



Nitrous oxide emissions from Chinese cropland fertilized with a range of slow-release nitrogen compounds

Jingyan Jiang^a, Zhenghua Hu^c, Wenjuan Sun^b, Yao Huang^{a,b,*}

^a College of Resources and Environmental Sciences, Nanjing Agricultural University, Nanjing, Jiangsu 210095, China

^b LAPC, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

^c Department of Environmental Science, Nanjing University of Information Sciences and Technology, Nanjing, Jiangsu 210044, China

ARTICLE INFO

Article history:

Received 20 May 2009

Received in revised form 27 September 2009

Accepted 29 September 2009

Available online 27 October 2009

Keywords:

N₂O emissions

Cropland

Coated nitrogen

Urea formaldehyde

Biochemical inhibitor

Precipitation

ABSTRACT

The consumption of synthetic nitrogen fertilizer in agriculture has increased over the past several decades and will continue to increase to meet the food and fibre demands of the growing global population, which will no doubt result in the release of additional N₂O into the atmosphere. A wise use of synthetic fertilizer N is important to mitigate N₂O emissions. Outdoor pot experiments during the winter wheat (*Triticum aestivum* L.) growing season and field experiments during the maize (*Zea mays* L.) growing seasons were undertaken from 2006 to 2008 at Nanjing in eastern China to evaluate the potential of a range of typical slow-release fertilizers to mitigate N₂O emissions. Five slow-release N fertilizers, including physically altered (Ca-Mg-P-coated urea, polymer-coated urea and sulfur-coated urea), chemically altered (urea formaldehyde) and biochemically inhibited (urea with dicyandiamide and hydroquinone) nitrogen were applied in this experiment. In comparison with commercial urea, the urea formaldehyde treatment reduced N₂O emissions by ~42% for the wheat growing season and 15–26% for the maize growing season, and the urea with dicyandiamide and hydroquinone treatment reduced N₂O emissions by 33–63% for the maize growing season. However, the treatments with Ca-Mg-P-coated urea, polymer-coated urea and sulfur-coated urea generally enhanced N₂O emissions in comparison to the emissions of the urea-treated fertilizer, especially when precipitation followed application. We conclude that the application of chemically altered or biochemically inhibited nitrogen fertilizers would have great potential to mitigate N₂O emissions, but the use of physically altered nitrogen fertilizers may have the opposite effect than desired.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

Climate change and global warming continue to be subject to considerable scientific debate and public concern. Nitrous oxide (N₂O) is an important trace gas that causes global warming and stratospheric ozone depletion. The concentration of atmospheric N₂O has increased 16% over the last 250 years at a rate of 0.25% year⁻¹ (IPCC, 2007). Furthermore, N₂O is about 300 times more potent than carbon dioxide (CO₂) in absorbing terrestrial thermal radiation in the troposphere and has a long residence time in the atmosphere (120 years) (IPCC, 2001). Agricultural soils account for approximately 42% of anthropogenic N₂O emissions (IPCC, 2007), and nitrogen fertilization is considered as a primary source of N₂O emissions from agricultural soils (Mosier et al., 1998; Mosier and Kroeze, 2000). Application of nitrogen fertilizer increased at a rate of 6–7% per year during the 1990s (Mosier, 2004), and the worldwide demand for nitrogen fertilizer is expected to increase at

an approximate annual rate of 1.4% from 2008 to 2012, an overall increase of 7.3 Tg. About 69% of this growth will take place in Asia (FAO, 2008).

China is now the world's largest consumer of synthetic N fertilizers. Consumption of N fertilizers in China has increased continuously since 1980. Synthetic N consumption increased to peak rates in 1998 and subsequently dropped slightly. More recently consumption of N fertilizers in China has again increased at an average rate of 0.33 Tg per year (National Bureau of Statistics, China, 2008). In 2007, the consumption of synthetic N fertilizer in China amounted to 23.0 Tg, about 23% of the total world amount (National Bureau of Statistics, China, 2008; FAO, 2008). Due to the decline of arable land area, the continuous population growth and the less efficient use of N fertilizer in China (FAO, 2008; Sun et al., 2008; Ma et al., 2009b), the use of synthetic nitrogen fertilizer will continue to increase for the foreseeable future in an effort to meet food demand. N₂O emissions from cropland in China in 1994 was estimated to be about 0.47 Tg, 57.8% of which originated from the application of synthetic nitrogen fertilizers (The People's Republic of China Initial National Communication on Climate Change, 1994). Xing and Yan (1999) also reported that the primary reason for the

* Corresponding author. Tel.: +86 25 84396406; fax: +86 25 84396286.
E-mail addresses: huangy@njau.edu.cn, huangy@mail.iap.ac.cn (Y. Huang).

rapid increase in N₂O emissions in China was the increase in the use of synthetic fertilizer, which accounted for 73.7% of the total emissions from soils in 1990. Consequently, it has become necessary to mitigate N₂O emission from the application of synthetic nitrogen (Zhu and Chen, 2002; Smith et al., 2008).

Nitrification and denitrification are the most important biological processes in the production of N₂O in soil (Firestone and Davidson, 1989). Controlling the mineral N supply is expected to be a useful method for reducing N₂O production. The type of N fertilizer and the application method affect N₂O emissions (Yan et al., 2001; Ma et al., 2009a). N₂O emissions can be significantly reduced when no-tillage is combined with a strategy that matches the N application rate and timing to the crop needs (Wagner-riddle et al., 2007). Additionally, to decrease N₂O emissions from N-fertilized soils, the band application of controlled-release N fertilizer is considered to be a good alternative to surface broadcasting (Hou and Tsuruta, 2003; Cheng et al., 2006).

Slow release N fertilizers (SRF) have been proposed as an alternative to conventional N fertilizer as they can increase the efficiency of N use to obtain high yield while reducing N loss through leaching and volatilization (Shoji et al., 1991; Mao et al., 2005). The global consumption of SRF was estimated at approximately 1.2 Tg in 2005 (Xu, 2006). Moreover, SRF have become a priority topic in the Chinese middle- and long-term science and technology development plan guidelines (2006–2007) (Xu, 2006). However, there have been contradictory observations of whether SRF can reduce N₂O emissions in various regions. Some studies reported that coated urea and urea with a nitrification inhibitor (DCD) significantly reduced N₂O emissions in comparison with conventional urea (Akiyama et al., 2000; Shoji et al., 2001; Pathak and Nedwell, 2001; Merino et al., 2002; Hou and Tsuruta, 2003; Cheng et al., 2006; Di et al., 2007). Others demonstrated that urea with a urease inhibitor, urea with a combination of urease and nitrification inhibitors (DCD), and a coated urea had limited impacts on N₂O emissions from intensive grassland (Dobbie and Smith, 2003a). Delgado and Mosier (1996) also reported that polyolefin coated urea (POCU) could reduce N₂O emissions compared to conventional urea in the first 21 days after fertilization, but emissions were higher from the POCU treatment during the following 60 days. The net N₂O emissions over 90 days showed no significant difference between POCU and conventional urea treatments. Some laboratory work demonstrated that using coated urea instead of easily decomposable urea did not reduce the total amount of N₂O emissions if the observation period was long enough, and that soil moisture influenced N₂O emission much more strongly than the form of urea (Hou et al., 2000). Moreover, the total N₂O emission from coated urea was significantly higher than calcium nitrate fertilizer (Akiyama and Tsuruta, 2002). Although many studies have been conducted to determine whether SRF could be an effective technique for reduction of N₂O emissions from fertilized soils, notable uncertainties remain because attempts to clarify N₂O emissions have been complicated by the variety of types of N fertilizer, a wide range of climate and field management practices, and inadequate knowledge of all the relevant factors.

Wheat and maize are the main crops in China, accounting for ~50% of the total sown area of grain crops. The main objective of this study was to study the effect of a range of commercially available slow-release urea based fertilizers on N₂O emissions from wheat and maize fields, and thereby gain information on the suitability of these to mitigate N₂O emissions.

2. Materials and methods

2.1. Description of the experiments

Outdoor pot experiments during the winter wheat growing season and field experiments during the maize growing season

were carried out from 2006 to 2008 at Nanjing Agricultural University Experimental Farm (32.0N, 118.8E). Soil was classified as anthrosol, consisting of 4% sand, 45% silt and 51% clay with an initial pH (H₂O) of 6.7. Total organic C and N were 13.1 and 1.1 g kg⁻¹, respectively. The bulk density of the soil was 1.15 g cm⁻³.

