Biogeosciences Discuss., 7, 4539–4563, 2010
www.biogeosciences-discuss.net/7/4539/2010/
doi:10.5194/bgd-7-4539-2010

Biogeosciences
Discussions

Nitrous oxide emission from highland winter wheat field after long-term fertilization

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Received: 9 April 2010 – Accepted: 27 May 2010 – Published: 16 June 2010

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Nitrous oxide (N_2O) is an important greenhouse gas. N_2O emissions from soils vary with fertilization and cropping practices. The response of N_2O emission to fertilization of agricultural soils plays an important role in global N_2O emission. The objective of this study was to assess the seasonal pattern of N_2O fluxes and the annual N_2O emissions from a rain-fed winter wheat (*Triticum aestivum* L.) field in the Loess Plateau of China. A static flux chamber method was used to measure soil N_2O fluxes from 2006 to 2008. The study included 5 treatments with 3 replications in a randomized complete block design. Prior to initiating N_2O measurements the treatments had received the same fertilization for 22 years. The fertilizer treatments were unfertilized control (CK), manure (M), nitrogen (N), nitrogen + phosphorus (NP), and nitrogen + phosphorus + manure (NPM). Soil N_2O fluxes in the highland winter wheat field were highly variable temporally and thus were fertilization dependent. The highest fluxes occurred in the warmer and wetter seasons. Relative to CK, M slightly increased N_2O flux while N, NP and NPM treatments significantly increased N_2O fluxes. The fertilizer induced increase in N_2O flux occurred mainly in the first 30 days after fertilization. The increases were smaller in the relatively warm and dry year than in the cold and wet year. Combining phosphorous and/or manure with mineral N fertilizer partly offset the nitrogen fertilizer induced increase in N_2O flux. N_2O fluxes at the seedling stage were mainly controlled by nitrogen fertilization, while fluxes at other plant growth stages were influenced by plant and environmental conditions. The cumulative N_2O emissions were always higher in the fertilized treatments than in the non-fertilized treatment (CK). Mineral and manure nitrogen fertilizer enhanced N_2O emissions in wetter years compared to dryer years. Phosphorous fertilizer offset 0.78 and 1.98 kg N_2O ha^{-1} increases, while manure + phosphorous offset 0.67 and 1.64 kg N_2O ha^{-1} increases by N fertilizer for the two observation years. Our results suggested that the contribution of single N fertilizer on N_2O emission was larger than that of NP and NPM and that manure and phosphorous had important roles in offsetting mineral N fertilizer induced N_2O

emissions. Relative to agricultural production and N_2O emission, manure fertilization (M) should be recommended while single N fertilization (N) should be avoided for the highland winter wheat due to the higher biomass and grain yield and less N_2O flux and annual emission in M than in N.

1 Introduction

Nitrous oxide (N_2O), an important greenhouse gas in the atmosphere, has increased from pre-industrial concentrations of 270 ppb to 319 ppb in 2005 (Forster et al., 2007). Soil is acknowledged as the major source of N_2O, accounting for about 70% of total emissions. Agricultural soils account for a large proportion (70–81%) of the increase in N_2O emissions to the atmosphere, with the increase linked to increased N fertilizer use (Bouwman, 1990). A recent calculation showed that 3.3 Tg N_2O-N yr^{-1} is emitted globally from fertilized cropland (Stehfest and Bouwman, 2006). However, the linkages between agricultural soil emissions and global emissions are still uncertain (Stehfest and Bouwman, 2006), and further understanding of N_2O emissions from cropped land are still necessary for accurate global N_2O emission prediction.

The response of soil N_2O emissions to N fertilization has been widely studied in different ecosystems. Zhang & Han (2008) reported a linear relationship between cumulative N_2O and N application rate in the semi-arid grassland of northern China, while McSwiney and Robertson (2005) found a nonlinear response of N_2O flux to incremental fertilizer additions in a continuous maize (*Zea mays L.*) cropping system in southwest Michigan. Although the response pattern of soil N_2O emission to N fertilizers was not identical, the increased N_2O emission associated with mineral N fertilizer application is widely acknowledged (Bouwman et al., 2002). As for manure fertilizer, Davidson (2009) showed that manure has been important for N_2O emission since 1860, whereas mineral fertilizer became important only during the last half of the twentieth century, suggesting that the contribution of manure fertilizer to N_2O emission cannot be ignored. However, estimations by Flynn et al. (2005) indicated that manure makes a significantly smaller contribution than mineral N fertilizers to N_2O emissions from cropped soils. Many other studies also showed that N_2O emission due to manure were less than that due to mineral N fertilizers (Dambreville et al., 2008; Alluvione et al., 2010). Nevertheless, little research has been performed to study how N_2O emissions respond to a combined application of manure and mineral N fertilizers. Combination of manure and mineral N fertilizers are used extensively around the world.

