only about 16% lower than those in 2008, the emission peaks from the two plots after the additional fertilizer applications were lower by a factor of 2–5 in 2009 than in 2008. The repeated measurements during the two maize seasons revealed that the spatial variations in each plot were usually less than 37% when N_2O fluxes were greater than 30 ng N/(m^2·sec). It is evident that the amount of N fertilizer application and the spatial variation could not explain the significant yearly variation. The NO_3^--N and NH_4^+-N contents in 2009 (NP plot: 40 mg N/kg; SN plot: 29 mg N/kg) were about 15% higher than those in 2008 (NP plot: 35 mg N/kg; SN plot: 25 mg N/kg), which was on the contrary with the yearly N_2O emissions. Only the evident differences of soil temperature and moisture between the two years might be responsible for the large yearly variation of N_2O emissions from the two fertilization plots. Average soil temperature in 2008 (26.5°C) was 2°C higher than that in 2009 and the soil moisture (WFPS) was focused on 70%–90% in 2008 and 50%–70% in 2009. In this study, the significant positive correlation between N_2O fluxes and soil temperature for the NP ($P < 0.01$) and SN ($P < 0.05$) plots in 2009 revealed that soil temperature played important roles for N_2O emissions from these plots. Although the correlations between N_2O fluxes and soil WFPS were less significant ($P > 0.05$), the positive correlations in NP ($0.2 < R_s < 0.4$) and SN ($0.127 < R_s < 0.314$) plots also indicated that WFPS stimulated N_2O emissions from the agricultural field. Nitrification and denitrification have been recognized as the main N_2O production processes in soils, and the favorable WFPS levels for nitrification and denitrification were generally occurred at 30%–70% and 70%–90%, respectively (Davidson, 1993; Granli and Bøkman, 1994; McTaggart et al., 1997). Compared with the soils having gley, McLain and Martens (2006) reported that heterotrophic nitrification processes strongly impact N_2O production in a well-drained semiarid soil (typic Torrifluvents). The investigated soil in this study is aquic inceptisol which has hydromorphic properties (gley), and denitrification may be more important than that in soils without gley. Our previous study in 2009 (Zhang et al., 2011) from the same field also confirmed that denitrification was the dominant process for N_2O emission during pre- and post-fertilization period, while nitrification as the dominant process only limited short period after fertilization.

The cumulative N_2O emissions from the SN plot were 6.6% and 16.4% more than those from the NP plot in 2008 and 2009, respectively. The slightly higher N_2O emissions from the SN plot during the two maize growing periods may be due to the additional N from the wheat straw. In addition, the higher oxygen demands following straw amendment conduced to denitrification for N_2O emission. Several studies have investigated the influence of crop residuals on N_2O emissions with different conclusions, e.g. in the laboratory study, Cai et al. (2001) observed that the addition of wheat straw reduced N_2O evolution at 70% WHC (water holding capacity), while Huang et al. (2004) reported that the application of crop residual could increase N_2O emissions. Therefore, long-term field measurements are still needed for confirming the influence of crop residuals on N_2O emissions from agricultural fields.

As for OM-1/2N and OMN plots, the highest emission rate was about 1300 ng N/(m^2·sec) after the basal fertilizer application in 2008 (Fig. 3). This value is 3–4 times higher than those from other fertilizer plots. The higher N_2O emission from OM-1/2N and OMN plots were mainly ascribed to the high N input rates that were about 2-fold higher than other plots. However, the EFs from the OM-1/2N and OMN plots were 13%–43% lower than those from the NP plot (Table 1), which indicated that the application of organic manures might effectively reduce the fertilizer loss rates as N_2O-N. To certify the above conclusion, N_2O flux was further investigated by application the chicken manure in the OM-1/2N plot during the maize growing period in 2009, but the amount of manure application in 2009 was about one fifth of that in 2008. The EF (0.51%) for OM-1/2N plot in 2009 was about half of that for the NP plot. Without considering the N_2O pulse emissions during fertilization period, no significant difference of the average N_2O fluxes among the three fertilization plots (*t*-test, $P > 0.05$) was found in 2008 and 2009, indicating negligible residual effect of the applied chicken manure on N_2O emission.

In addition to N_2O emission, the loss pathway of N fertilizer also includes denitrification, NO_3^--N leaching, NH_3 volatilization and so on. Several researches on the loss pathway of N fertilizer have been conducted in the NCP. Ding et al. (2002) and Zhang et al. (2004) reported the rates of denitrification during the maize season were in the range of 2.11–4.71 kg N/ha, accounting for 0.67%–2.9% of the applied N fertilizer. The investigation of Liu et al. (2003) in the NCP indicated that NO_3^--N leaching was the main loss pathway in the winter wheat-maize cropping system, which accounted for 67% of total N loss during two cycles of wheat-maize rotation. And we also conducted ammonia volatilization and NO emission during the maize growing season in 2009 (Zhang et al., 2011), the fertilizer loss rates were 1.93% (NP plot) and 0.76% (SN plot) as NO-N, and were 5.24% (NP plot) and 3.03% (SN plot) as NH_3-N. Therefore, considering nutrient cycling in the agricultural field of the NCP, N_2O emission is a minor flux compared to the larger leaching, denitrification and ammonia flows. However, N_2O makes important contribution to current global warming and stratospheric ozone depletion, its emission from agricultural field should not be neglected.