According to the mode of action, SRF can be generally classified into three types: physically altered, chemically altered and a biochemical type (Oertli, 1980; Shaviv, 2001). Physical alteration entails a change in the physical properties of the nitrogen fertilizer, such as coating or encapsulating urea in a membrane to control the rate of nutrient release (Oertli, 1980; Shaviv, 2001; Du et al., 2006). Chemical alteration refers to urea that is chemically altered to render a portion of its water insoluble, such as urea formaldehyde or isobutylidene diurea. In this case, the nutrients will be gradually released by microbial activity in the soil (Oertli, 1980; Shaviv, 2001). Biochemical alteration inhibits the soil microorganisms and enzymes from decomposing urea by adding nitrification inhibitors and urease inhibitors to the formulation, and it controls the release process of nitrogen fertilizer (Shoji et al., 2001; Yan et al., 2008). According to the above classification, we selected five slow-release N fertilizers and a commercial urea (U) in this experiment. No N fertilizer (CK) was employed as a control. As shown in Table 1, the codes of U-CaMg, U-P and U-S represent three physically altered coated nitrogen fertilizers. U-CaMg is a fertilizer made from urea coated with calcium magnesium phosphate (Ca-Mg-P) fertilizer, U-P is a polymer-coated urea, and U-S is a sulfur-coated urea, manufactured by coating hot urea with molten sulfur. The total nitrogen of the three coated fertilizers is released over three months at a constant temperature of 25 °C at a sigmoidal rate. The other codes of UF and U + DCD + HQ represent chemically and biochemically altered formulations, respectively. UF stands for urea formaldehyde, the chemically altered fertilizer, and U + DCD + HQ consists of urea with urease inhibitor hydroquinone (HQ) and nitrification inhibitor dicyandiamide (DCD) with a commercial base. Based on conventional fertilization practices in this region, the total amounts of nitrogen applied in the wheat and maize growing seasons were 250 and 300 kg N ha⁻¹, respectively. All treatments received 250 kg P₂O₅-K₂O ha⁻¹ in the winter wheat growing season and 300 kg P₂O₅-K₂O ha⁻¹ in the maize growing season as basal fertilizer in the forms of KH₂PO₄ and K₂SO₄, respectively.

In the 2006–2007 winter wheat growing season, pots made of pottery clay, 22 cm high with an inside diameter of 20 cm, were employed. The bottom of the pot contained a 2 cm diameter hole to percolate the rainfall. Five kilograms of air-dried soil were placed in each pot before crop sowing, yielding a soil depth of approximately 18 cm. To reduce the potential unevenness of temperature distribution among pots, about four-fifths of the height of the pot was buried in soil. Three pots for each treatment were employed as replicates. Wheat seeds (cv. NINGMAI#13) were sown on 15 November 2006 and emergence occurred approximately 10 days later. Ten seedlings per pot were determined two weeks after emergence. Plant heading occurred on 4 April and plants were harvested on 13 May 2007. Based on the local agricultural practice, the SRF were all broadcast applied at the rate of 250 kg N ha⁻¹ on 15 November 2006, while urea alone was applied in 3 split applications of 75 kg N ha⁻¹, 112.5 kg N ha⁻¹ and 62.5 kg N ha⁻¹ on 15 November 2006, 21 February and 20 March 2007, respectively.

Field microplot (6 m²) experiments were conducted in the 2007–2008 maize growing seasons, with a 3-replicate randomized complete block design. Maize seeds were directly sown into each plot on 21 June in the 2007 and 2008 growing seasons. Maize cv. NONGXIN was planted in 2007. Because the seeds of cv. NONGXIN were not available, we planted maize cv. SU NUO# 1 in 2008. The

Table 1
Description of the experiments.

Code	Fertilizer type	Manufacture	Application rate	
			Winter wheat growing season in 2006–2007	Maize growing seasons in 2007 and 2008
U	Urea	Jiangsu Hengsheng Fertilizer CO. LTD	250 kg N ha ⁻¹ , broadcast at planting (30%), turning green (45%) and elongation stages (25%)	300 kg N ha ⁻¹ , broadcast at plant emergence (40%) and ear sprouting (60%)
U-CaMg	Ca-Mg-P-coated urea	Zhengzhou University, China	250 kg N ha ⁻¹ , broadcast at planting (100%)	300 kg N ha ⁻¹ , broadcast at plant emergence (100%)
U-P	Polymer-coated urea	Shanghai Hanfeng Group, China	Same as that in U-CaMg	Same as that in U-CaMg
U-S	Sulfur-coated urea	Shanghai Hanfeng Group, China	Same as that in U-CaMg	Same as that in U-CaMg
UF	Urea formaldehyde	Shanghai Hanfeng Group, China	Same as that in U-CaMg	Same as that in U-CaMg
U+DCD+HQ	Urea with DCD and HQ	Shenyang Zhongke Feiliao CO. LTD	–	300 kg N ha ⁻¹ , broadcast at plant emergence (100%) with 32.6 kg dicyandiamide and 1.96 kg hydroquinone per hectare
CK			No fertilizer applied	No fertilizer applied ^a

^a Only in 2008 growing season.

developmental stages of these two cultivars were similar in the two-year experiment. Plant emergence and tasseling occurred on 24 June and 27 July in both years, respectively. Maize was harvested on 9 September 2007 and on 6 September 2008. The SRF were broadcast applied with a rate of 300 kg N ha⁻¹ at plant emergence. Urea was applied in 2 split applications, 120 kg N ha⁻¹ at plant emergence and 180 kg N ha⁻¹ during the tasseling stage, respectively. Additional field management was carried out following the local agricultural practice, and no irrigation was practiced during the growing seasons. To make measurements of N₂O emissions, plastic PVC-frame bases (50 cm × 50 cm) with grooves were inserted into a depth of 8 cm randomly in the center of each plot after plant emergence and remained fixed throughout the study period. Two seedlings were included in the frame base.

2.2. Measurements and statistical analysis

N₂O measurements were made between local time 08:00 and 11:00 h, by taking samples of the headspace gas in an open-bottomed chamber. In the 2006–2007 wheat growing season, the open-bottom cylindrical chamber made of nontransparent PVC was 100 cm high and insulated by a layer of sponge and aluminum foil to minimize temperature changes during the period of sampling (Huang et al., 2002). A cubic stainless steel chamber (50 cm × 50 cm × 50 cm), equipped with a circulating fan inside to ensure complete gas mixing, was used in the maize growing seasons. While taking gas samples, the chamber was placed over the vegetation with the rim of the chamber fitted into the groove of the pot (wheat season) or the groove of the frame base (maize seasons). Water was filled in the grooves to ensure gas tightness (Zou et al., 2005). When the maize crop was higher than 50 cm, a hollow steel frame (50 cm × 50 cm × 50 cm) with groove was placed to the base frame to increase the chamber's height. The chamber was removed after sampling.

N₂O flux was measured from plant sowing to harvest. In the 2006–2007 wheat growing season, N₂O measurements were generally taken once every two days over two weeks after fertilization, and once a week in other periods. Due to a problem in the gas chromatography, we did not get N₂O fluxes from 22 April to 13 May 2007. During the 2007 and 2008 maize growing seasons, the flux measurements were generally taken once a day over one week after fertilization, and twice a week in other periods. Adjustments in sampling dates and frequency were made when heavy rainfall occurred.

N₂O mixing ratios were obtained by gas chromatography (Agilent 4890D) fitted with an electron capture detector (Wang

and Wang, 2003). The columns were packed with PORAPAK Q, and the carrier gas was 5% methane in argon. The emission was determined from the slope of the change in the mixing ratio over time for the three samples taken at 0, 10 and 20 min after chamber closure. Sample sets that did not yield a linear regression value of r^2 greater than 0.90 were rejected. Average flux and standard error of N₂O emissions were calculated from three replicates. Seasonal amounts of N₂O emissions (E_{N_2O}) were sequentially accumulated from the emissions between every two adjacent days of the measurements by

$$E_{N_2O} = \sum_{i=1}^n 0.5 \times (F_i + F_{i+1}) \times (t_{i+1} - t_i) \times 24 \quad (1)$$

where F is N₂O flux ($\mu\text{g m}^{-2} \text{h}^{-1}$). The subscript i represents the i th measurement. The term of $(t_{i+1} - t_i)$ denotes the days between two adjacent days of the measurements. Finally, n is the total times of the measurements.

Using mercury thermometers, air temperature inside the chamber and soil temperature at 5 cm depth were measured while taking gas samples. Data of daily precipitation were obtained from the meteorological station of Nanjing City. Soil moisture (volumetric water content) was measured by MPM-160 (TDR), made by Jiangsu Academy of Agricultural Sciences, China. Soil water content (v/v) was then expressed as WFPS (water filled pore space) values according to bulk density.

Aboveground biomass at the end of crop growing season was measured as dry weight in all experiments. For the pot experiment, all the wheat plants in the pot were harvested and kept separately for each pot as replicates. With respect to the field experiment, 10 stems of maize plants per treatment were randomly sampled as replicates. The plants were cleaned with water and then oven dried to constant weight at 90 °C.