Wheat is an important contributor to global food supply. The wheat area in 2007 around the world is 210 million ha, while that in China is 23 million ha. N fertilization is fundamental for wheat production. In 1996, a total of 4.97 million tons of N fertilizer were applied for global cereal production, and wheat accounted for approximately 29% of the total (Raun and Johnson, 1999). However, the nitrogen use efficiency is low and the loss of N attracts much attention from scientists at different fields (Xing & Zhu, 2000; Silgram et al., 2001; Bouwman et al., 2005; Sudling et al., 2005; Vitousek et al., 2009). As global wheat production expands, there is an increase application of N fertilizer in wheat production, and the N fertilizer induced N_2O emission in wheat field accounts for a large proportion of global N_2O emission. Further study of N fertilizer on wheat is needed as a basis for supporting acute estimation of global N_2O emission.

The response of N_2O emission to fertilization varied greatly with fertilization years (Hall and Matson, 1999), which could be ascribed to the unstable fertilization effects at the first several years of the experiment and the relatively stable effects at the middle or latter periods of the experiment. To avoid treatment starting response of N_2O to fertilization, N_2O emissions under long-term fertilized conditions should be investigated in order to objectively appreciate stable fertilization effects on N_2O emission.

In this study, a two-year N_2O flux observation was conducted in a highland winter wheat field after 22 years fertilization in the Loess Plateau of China. The objective was to assess seasonal pattern of N_2O flux and annual emission as affected by long-term fertilization in a rain-fed winter wheat field.

2 Materials and methods

2.1 Study sites and experimental design

The long-term field experiment was initiated in September 1984 at the Agro-ecological Experiment Station of the Chinese Academy of Science, Changwu County, Shaanxi Province, China (35°12′ N, 107°40′ E). The average annual temperature of this site is 9.1 °C and annual precipitation is 585 mm. The soil is a Hei Lu soil according to the Chinese classification system, which corresponds to a Calcarid Regosol according to the FAO/UNESCO classification system (FAO/Unesco, 1988).

The cropping system is continuously cropped winter wheat (*Triticum aestivum* L.). The fertilizer treatments were unfertilized control (CK), manure (M), nitrogen (N), nitrogen + phosphorus (NP), and nitrogen + phosphorus + manure (NPM). Urea and superphosphate were used as the source of N and P. The manure came from cattle. In all of the fertilizer treatments, the N rate was 120 kg ha^{-1}, the P rate was 26.2 kg ha^{-1}, and the M rate was 75 ton ha^{-1}. The mean total N content of the manure was 1.97 g kg^{-1} and the available N was 91 mg kg^{-1}.

Fertilization treatments were replicated three times in a randomized complete block design. Each plot was 10.3 m by 6.5 m. Routine crop management practices for this region were used. Prior to seeding, fertilizers were broadcast on the soil surface and then the land was plowed two times with a cattle-drawn plow to a depth of about 10-cm. Wheat was sown in rows 20 cm apart. After seeding, the soil was raked to cover the seed. Weeds were removed by hand in all of the treatments. When the wheat reached maturity, it was harvested at the ground-level, the straw and grain were removed, and then the soil was plowed two times to a depth of about 15 cm.

2.2 Measurement of N_2O flux

The N_2O fluxes were measured from September 2006 to September 2008. The soil fertility conditions in each treatment before N_2O flux measurement are shown in Table 1.

A static closed-chamber technique was used to investigate N_2O flux. The closed-chambers, with base area of 20 cm×25 cm and height of 20 cm, made of polyvinyl chloride, were inserted 10 cm into the ground on each plot. The chambers remained open for at least 2 h between each measurement cycles. Four samples, at intervals 15 min each, were collected by using a 25 mL glass syringe from enclosed interspaces. Tang et al. (2006) showed that greenhouse gases fluxes, including N_2O, measured at 9:00 am were close to daily means, so we collected gas samples 9:00 am every 10 days in the winter and every 4–6 days in the other seasons.

A gas chromatograph (Shimadzu GC-14B), fitted with a 4 mm×3 m stainless steel column packed with Porapack Q (80–100 mesh) and an ^{63}Ni electron capture detector (ECD), was used to measure N_2O concentrations. High-purity Ar_2/CH_4 (95% Ar_2 + 5% CH_4) was used as carrier gas and the flow rate was maintained at 40 mL min^{-1}. The column and the detector temperatures were set at 65 and 300 °C, respectively. The standard N_2O gas was supplied by Japanese National Institute of Agro-Environmental Sciences.