2.2 Comparison with previous studies

A great number of studies have investigated N_2O emissions from various agricultural fields. To simplify the comparison, only the data from maize fields with similar fertilizer method as ours (chemical fertilizer and top-dressing) in the NCP are shown in Table 2. The soil types listed in Table 2 are all classified as fluvo-aquic soil (Ding et al., 2002; Dong et al., 2001; Wang et al., 2009; Zou et al., 2001). It is evident that the mean N_2O emission rate (4.21–74.6 ng N/(m^2·sec)) and EFs (0.006%–1.9%) varied in a wide range. In this study, the mean N_2O emission rates in 2008 (72.1–76.6 ng N/(m^2·sec)) were close to the upper limit and EFs (3.2%–3.8%, 2008) were much higher than the reported upper limit. As for the data in 2009, our values were within the large ranges. The EF values in this study were basically within the uncertainty range proposed by the IPCC (2006) 0.3% to 3%.

Table 2 Summary of N_2O emissions from maize soils in the North China Plain

Location	Period (day)	Total N (kg N/ha)	Mean fluxes (ng N/(m^2·sec))	EF (%)	Reference
Wangdu, Hebei	116	172	72.1	3.8	This study, 2008
	116	218	76.6	3.2	
	106	168	30.0	1.1	This study, 2009
	106	189	35.0	1.2	
Luancheng, Hebei	45	100	5.3	0.04	Wang et al., 2009
		200	5.3	0.006	Wang et al., 2009
	107	100	10.8	0.41	Zhang et al., 2004
		200	8.11	0.08	Zhang et al., 2004
		300	17.2	0.34	Zhang et al., 2004
	105	150	5.25	0.19	Wang et al., 1994
Yucheng, Shandong	124	90	16	1.9*	Sun et al., 2008
	122	210	40.2	0.51	Dong et al., 2001
	89	207	43.8–47.1	1.2–1.3	Dong et al., 2005
Fengqiu, Henan	105	150	22.2	1.1	Ding et al., 2007
		250	41.7	1.3	Ding et al., 2007
	102	150	4.21–5.71	0.20–0.28	Meng et al., 2005
	66	150	56.8	1.9	Ding et al., 2002
Beijing	75	300	74.6	1.6*	Zou et al., 2001

* Background N_2O emission was not subtracted.

It has been well recognized that N_2O emission from agricultural field is strongly affected by fertilizer rate (Liu et al., 2005; Ding et al., 2007; Ma et al., 2007; Kim and Dale, 2008). In this study, significant correlation was also found between the total amounts of the N fertilizer application and the cumulative N_2O emissions in 2008 (R = 0.965, P < 0.05, N = 4). As for the data in Luancheng, Hebei Province, the fertilizer rates almost had no influence on N_2O emissions in the same year by the same investigators (Zhang et al., 2004; Wang et al., 2009). To disclose the reason, further field measurements or laboratory simulations are still needed. The cumulative N_2O emission from the conventional cultivated maize field (SN plot) with 106-day duration in 2009 was within the range of 1.11–3.78 kg N/ha reported by Ding et al. (2007) from a maize field in Henan with fertilizer rates of 150 kg N/ha and 250 kg N/ha. However, at least double increment of N_2O emission was observed in 2008 from NP and SN plots. Therefore, long-term field measurements are still needed for better estimating the contribution of N_2O from agricultural fields to the global budget.

3 Conclusions

Soil temperature and WFPS were suspected to be responsible to the large yearly variation of N_2O emission. The addition of wheat straw slightly increased N_2O emission in the two maize seasons. The coupling application of organic manure and chemical fertilizers could remarkably reduce fertilizer-induced N_2O-N loss rate from the maize field. Hydromophic properties of the soil (with gley) investigated in this study are fit for denitrification.

The significant yearly variation of N_2O emission from the investigated maize field under almost the same amount of fertilizer application and the large reported ranges of the mean N_2O emission rates from the maize fields in the NCP indicate that long-term field measurements at different areas in the NCP are still needed for better estimating the contribution of N_2O from the agricultural fields to the global budget. In order to develop an efficient control measure, the contributions of soil nitrification and denitrification to N_2O emission from the maize field in the NCP are still needed to be disclosed.

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