Statistical analysis was conducted using SPSS 13.0 (SPSS Inc., 2004). When there was a significant treatment effect, means were compared using the Duncan Multiple Range test (DMRT).

3. Results

3.1. Seasonal variation in N₂O emission

3.1.1. 2006–2007 winter wheat growing season

The different rates of N release characteristic of each fertilizer after application resulted in different seasonal N₂O emissions between the several fertilizer types. As shown in Fig. 1a, a wide variation in seasonal N₂O emissions among different fertilizer

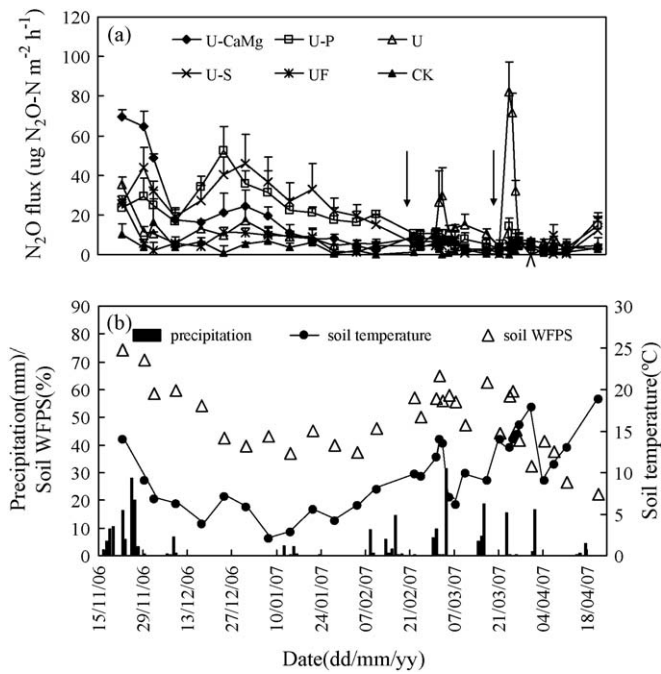


Fig. 1. Seasonal variations in N₂O emissions and environmental factors during the 2006–2007 winter wheat growing season: (a) N₂O emissions; (b) environmental factors. The vertical bars are standard errors from three replicates. Arrows denote the date of topdressing in the urea treatment.

treatments was observed during the winter wheat growing season. The N release characteristics of each fertilizer depend on soil temperature, soil moisture and soil microbial activity. Soil temperature fluctuated sharply from 2.0 to 18.8 °C and averaged 9.4 ± 4.8 °C during the winter wheat growing season. A total of 46 precipitation events occurred during the sampling period. It rained for more than one week after basal fertilization and then there was a drought lasting several days. Due to the temporal variation of precipitation, soil WFPS varied sharply over the whole season between 22.1%–74.2% and averaging 48.9% (Fig. 1b). Moreover, there were obvious emission peaks for the coated treatments (U-CaMg, U-P and U-S) about 60 days after basal fertilization. The highest values of N₂O fluxes for U-CaMg ($69.7 \pm 3.3 \mu\text{g N m}^{-2} \text{h}^{-1}$), U-P ($52.3 \pm 12.4 \mu\text{g N m}^{-2} \text{h}^{-1}$) and U-S ($46.2 \pm 14.3 \mu\text{g N m}^{-2} \text{h}^{-1}$) occurred on 22 November, 24 December and 31 December 2006, respectively. The UF treatment had lower N₂O emissions after fertilization in the 2006–2007 winter wheat growing season compared with the other fertilizer treatments, the highest value of N₂O flux was only $27.4 \pm 0.40 \mu\text{g N m}^{-2} \text{h}^{-1}$ (Fig. 1a). For the U treatment, N₂O emissions mainly occurred over 5–10 days after urea fertilization. The highest value of N₂O flux for the U treatment was $82.1 \pm 15.3 \mu\text{g N m}^{-2} \text{h}^{-1}$, which occurred on 24 March 2007 after the second topdressing. In addition, N₂O emissions in the CK treatment were consistently low and ranged from 0 to $16.5 \mu\text{g N m}^{-2} \text{h}^{-1}$ during the experimental period (Fig. 1a).

3.1.2. 2007 and 2008 maize growing seasons

Even though the same soil and agricultural management regimes were used in 2007 and 2008, the seasonal variation patterns of N₂O emissions were quite different between the two years (Fig. 2a and c). The soil temperature remained relatively stable during the maize growing season, ranging from 22.4 to 31.2 °C (averaging 27.2 °C) during the 2007 maize growing season and from 21.0 to 29.0 °C (averaging 26.9 °C) in the 2008 maize growing season (Fig. 2b and d). The precipitation events differed for each growing season, thus soil WFPS varied sharply, ranging from 31.6% to 64.9% in 2007 and 24.4% to 66.2% in 2008. The mean soil WFPS for 2007 (48.9%) was higher

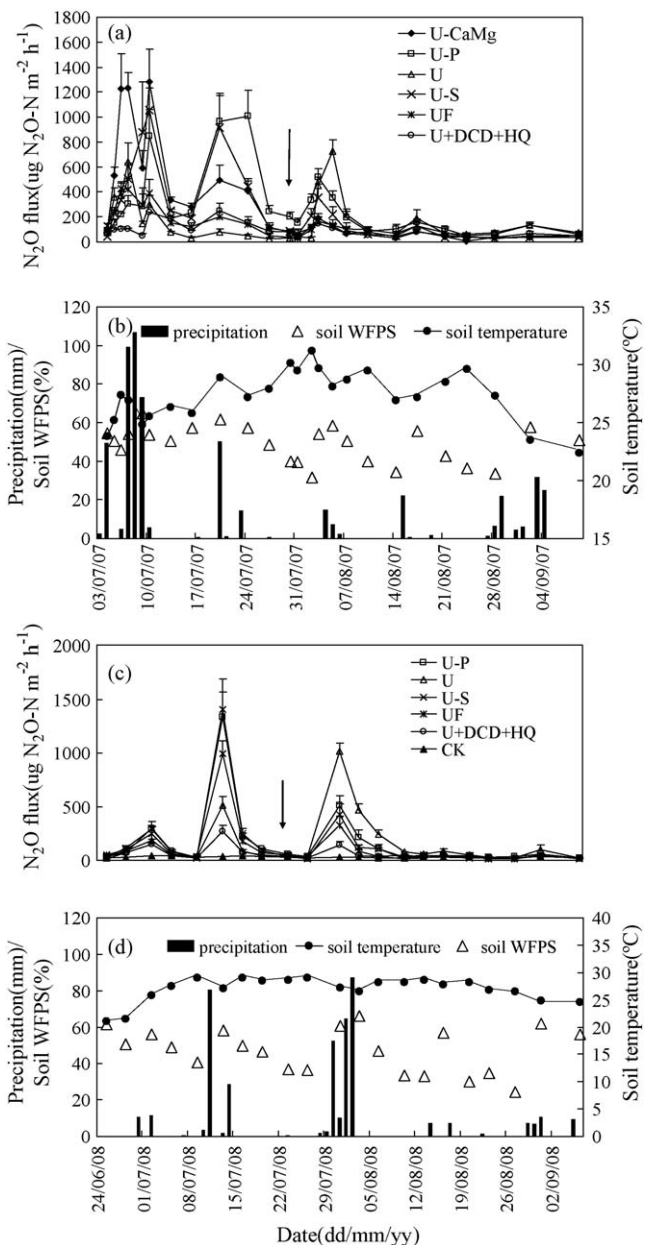


Fig. 2. Seasonal variations in N₂O emissions and environmental factors during the 2007 and 2008 maize growing seasons: (a) and (c) N₂O emissions; (b) and (d) environmental factors. The vertical bars are standard errors from three replicates. Arrows indicate the date of topdressing in the urea treatment.

than that for 2008 (47.1%). The continuous precipitation over about one week followed basal fertilization in 2007, while an extended drought was experienced in the 2008 maize growing season over the same period. Higher emissions from the physically coated treatments occurred during the period of 18 days after basal application in 2007 (Fig. 2a). As compared with the 2006–2007 winter wheat growing season, the similar precipitation events after basal fertilization in the 2007 maize growing season resulted in similar seasonal variation patterns of N₂O emissions. The higher N₂O emissions for U-CaMg treatment (about $1200 \mu\text{g N m}^{-2} \text{h}^{-1}$) occurred on just the third day (6 July 2007) after application, and these higher emissions persisted for the following four days. The highest values of N₂O flux for the other coated fertilizer treatments, U-S ($1058.1 \pm 171.5 \mu\text{g N m}^{-2} \text{h}^{-1}$) and U-P ($1006.6 \pm 209.9 \mu\text{g N m}^{-2} \text{h}^{-1}$), occurred on the 7th day and 21st day after basal application, respectively. UF and U + DCD + HQ treatments almost

Table 2

Total amount of precipitation and daily soil temperature at 5 cm depth during the early and late growth stages of wheat and maize crops.