2.3 Climate and soil environment measurement

The climate data were determined at a weather station at the Agro-ecological Experiment Station, part of the Chinese Ecosystem Research Network (CERN). Rainfall and air temperature at 1.2 m height were automatically measured on an hourly basis at the weather station. The daily values of the two parameters were calculated from hourly values from 10:00ȧ.m. to 9:00 a.m. the following day.

Soil temperature and moisture (volumetric water content) at a depth of 5 cm were monitored by a Delta-T Profile Probe (ML2X) and HH2 reader (Delta-T Devices Ltd, UK) in each plot at the time when gas samples were collected. Water-filled pore space (WFPS) was calculated using the measured soil bulk density data and a particle density of 2.65 g cm^{-3}.

2.4 Statistical analysis

The frequency distributions of observed N_2O fluxes were tested. The N_2O flux data in this study showed log normal or highly skewed distributions. Therefore, the original data were log-transformed to meet the normality before performing ANOVA analysis. The repeated measures ANOVA was conducted to test the effects of fertilization and growth stage on soil N_2O flux. The correlation analysis was conducted to assess the relationships between N_2O flux and soil temperature and WFPS for each fertilization treatment. All statistical analyses were performed using SAS software (SAS Institute, 1999).

3 Results

3.1 Overview of environmental conditions

In this study, an observation year included a winter wheat season (from September to June in the following year) and a fallow season (June to September). The mean daily air temperatures at the study site for the 2006–2007 and the 2007–2008 observation years were 10.8°C and 9.6°C, respectively. In these 2 observation years, the winter wheat seasons were characterized by relatively low air temperatures, which were 160% and 218% lower than those in the fallow seasons, respectively. Generally, the lowest daily air temperatures were observed in December and January (within the wheat season) while the highest daily air temperatures were observed in July (within the fallow season) (Fig. 1a). The rainfalls for the 2 observation years were 358 and 509 mm, of which 55 and 53% fell during the periods of winter wheat growth (Fig. 1a). The average daily rainfalls were 0.72 and 0.99 mm for the wheat seasons, and 1.74 and 2.6 mm during the fallow seasons, respectively. Therefore, the study site was characterized by dry and cold wheat seasons and wet and warm fallow seasons.

Soil temperature (5 cm depth) varied seasonally in response to air temperature (Fig. 1b). The largest soil temperature (observed in CK) occurred in August, while the smallest soil temperature occurred (observed in NPM) in February. Soil temperatures in CK were 0–2.4°C and 0–2.0°C larger than in the fertilized treatment for 2006–2007 and 2007–2008 observation years depending on the sampling date. Nevertheless, repeated measures ANOVA showed that no significant soil temperature occurred within the fertilization treatments.

Relatively large WFPS of surface soil was observed during the study period, and it varied temporally in response to rainfall and wheat growth (Fig. 1c). For the 2 observation years, WFPS was highest during the wet season and decreased with wheat growth. Soil WFPS was significantly influenced by fertilization. Generally, CK, N and NP had WFPS ranging from 37.3 to 77.1, 34.5 to 81.5 and 35.1 to 82.8, while M and NPM had WFPS ranging from 33.4 to 79.1 and 33.4 to 75.8, respectively. The WFPS in CK, N and NP were 3 to 20% higher than in M and NPM.

3.2 Fertilization effects on N_2O fluxes

Soil N_2O fluxes were temporally variable and fertilization dependent (Fig. 2). For the CK treatment, N_2O fluxes ranged from 5 to 99 ug N_2O m^{-2} h^{-1}, with an average flux of 33 and 28 ug N_2O m^{-2} h^{-1} for 2006–2007 and 2007–2008 observation years. The highest N_2O fluxes occurred in warm and wet seasons. Application of manure slightly increased N_2O flux. The average fluxes in the M treatment were 25 and 35% higher than those in CK for the 2 observation years, respectively. The application of N, NP and NPM significantly increased N_2O fluxes. For the observation period from 2006 to 2008, the fluxes in N, NP and NPM ranged from 7.7 to 981, 9.6 to 700, and 12.0 to 713 ug N_2O m^{-2} h^{-1}, with average fluxes of 101, 76 and 76 ug N_2O m^{-2} h^{-1}, which were 3.3, 2.5 and 2.5 times the average flux in CK.

Generally, the largest increase in N_2O flux due to fertilization was observed in the 2007–2008 observation year. The increases in N_2O flux by N and NP treatments in the 2007–2008 were all 1.1 times those in 2006–2007.

The significant increase in N_2O flux due to fertilization occurred mainly in the first 30 days after fertilization (Table 2). After that period, the increase became small. For example, the average N_2O flux in the first 30 days after fertilization were 1057%, 681% and 614% higher in the N, NP and NPM treatments than in CK during the 2 observation years (2006–2008), while the average flux in the following periods were 42%, 26% and 44% higher than in CK, respectively. Additionally, the effects of fertilization on N_2O flux in the first 30 days were dependent on temperature and rainfall. The increase was smaller in the relatively warmer and dryer 2006–2007 compared to the colder and wetter 2007–2008 for the M, N, NP and NPM treatment.