Crop	Stage	Period (dd/mm/yy–dd/mm/yy)	Days of the period	Precipitation (mm)	Soil temperature (°C)	
					Minimum/Maximum	Average
Winter wheat (2006–2007)	Early	15/11/06–10/02/07	87	128.0	2.0/14.0	6.2
	Late	22/02/07–21/04/07	70	119.0	6.1/18.8	12.2
Maize (2007)	Early	03/07/07–10/08/07	38	428.0	23.8/31.2	27.5
	Late	11/08/07–09/09/07	30	120.0	22.4/29.6	26.9
Maize (2008)	Early	24/06/08–10/08/08	47	355.1	21.0/29.0	26.9
	Late	11/08/08–06/09/08	27	48.9	24.5/28.6	26.7

always maintained lower N₂O emissions compared with the other treatments, and the highest value of N₂O flux was only 426.6 ± 45.3 μg N m⁻² h⁻¹ for UF and 247.5 ± 61.1 μg N m⁻² h⁻¹ for U + DCD + HQ treatments. Additionally, for the U treatment, N₂O emissions mainly occurred over 4–5 days following urea fertilization. The highest value of N₂O flux was 723.3 ± 95.5 μg N m⁻² h⁻¹, which occurred on 5 August 2007 following the second topdressing (Fig. 2a).

In comparison with the 2007 maize growing season, lower N₂O emissions were observed during the 18 days following basal application in 2008 (Fig. 2c). Since two-thirds of the total precipitation was relatively concentrated in two periods (11–14 July and 30 July–2 August) and since little rain fell during most of the remaining period of the 2008 season (Fig. 2d), the seasonal patterns of N₂O emissions from different fertilizer treatments in 2008 were similar across treatments. Except for the CK treatment, all of the fertilizer treatments had two obvious pulse emission peaks that occurred on 13 July and 31 July, when soil WFPS was 58.3% and 60.8%, respectively. The highest values of N₂O fluxes of 1329.9 ± 240.7 μg N m⁻² h⁻¹ for U–P treatment, 1405.4 ± 282.4 μg N m⁻² h⁻¹ for U–S treatment and 991.9 ± 120.1 μg N m⁻² h⁻¹ for UF treatment occurred on the same day (13 July 2008). Moreover, U + DCD + HQ treatment always maintained lower N₂O emissions compared with the other fertilizer treatments, ranging from 12.5 to 269.6 μg N m⁻² h⁻¹ over the entire growing season. For U treatment, the highest N₂O flux of 1013.2 ± 77.3 μg N m⁻² h⁻¹ occurred on 31 July 2008, after

the second topdressing (Fig. 2c). Moreover, the CK treatment had no obvious peak emission and the average flux was 29.2 ± 7.1 μg N m⁻² h⁻¹ over the 2008 maize growing season.

3.2. Seasonal total of N₂O emission

We divided the winter wheat and maize growth periods into 'early' and 'late' growth stages (Table 2). The early stages of winter wheat and maize development are defined as from emergence to over-wintering and from emergence to tasseling, respectively. The late stages of winter wheat and maize development are defined from turning green to heading and from silking to maturity, respectively. The early stage was the peak period for application of SRF, and the majority of N₂O was emitted during this stage, with N₂O emission rates remaining small over the late stage (Figs. 1a and 2a and c). As Table 2 shows, environmental factors differed during the early and late stages in different crop growing seasons. The average soil temperatures in the early winter wheat stage were lower than in the late stage, while the temperature was almost similar between the early and late stages of the 2007 and 2008 maize growing seasons. The total precipitation was 247 mm in the 2006–2007 winter wheat growing season, 548 mm in 2007 and 404 mm during the 2008 maize growing season. 78–89% of the total precipitation was concentrated in the early stages during the maize growing seasons, while the precipitation was relatively similar between the early and late stages during the winter wheat

Table 3N₂O emissions during the two growth stages and during the entire growing season fertilized with conventional urea and a range of slow release urea based fertilizers.

Code	N ₂ O emissions (kg N ₂ O–N ha ⁻¹) ^a			Relative to U (%)
	Early stage	Late stage	Entire season	
Winter wheat growing season in 2006–2007				
U	0.23 ± 0.01b	0.20 ± 0.03a	0.43 ± 0.03a	100
U–CaMg	0.48 ± 0.08a	0.07 ± 0.01c	0.55 ± 0.09a	128
U–P	0.54 ± 0.09a	0.14 ± 0.02b	0.68 ± 0.11a	158
U–S	0.60 ± 0.11a	0.08 ± 0.01c	0.69 ± 0.11a	160
UF	0.17 ± 0.01b	0.08 ± 0.01c	0.25 ± 0.02b	58
CK	0.10 ± 0.02c	0.04 ± 0.01d	0.14 ± 0.03c	33
Maize growing season in 2007				
U	1.55 ± 0.26b	0.71 ± 0.08a	2.26 ± 0.34b	100
U–CaMg	3.38 ± 0.09a	0.32 ± 0.05b	3.70 ± 0.05a	164
U–P	3.79 ± 0.43a	0.70 ± 0.02a	4.49 ± 0.45a	199
U–S	3.27 ± 0.44a	0.36 ± 0.08b	3.63 ± 0.39a	161
UF	1.48 ± 0.29b	0.45 ± 0.09b	1.93 ± 0.34b	85
U + DCD + HQ	1.14 ± 0.14b	0.38 ± 0.09b	1.52 ± 0.22b	67
Maize growing season in 2008				
U	2.46 ± 0.06a	0.36 ± 0.10a	2.82 ± 0.11a	100
U–P	2.62 ± 0.20a	0.23 ± 0.02ab	2.85 ± 0.18a	101
U–S	2.53 ± 0.36a	0.18 ± 0.03b	2.71 ± 0.35ab	96
UF	1.91 ± 0.25a	0.19 ± 0.02b	2.10 ± 0.24b	74
U + DCD + HQ	0.82 ± 0.06b	0.22 ± 0.02ab	1.04 ± 0.06c	37
CK	0.35 ± 0.05c	0.17 ± 0.04b	0.52 ± 0.07d	18

^a N₂O emissions are shown as arithmetic means with standard errors (n = 3); different small letters in a column indicate significant differences between treatments at p < 0.05.

growing season. Moreover, the cumulative precipitation in the 2008 maize growing season was less (76%) than that of the 2007 maize growing season.

Table 3 shows the cumulative N₂O emissions from treatments during the early and late stages and during the entire growing season. During the winter wheat growing season, more than 80% of the total N₂O emissions from U-CaMg, U-P and U-S and more than 66.0% of the total N₂O emissions from UF, occurred in the early stage. Among all fertilizer treatments, the highest emission came from U-S with a value of 0.69 kg N ha⁻¹, and the lowest was from UF with a value of 0.25 kg N ha⁻¹. During the 2007 and 2008 maize growing seasons, more than 85% of the total N₂O emissions from the coated fertilizers (U-CaMg, U-P and U-S) occurred in the early stage, and about 75% of the total N₂O emissions from UF and U + DCD + HQ were emitted in this stage. The highest emissions came from the U-P treatment were 4.49 kg N ha⁻¹ for 2007 and 2.85 kg N ha⁻¹ for 2008, respectively. The lowest emissions in each year were from U + DCD + HQ treatments, with a value of 1.52 kg N ha⁻¹ for 2007 and 1.04 kg N ha⁻¹ for 2008. In each crop growing season, there was an approximately three-fold difference between the highest and lowest N₂O emissions among all fertilizer treatments.

As shown in Table 3, although some SRF treatments did not differ significantly in comparison with U, the average cumulative N₂O emissions from different treatments followed the order of U-S > U-P > U-CaMg > U > UF > CK for the 2006–2007 wheat season, U-P > U-CaMg > U-S > U > UF > U + DCD + HQ for the 2007 maize season and U-P > U > U-S > UF > U + DCD + HQ > CK for the 2008 maize season, respectively. N₂O emissions from the coated treatments (U-CaMg, U-P and U-S) were 1.28–1.60 and 1.61–1.99 times higher than those from urea treatment in the 2006–2007 wheat season and in the 2007 maize season, respectively. In the 2008 maize season, N₂O emissions from the coated and urea treatments were almost identical. The chemically altered fertilizer (UF) decreased N₂O emissions over all three cropping seasons, with a reduction of 42% for wheat in 2006–07 and 15% and 26% for maize in 2007 and 2008, respectively. Compared to the chemically altered fertilizer, application of the biochemical fertilizer emitted much less N₂O during maize growing seasons, and N₂O reductions were 33% in 2007 and 63% in 2008. Overall, the seasonal average N₂O emissions from the chemically altered and biochemically inhibited fertilizers were lower than those from urea during both the wheat and maize seasons. However, the average N₂O emissions from the coated fertilizer treatments were higher than the urea treatment, especially when relatively long periods of precipitation followed fertilizer application.

3.3. Crop biomass

As shown in Table 4, the average dry mass of different treatments followed the order of U-P > U-S > U > U-

CaMg > UF > CK for the wheat season. However, the order for the maize crop did not agree well with that for the wheat crop. The biomass of U-P in the 2007 maize season was obviously lower than the biomass for the other treatments, likely due to the presence of insects in this season. The UF treatment led to a reduction in the dry mass of the wheat crop in comparison with the U treatment. While the UF and U + DCD + HQ treatments resulted in an improvement of maize crop biomass, these increases were not statistically significant at $p < 0.05$ (not including UF treatment in the 2008 maize growing season, which significantly promoted maize biomass). Moreover, the dry mass of each treatment in 2007 was only half of that in 2008. The reason was likely that the time of basal application was late and that there were serious insect problems in 2007 or perhaps the difference in corn variety.

4. Discussion

4.1. Uncertainties of the N₂O measurements

Seasonal variation in N₂O flux is generally related to the timing of fertilization, soil moisture and temperature and climatic parameters (Zheng et al., 2000; Flechard et al., 2007; Jantalia et al., 2008; Scheer et al., 2008). The uncertainty of the cumulative emissions [Eq. (1)] also depends on the pattern of fertilization and precipitation events. Using infrequent sampling may miss a short peak of emissions and thus lead to a strong underestimation of the cumulative emissions, whereas the sampling frequency may be less uncertain when such emission peaks are absent. A recent study by Parkin (2008) indicated that the chamber-based N₂O–N flux estimates were within ±10% of the expected value at relatively frequent sampling intensities (i.e., once every 3 d). Even up to sampling intervals of once every 8 d, most of the possible cumulative N₂O–N flux estimates were within ±20% of the “true” value (Parkin, 2008). Nevertheless, the variances associated with cumulative N₂O flux estimates increased as sampling interval increased from 7 to 21 d (Parkin, 2008). We had sampling intervals of 1–7 d in this study. The uncertainties associated with cumulative N₂O flux estimates may be within ±20% according to Parkin (2008).

4.2. Factors regulating N₂O emissions under the application of different fertilizers

Previous studies addressed the effects of environmental factors on the emission of N₂O from agricultural soils. Soil temperature, moisture and fertilizer management (e.g., rate, type and application mode) are considered as the main factors that dominate N₂O emissions (Bouwman, 1996; Skiba et al., 1998; Dobbie et al., 1999; Skiba and Smith, 2000; Dobbie and Smith, 2003b; Cheng et al., 2004; Ding et al., 2007; Toma et al., 2007). In general, the range of appropriate temperatures for most nitrifying bacteria activities is 20–35 °C (Chen, 1989), and the primary mechanism of N₂O emission is nitrification for WFPS levels of 35–60% (Bateman and

Table 4
Dry weight of the harvested aboveground biomass of wheat and maize crops^a.

Code	Winter wheat (2006–2007)		Maize (2007)		Maize (2008)	
	Dry mass (g pot ⁻¹)	Relative to U (%)	Dry mass (g plant ⁻¹)	Relative to U (%)	Dry mass (g plant ⁻¹)	Relative to U (%)
U	37.6 ± 2.0b	100	51.3 ± 6.3ab	100	101.7 ± 10.1b	100
U-CaMg	37.5 ± 1.3b	100	46.0 ± 5.9ab	90	–	–
U-P	53.2 ± 4.5a	142	34.0 ± 6.0b	66	131.1 ± 11.2ab	129
U-S	50.3 ± 2.5a	134	64.2 ± 13.0a	125	136.1 ± 12.5ab	134
UF	29.7 ± 0.8c	79	55.2 ± 5.1ab	108	146.1 ± 11.5a	144
U + DCD + HQ	–	–	57.2 ± 14.8a	112	128.7 ± 13.1ab	126
CK	12.4 ± 0.9d	33	–	–	69.0 ± 3.9c	68

^a Data are shown as arithmetic means with standard error. $n = 3$ for pot experiment, i.e. three pots per treatment; $n = 10$ for field experiments, i.e. ten individual maize plants per treatment were sampled for dry mass determination. Different small letters in a column indicate significant differences between treatments at $p < 0.05$.

Baggs, 2005). Low temperatures significantly reduce the nitrification rates (Goodroad and Keeney, 1984). Soil temperature during winter wheat growing periods ranged from 2.0 to 18.8 °C, which is suboptimal for N₂O production (Table 2). Therefore, N₂O emissions during the wheat growing season mainly depended on soil temperature rather than on WFPS. This is one reason why no higher N₂O emission peak emerged and why the cumulative N₂O emissions from different treatments in the winter wheat growing season were far lower (averaged only 15%) than those in the maize growing season (Table 3). On the contrary, the soil temperature, ranging from 21.0–31.2 °C over the maize growing season, was not the major limiting factor of N₂O production. N₂O emission was greatly affected by precipitation and hence soil moisture. Due to no significant difference in soil moisture observed between different treatments ($p > 0.1$), the data of soil WFPS are shown as arithmetic means (Figs. 1b and 2b and d). The results of this study show that the optimum WFPS for high N₂O emission was at 50–65% in the field condition (Fig. 2). This proved similar to results reported by McTaggart and Tsuruta (2003), who found N₂O emissions from an andosol to be higher at a WFPS of 55% than at 70–80%. Our results agree with a previous study at the North China Plain showing that N₂O emission was greatly affected by soil moisture during the maize growing season and by soil temperature during the wheat growing season (Ding et al., 2007).

With the exception of conventional urea and urea formaldehyde, the seasonal total N₂O emissions from slow-release fertilizer treatments in 2008 were generally lower than the totals in the 2007 maize growing season for the same soil and agricultural management (Table 3). Since the soil temperatures were similar for 50 days after basal application (27.7 ± 1.9 °C in 2007 and 27.1 ± 2.5 °C in 2008), the precipitation seems to be a potential source for the difference in N₂O emissions between the two maize growing seasons. The relationship between the cumulative N₂O emissions and precipitation every 10 days after basal application, in the 2007 and 2008 maize seasons, was further analyzed (Fig. 3). The $\Delta\sum\text{N}_2\text{O}$ emission in Fig. 3 is defined by the difference obtained by subtracting the total N₂O emission per 10 days after basal application in 2008 from that in 2007, and $\Delta\sum\text{precipitation}$ refers to the resulting cumulative precipitation per 10 days after basal application in 2008 subtracted from that in 2007. Fig. 3 suggests that compared to 2008, the precipitation over a 50-day period after basal fertilization in 2007 was much higher over the first 10-day period, lower in the second and fourth 10-day periods and comparable for the third and fifth periods. The higher precipitation during the first 10 days after basal application in 2007 resulted in higher N₂O emissions for different treatments (Fig. 3). Although the precipitation was lower in the following two 10-day periods in 2007, the U-P treatment still emitted higher N₂O than was emitted in 2008, while the U and UF treatments emitted lower N₂O. Compared to 2008, the U + DCD + HQ treatment of 2007 slightly improved N₂O emissions during the 50 days after

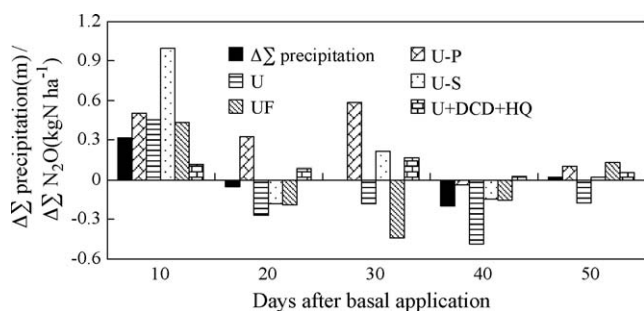


Fig. 3. Relationship between N₂O emissions and precipitation during different stages after basal application. $\Delta\sum\text{N}_2\text{O}$ is the total N₂O emissions per 10 days after basal application of 2007 minus that in 2008, and $\Delta\sum\text{precipitation}$ is the cumulative precipitation per 10 days after basal application of 2007 minus that in 2008.

application, which indicates that the precipitation had no obvious effect on N₂O emissions for the U + DCD + HQ treatment. The accumulated N₂O emissions per 10 days from the U-S treatment were positively correlated with the precipitation during this stage ($R^2 = 0.871$, $p < 0.05$). This shows that N₂O emissions from the U-S increased when the total seasonal precipitation increased. The nitrogen release rate of the coated fertilizer application is dependent on soil moisture and on the thickness or the weight of the coating (Oertli, 1980; Shaviv, 2001; Du et al., 2006). This study indicates that N₂O emissions from the coated and urea fertilizers were easily affected by the heavy precipitation event followed by basal fertilization. This agreed well with Dobbie and Smith's work (2003a), which showed that there was a greater response of N₂O emissions to precipitation around the time of fertilizer application.

4.3. Influence of fertilizer types on N₂O emission

For all three crop seasons, N₂O emissions from UF were generally lower than those from the U treatment, especially during 2006–2007 winter wheat and 2008 maize seasons, in which the UF treatment significantly reduced N₂O emissions by 42% and 26%, respectively (Table 3). In addition, the application of urea with HQ and DCD reduced N₂O emissions by 33% in 2007 and by 63% in the 2008 maize season compared to the urea treatment, despite the variation in precipitation between 2007 and 2008 (Tables 2 and 3). Our results agreed with previous studies showing that the application of urea in combination with HQ plus DCD was effective in reducing N₂O emissions from dryland cropping systems (Akiyama et al., 2000; Boeckx et al., 2005; Jumadi et al., 2008). However, the application of the coated fertilizer had higher direct N₂O emissions compared to the conventional urea for all three crop seasons (Table 3), especially in 2006–07 winter wheat and 2007 maize seasons, when precipitation events occurred following basal application. The increase rate ranged from 28% to 60% in the 2006–2007 winter wheat growing season and 61% to 99% in the 2007 maize growing season. This is similar to previous reports that documented using coated urea instead of easily decomposable urea did not reduce the total amount of N₂O emissions if the observation period was long enough (Delgado and Mosier, 1996; Hou et al., 2000; Dobbie and Smith, 2003a). Since N₂O emissions from the coated urea were more easily affected by soil moisture, and some reports that the coated urea could significantly reduce N₂O emissions were opposite to this result (Akiyama et al., 2000; Cheng et al., 2006), more research covering several years is still needed to verify this observation.

Using the definition by IPCC (2006), we calculated the N₂O emission factor (EF) by $EF = (E - E_0)/N \times 100\%$. Here, E and E_0 represent N₂O–N emission from plots with and without N fertilizer application, respectively. N is the total amount of N application over an entire growing season. The calculation suggested that EF for the 2006–2007 winter wheat growing season was 0.12%, 0.16%, 0.22%, 0.22% and 0.04% in the U, U-CaMg, U-P, U-S and UF treatments, respectively. These values are lower than the current default emission factor of 1.00% (IPCC, 2006) but are comparable with the values of 0.16–0.18% observed in the North China Plain (Ding et al., 2007), with the exception of UF treatment. Due to a lack of measurement in the non-fertilized plots in the 2007 maize growing season, we used N₂O emission of 0.52 kg N₂O–N ha⁻¹ in 2008 CK plots (Table 3) to calculate the EF for the maize growing season. The average values of EF over the two-year experiment were estimated to be 0.67%, 1.05%, 0.88%, 0.50% and 0.25% in U, U-P, U-S, UF and U + DCD + HQ treatments, respectively. Clearly, the application of urea formaldehyde or urea with HQ and DCD reduced the N₂O emission factor, while the application of physically altered coated nitrogen fertilizers (U-P, U-S) increased

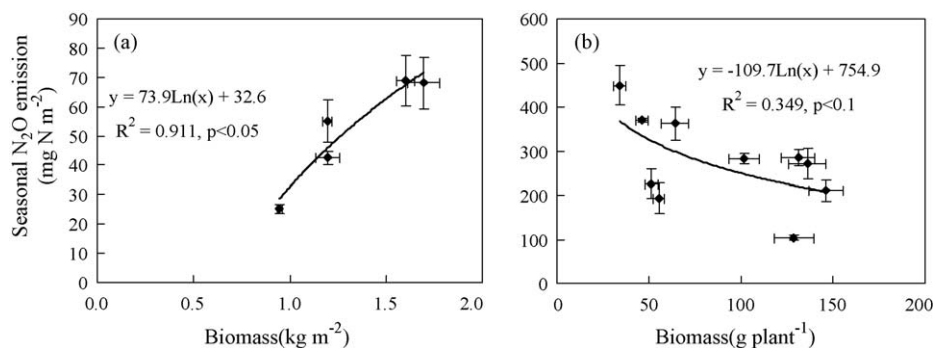


Fig. 4. Correlation of seasonal N_2O emission to the aboveground biomass: (a) 2006–2007 winter wheat growing season; (b) 2007 and 2008 maize growing seasons. Error bars represent standard errors.

the emission factor compared to the urea application in maize growing season.

4.4. N_2O mitigation, crop biomass production and nitrogen loss

A recent study indicated that the seasonal N_2O emission from a 3-year field experiment conducted in Southeast China correlated positively with aboveground biomass of winter wheat at the end of the growing season (Chen et al., 2008). A similar relationship between seasonal N_2O emission and aboveground biomass was also found in this study (Fig. 4a). Although urea formaldehyde could mitigate N_2O emissions from wheat field (Table 3), it reduced wheat biomass (Table 4). Thus, the addition of urea formaldehyde in wheat field may not be a mitigation option. Nevertheless, it is too early to evaluate the function of urea formaldehyde in N_2O mitigation because we only have a one season experiment. A multi-year experiment should be required to quantify the role of urea formaldehyde in N_2O mitigation and wheat production.

In contrast, the two-year experiment suggested a negative relationship between seasonal N_2O emissions and aboveground biomass of maize (Fig. 4b). The broadcasting of 300 kg N ha^{-1} in this study might be near or even beyond the maximum of the N-fertilization growth dependence. Subsequently, decreasing biomass is coupled with higher N_2O emissions. Although the difference in the photosynthetic pathways and N-use efficiency among C_4 plants (e.g., maize) and C_3 plants (e.g., wheat) has been well recognized (Hopkins and Huner, 2008), we simply don't know why the response of N_2O emissions to crop biomass production is opposite between winter wheat and maize.

It is noteworthy that the application of urea formaldehyde or urea with DCD + HQ in maize plots reduced N_2O emission significantly (Table 3) but did not decrease maize biomass (Table 4). The average rates of N_2O emission from the treatments of U, UF and U + DCD + HQ were 2.54 ± 0.20 , 2.02 ± 0.19 and $1.28 \pm 0.15 \text{ kg N}_2\text{O-N ha}^{-1}$ when 300 kg N ha^{-1} was applied in the two-year experiment. The N_2O emission was reduced by 0.52 and $1.26 \text{ kg N}_2\text{O-N ha}^{-1}$ for treatments of UF and U + DCD + HQ, respectively. The emission factor reduced accordingly by 0.17% and 0.42%. The maize-cultivated area in China is 29.48 million ha, accounting for approximately 19% of the total sown area (National Bureau of Statistics, China, 2008). Assuming that the urea application rate ranges from 200 to 300 kg N ha^{-1} in maize fields (Ju et al., 2009), the N_2O mitigation potential was estimated to be 10–15 Gg $\text{N}_2\text{O-N season}^{-1}$ with the application of urea formaldehyde and 25–37 Gg $\text{N}_2\text{O-N season}^{-1}$ with the addition of DCD + HQ. According to Lu et al. (2006), the annual amount of synthetic fertilizer-induced N_2O emission in China was 198.89 Gg $\text{N}_2\text{O-N}$ in the late 1990s. In this case, the N_2O mitigation would account for 5–19% of the total synthetic fertilizer-induced N_2O emissions when urea formaldehyde

and/or U + DCD + HQ are applied. Though the estimates of mitigation potential are rather rough due to insufficient measurements, it is of great importance in N_2O mitigation. Long-term field experiments under various conditions of climate, soils and agricultural practices would be necessary in order to properly quantify the mitigation potential with a higher reliability because the N_2O emission factor depends on agricultural practice (Zheng et al., 2004), soils (Gu et al., 2009) and climate (Lu et al., 2006).

Although the application of synthetic N fertilizers has made a great contribution to the recent increase in crop production, only about half of the N fertilizer input to cropland is actually recovered in the harvested crops (Smil, 1999). A major portion of the other half of the N fertilizer is lost to the environment by different pathways, including ammonia (NH_3) volatilization, denitrification forming molecular N_2 , N_2O and NO , and leaching of nitrate (Galloway et al., 2004). Direct measurements of nitrate leaching and soil NH_3 volatilization are beyond the scope of this study, but it is likely that the application of urea formaldehyde or urea with HQ and DCD in maize fields resulted in a reduction in N_2O and NO_3^- leaching and NH_3 losses (Zaman et al., 2008). Long-term field studies *in situ* are needed to quantify and better understand the factors that govern N losses under different slow release fertilizer applications and different agrotypes conditions. It is also important to investigate crop quality in addition to yield after the application of urea with HQ and DCD in future studies. Future studies should also emphasize the economics of using these modified fertilizers.

5. Conclusion

The application of urea formaldehyde or urea with biochemical inhibitors could reduce N_2O emissions, while the use of Ca-Mg-P-coated, polymer-coated and sulfur-coated urea generally enhanced N_2O emissions from wheat and maize croplands when fertilization followed an extreme precipitation event. Further efforts should be made on an integrated study of N_2O , NO and NH_3 emissions, nitrate leaching and crop yield under various conditions of climate, soils and agricultural practices with physically altered, chemically altered and biochemically inhibited nitrogen fertilizers, so as to assess the effects of these fertilizers on the environment and crop production.

Acknowledgments

Funding for this study was provided by the National Natural Science Foundation of China (grant number: 40605029). We thank X. Yao, D. Deng, Y.Y. Zhu and H. Fen for their help in sample measurement. We would also like to thank the School of Chemical Engineering, Zhengzhou University and the Shanghai Hanfeng Group for supplying fertilizers for this research.

References

- Akiyama, H., Tsuruta, H., 2002. Effect of chemical fertilizer form on N₂O, NO and NO₂ fluxes from Andisol field. *Nutr. Cycl. Agroecosyst.* 63, 219–230.
- Akiyama, H., Tsuruta, H., Watanabe, T., 2000. N₂O and NO emissions from soils after the application of different chemical fertilizers. *Chemosph. Global Change Sci.* 2, 313–320.
- Bateman, E.J., Baggs, E.M., 2005. Contributions of nitrification and denitrification to N₂O emissions from soils at different water-filled pore space. *Biol. Fertil. Soils* 41, 379–388.
- Boeckx, P., Xu, X., Cleemput, O., Van., 2005. Mitigation of N₂O and CH₄ emission from rice and wheat cropping systems using dicyandiamide and hydroquinone. *Nutr. Cycl. Agroecosyst.* 72, 41–49.
- Bouwman, A.F., 1996. Direct emission of nitrous oxide from agricultural soils. *Nutr. Cycl. Agroecosyst.* 46, 53–70.
- Chen, S.T., Huang, Y., Zou, J.W., 2008. Relationship between nitrous oxide emission and winter wheat production. *Biol. Fertil. Soils* 44, 985–989.
- Chen, W.X., 1989. *Soil and Environment Microbiology*. Beijing Agricultural Press, Beijing, pp. 134–140 (in Chinese).
- Cheng, W., Tsuruta, H., Chen, G.X., Yagi, K., 2004. N₂O and NO production in various Chinese agricultural soils by nitrification. *Soil Biol. Biochem.* 36, 953–963.
- Cheng, W.G., Sudo, S., Tsuruta, H., Yagi, K., Hartley, A., 2006. Temporal and spatial variations in N₂O emissions from a Chinese cabbage field as a function of type of fertilizer and application. *Nutr. Cycl. Agroecosyst.* 74, 147–155.
- Delgado, J.A., Mosier, A.R., 1996. Mitigation alternatives to decrease nitrous oxides emissions and urea-nitrogen loss and their effect on methane flux. *J. Environ. Qual.* 25, 1105–1111.
- Di, H.J., Cameron, K.C., Sherlock, R.R., 2007. Comparison of the effectiveness of a nitrification inhibitor, dicyandiamide, in reducing nitrous oxide emissions in four different soils under different climatic and management conditions. *Soil Use Manage.* 23, 1–9.
- Ding, W.X., Cai, Y., Cai, Z.C., Yagi, K., Zheng, X.H., 2007. Nitrous oxide emissions from an intensively cultivated maize–wheat rotation soil in the North China Plain. *Sci Total Environ.* 373, 501–511.
- Dobbie, K.E., McTaggart, I.P., Smith, K.A., 1999. Nitrous oxide emissions from intensive agricultural systems: variations between crops and seasons; key driving variables; and mean emission factors. *J. Geophys. Res.* 104, 26891–26899.
- Dobbie, K.E., Smith, K.A., 2003a. Impact of different forms of N fertilizer on N₂O emissions from intensive grassland. *Nutr. Cycl. Agroecosyst.* 67 (1), 37–46.
- Dobbie, K.E., Smith, K.A., 2003b. Nitrous oxide emission factors for agricultural soils in Great Britain the impact of soil water-filled pore space and other controlling variables. *Global Change Biol.* 9, 204–218.
- Du, C.W., Zhou, J.M., Shaviv, A., 2006. Release characteristics of nutrients from polymer-coated compound controlled release fertilizers. *J. Polym. Environ.* 14, 223–230.
- Firestone, M.K., Davidson, E.A., 1989. Microbiological basis of NO and N₂O production and consumption in soil. In: Andreae, M., Schimel, D. (Eds.), *Exchange of Trace Gases Between Terrestrial Ecosystems and the Atmosphere*. John Wiley and Sons, Chichester, pp. 7–21.
- Flechar, C.R., Ambus, P., Skiba, U., Rees, R.M., Hensen, A., van Amstel, A., van den Pol-van Dassel, A., Soussana, J.-F., Jones, M., Clifton-Brown, J., Raschi, A., Horvath, L., Neftel, A., Jocher, M., Ammann, C., Leifeld, J., Fuhrer, J., Calanca, P., Thalman, E., Pilegaard, K., Di Marco, C., Campbell, C., Nemitz, E., Hargreaves, K.J., Levy, P.E., Ball, B.C., Jones, S.K., van de Bulk, W.C.M., Groot, T., Blom, M., Domingues, R., Kasper, G., Allard, V., Ceschia, E., Cellier, P., Laville, P., Henault, C., Bizouard, F., Abdalla, M., Williams, M., Baronti, S., Berretti, F., Grosz, B., 2007. Effects of climate and management intensity on nitrous oxide emissions in grassland systems across Europe. *Agric Ecosyst. Environ.* 121 (1–2), 135–152.
- Food and Agricultural Organization of the United Nations, 2008. FAOSTAT Database <http://www.fao.org/faostat/>.
- Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Asner, G.P., Cleveland, C.C., Green, P.A., Holland, E.A., Karl, D.M., Michaels, A.F., Porter, J.H., Townsend, A.R., Vorosmarty, C.J., 2004. Nitrogen cycles: past, present and future. *Biogeochemistry* 70, 153–226.
- Goodroad, L.L., Keeney, D.R., 1984. Nitrous oxide production in aerobic soils under varying pH, temperature and water content. *Soil Biol. Biochem.* 16 (1), 39–43.
- Gu, J.X., Zheng, X.H., Zhang, W., 2009. Background nitrous oxide emissions from croplands in China in the year 2000. *Plant Soil* 320, 307–320.
- Hopkins, W.G., Huner, N.P.A., 2008. *Introduction to Plant Physiology*. John Wiley & Sons, New York.
- Hou, A., Akiyama, H., Nakajima, Y., Sudo, S., Tsuruta, H., 2000. Effects of urea form and soil moisture on N₂O and NO emissions from Japanese Andosols. *Chemosph. Global Change Sci.* 2, 321–327.
- Hou, A., Tsuruta, H., 2003. Nitrous oxide and nitric oxide fluxes from an upland field in Japan: effect of urea type, placement, and crop residues. *Nutr. Cycl. Agroecosyst.* 65, 191–200.
- Huang, Y., Jiao, Y., Zong, L.G., Wang, Y.S., Sass, R.L., 2002. Nitrous oxide emissions from the wheat-growing season in eighteen Chinese paddy soils: an outdoor pot experiment. *Biol. Fertil. Soils* 36, 411–417.
- Intergovernmental Panel on Climate Change (IPCC), 2001. *Climate Change 2001: the scientific basis*. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., Van der Linden, P.J. (Eds.), *Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York.
- Intergovernmental Panel on Climate Change (IPCC), 2006. *Volume 4 Agriculture, Forestry and Other Land Use*. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K. (Eds.), *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan.
- Intergovernmental Panel on Climate Change (IPCC), 2007. *Chapter 8: Agriculture*. In: Metz, B., Davidson, O., Bosch, P., Dave, R., Meyer, L. (Eds.), *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York.
- Jantalia, C.P., Dos Santos, H.P., Urquiaga, S., Boddey, R.M., Alves, B.J.R., 2008. Fluxes of nitrous oxide from soil under different crop rotations and tillage systems in the South of Brazil. *Nutr. Cycl. Agroecosyst.* 82, 161–173.
- Ju, X.T., Xing, G.X., Chen, X.P., Zhang, S.L., Zhang, L.J., Liu, X.J., Cui, Z.L., Yin, B., Christie, P., Zhu, Z.L., Zhang, F.S., 2009. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *PNAS* 106, 3041–3046.
- Jumadi, O., Hala, Y., Muis, A., Ali, A., Palennari, M., Yagi, K., Inubushi, K., 2008. Influences of chemical fertilizers and a nitrification inhibitor on greenhouse gas fluxes in a corn (*Zea mays* L.) field in Indonesia. *Microbes Environ.* 23 (1), 29–34.
- Lu, Y.Y., Huang, Y., Zou, J.W., Zheng, X.H., 2006. An inventory of N₂O emissions from agriculture in China using precipitation-rectified emission factor and background emission. *Chemosphere* 65, 1915–1924.
- Ma, B.L., Wu, T.Y., Tremblay, N., Deen, W., Morrison, M.J., McLaughlin, N.B., Gregorich, E.G., Stewart, G., 2009a. Nitrous oxide fluxes from corn fields: On-farm assessment of the amount and timing of nitrogen fertilizer. *Global Change Biol.* doi:10.1111/j.1365-2486.2009.01932.x (in press).
- Ma, W.Q., Li, J.H., Ma, L., Wang, F.H., Sisák, I., Cushman, G., Zhang, F.S., 2009b. Nitrogen flow and use efficiency in production and utilization of wheat, rice, and maize in China. *Agricult. Syst.* 99, 53–63.
- Mao, X.Y., Sun, K.J., Wang, D.H., Liao, Z.W., 2005. Controlled-release fertilizer (CRF): A green fertilizer for controlling non-point contamination in agriculture. *J. Environ. Sci.* 17 (2), 181–184.
- McTaggart, I.P., Tsuruta, H., 2003. The influence of controlled release fertilizers and the form of applied fertilizer nitrogen on nitrous oxide emissions from an andosol. *Nutr. Cycl. Agroecosyst.* 67, 47–54.
- Merino, P., Estavillo, J.M., Gracioli, L.A., Pinto, M., Lacuesta, M., Muñoz-Rueda, A., Gonzalez-Murua, C., 2002. Mitigation of N₂O emissions from grassland by nitrification inhibitor and Actilith F2 applied with fertilizer and cattle slurry. *Soil Use Manage.* 18, 135–141.
- Mosier, A.R., 2004. *Agriculture and the Nitrogen Cycle. Assessing the impacts of fertilizer use on food production and the environment*. SCOPE Series NO. 65. Island Press, Washington, DC.
- Mosier, A.R., Kroeze, C., 2000. Potential impact on the global atmospheric N₂O budget of the increased nitrogen input required to meet future global food demands. *Chemosph. Global Change Sci.* 2, 465–473.
- Mosier, A.R., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S., VanCleemput, O., 1998. Closing the global N₂O budget: Nitrous oxide emissions through the agricultural nitrogen cycle. *Nutr. Cycl. Agroecosyst.* 52, 225–248.
- National Bureau of Statistics, China, 2008. *China Statistical Yearbook–2008*. China Statistics Press, Beijing (in Chinese).
- Oertli, J.J., 1980. Controlled-release fertilizers. *Fertil. Res.* 1, 103–123.
- Parkin, T.B., 2008. Effect of Sampling Frequency on Estimates of Cumulative Nitrous Oxide Emissions. *J. Environ. Qual.* 37, 1390–1395.
- Pathak, H., Nedwell, D.B., 2001. Nitrous oxide emission from soil with different fertilizers, water levels and nitrification inhibitors. *Water Air Soil Pollut.* 129 (1–4), 217–228.
- Scheer, C., Wassmann, R., Kienzler, K., Ibragimov, N., Eschanov, R., 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.
- Shaviv, A., 2001. Advances in controlled release fertilizers. *Adv. Agron.* 71, 1–49.
- Shoji, S., Delgado, J., Mosier, A., Miura, Y., 2001. Use of controlled release fertilizers and nitrification inhibitors to increase nitrogen use efficiency and to conserve air and water quality. *Commun. Soil Sci. Plant Anat.* 32 (7 & 8), 1051–1070.
- Shoji, S., Gandeza, A.T., Kimura, K., 1991. Simulation of crop response to polyolefin-coated urea. II. Nitrogen uptake by corn. *Soil Sci. Soc. Am. J.* 55, 1468–1473.
- Skiba, U., Smith, K.A., 2000. The control of nitrous oxide emissions from agricultural and natural soils. *Chemosph. Global Change Sci.* 2, 379–386.
- Skiba, U.M., Sheppard, L.J., MacDonald, J., Fowler, D., 1998. Some key environmental variables controlling nitrous oxide emissions from agricultural and semi-natural soils in Scotland. *Atmos. Environ.* 19, 3311–3320.
- Smil, V., 1999. Nitrogen in crop production: An account of global flows. *Global Biogeochem. Cycl.* 13, 647–662.
- Smith, P., Martino, D., Cai, Z.C., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smit, J., 2008. Greenhouse gas mitigation in agriculture. *Philos. Trans. R. Soc. B.* 363, 789–813.
- Sun, B., Shen, R.P., Bouwman, A.F., 2008. Surface N balances in agricultural crop production systems in China for the period 1980–2015. *Pedosphere* 18 (3), 304–315.
- The People's Republic of China Initial National Communication on Climate Change, 1994. *National Greenhouse Gas Inventory*. China Government, Beijing, pp. 31–32 (Chapter 2).
- Toma, Y., Kimura, S.D., Hirose, Y., Kusa, K., Hatano, R., 2007. Variation in the emission factor of N₂O derived from chemical nitrogen fertilizer and organic matter: A

- case study of onion fields in Mikasa, Hokkaido, Japan. *Soil Sci. Plant Nutr.* 53, 692–703.
- Wagner-riddle, C., Furon, A., Mclaughlin, N., Ivanlee, Barbeau, J., Ayasundara, S., Parkin, G., Bertoldi, P.V., Warland, J., 2007. Intensive measurement of nitrous oxide emissions from a corn–soybean–wheat rotation under two contrasting management systems over 5 years. *Global Change Biol.* 13, 1722–1736.
- Wang, Y.S., Wang, Y.H., 2003. Quick measurement of CH₄, CO₂ and N₂O emissions from a short-plant ecosystem. *Adv. Atmos. Sci.* 20, 842–844.
- Xing, G.X., Yan, X.Y., 1999. Direct nitrous oxide emissions from agricultural fields in China estimated by the revised 1996 IPCC guidelines for national greenhouse gases. *Environ. Sci. Policy* 2, 355–361.
- Xu, X.C., 2006. Prospects for the production and application of slow and controlled release fertilizers. *Phosphate Compound Fertil.* 21 (6), 9–11 (in Chinese).
- Yan, X., Hosen, Y., Yagi, K., 2001. Nitrous oxide and nitric oxide emissions from maize field plots as affected by N fertilizer type and application method. *Biol. Fertil. Soils* 34, 297–303.
- Yan, X., Jin, J.Y., He, P., Liang, M.Z., 2008. Recent Advances on the technologies to increase fertilizer use efficiency. *Agr. Sci. China* 7 (4), 469–479.
- Zaman, M., Nguyen, M.L., Blennerhassett, J.D., Quin, B.F., 2008. Reducing NH₃, N₂O and NO₃⁻–N losses from a pasture soil with urease or nitrification inhibitors and elemental S-amended nitrogenous fertilizers. *Biol. Fertil. Soils* 44, 693–705.
- Zheng, X.H., Han, S.H., Huang, Y., Wang, Y., Wang, M.X., 2004. Re-quantifying the emission factors based on field measurements and estimating the direct N₂O emission from Chinese croplands. *Glob. Biogeochem. Cycles* 18, GB2018, doi:10.1029/2003GB002167.
- Zheng, X.H., Wang, M.X., Wang, Y.S., Shen, R.X., Gou, J., Li, J., Jin, J.S., Li, L.T., 2000. Impacts of soil moisture on nitrous oxide emission from croplands: a case study on the rice-based agro-ecosystem in Southeast China. *Chemosph. Global Change Sci.* 2, 207–224.
- Zhu, Z.L., Chen, D.L., 2002. Nitrogen fertilizer use in China – Contributions to food production, impacts on the environment and best management strategies. *Nutr. Cycl. Agroecosyst.* 63 (2–3), 117–127.
- Zou, J.W., Huang, Y., Jiang, J.Y., Zheng, X.H., Sass, R.L., 2005. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue and fertilizer application. *Glob. Biogeochem. Cycles* 19, GB2021, doi:10.1029/2004GB002401.