The N treatment led to the largest increase in N_2O flux with an increase range of 0–951 $\mathrm{ug\,N_2O\,m^{-2}\,h^{-1}}$ during the 2 experimental years, while M treatment led to the least increase in flux, ranging from 0 to 59 $\mathrm{ug\,N_2O\,m^{-2}\,h^{-1}}$. The increase by the NP and NPM treatments ranged from 0 to 670 $\mathrm{ug\,N_2O\,m^{-2}\,h^{-1}}$ and 0 to 689 $\mathrm{ug\,N_2O\,m^{-2}\,h^{-1}}$, respectively, indicating that phosphorous or manure could partly offset the single mineral N fertilizer induced higher N_2O flux. In this study, the phosphorous and manure + phosphorous offset 36% and 35% of the increased flux by single mineral N fertilizer.

3.3 Seasonal patterns of N_2O fluxes as influenced by fertilization

The seasonal pattern of soil N_2O flux was mainly influenced by fertilization, wheat growth and environmental conditions (Fig. 2 and Table 3). Both CK and M treatments had the lower N_2O fluxes, and the fluxes in both treatments could be viewed as background fluxes for the site. The background fluxes were higher in relatively wet and warm seedling period and during the maturity stages and fallow season compared with the dryer and colder growth stages in 2006–2007. Higher background N_2O fluxes corresponded to higher soil WFPS and/or temperature. Fertilization significantly influenced treatments, N, NP, and NPM, and the fluxes were highest in the seedling stage with average values of >200 ug N_2O m^{-2} h^{-1} for both 2006–2007 and 2007–2008. However, in other growing stages and fallow season, the average fluxes were less than 60 ug N_2O m^{-2} h^{-1} and were also had a relatively high level in the wetter and warmer fallow season.

The seasonal patterns of N_2O flux varied with fertilizations. The fluxes in fertilized treatments (M, N, NP, and NPM) were nearly always higher during the growing seasons and fallow seasons in 2006–2007 and 2007–2008. However, the differences of fluxes in fertilized treatments were not significant in the later growing stages and the fallow seasons. These results indicate that N_2O fluxes at the seedling stage were mainly controlled by nitrogen fertilization, while fluxes at the other growing stages were mainly influenced by plant and environmental conditions.

3.4 Overall emissions

The overall N_2O emissions were generally always higher in fertilized treatments than in CK for the growing season and fallow season (Fig. 3). The significant differences in emissions among the five treatments were observed in seedling, tillering, jointing stages and fallow season during 2006–2007, and in all growing stages and fallow season for 2007–2008. The least increase of N_2O emissions during the growing season and fallow season occurred in M, and the largest increase occurred in the N treatment. Although the NP and NPM treatments also resulted in increases in N_2O emissions, the increases were less than the single mineral N fertilizer increase, suggesting that phosphorous and manure fertilizers have the potential to inhibit the mineral N fertilizer increased N_2O emission in the studied area.

For the observation year 2007–2008, the emissions for all treatments were higher from seedling to booting and lower in heading to maturity and fallow season compared with 2006–2007. Totally 191 mm and 130 mm rain fell from seedling to booting in 2007–2008 and 2006–2007, indicating that an increase in rainfall during this period contributed more to the N_2O emission than did fertilized or no. Additionally, the effects

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of fertilization on emissions also varied with rainfall. The annual emissions in CK and M were 10.7% and 5.1% less in the wetter 2007–2008 than in the dryer 2006–2007, while for N, NP and NPM those were 41.3%, 22.1% and 26.6% higher in 2007–2008 than in 2006–2007, demonstrating that nitrogen fertilizer enhanced N_2O emissions more in the wetter year than in the dryer year, in the seedling to booting stages.

4 Discussion

4.1 Fertilization effects on N_2O fluxes

In our experiment, N_2O flux peaks following nitrogen fertilizer application for the 2 years. Our annual average fluxes due to fertilization were relatively high compared to reported fluxes from other ecosystems. Generally, the N_2O fluxes in forest soils and grassland are typically low and increases associated with N fertilizer are also low compared with farmland (Davidson et al., 1997, Hall and Matson, 1999; Venterea et al., 2003; Du et al., 2006; Zhang and Han, 2008). The limited effects of N fertilizer for forest and grassland soil might be due to the relatively low N application levels, while the relatively large input of N fertilizer to crop soil often results in a large N_2O flux (Wagner-Riddle et al., 2007; Barton et al., 2008; Scheer et al., 2008). Irrigation in cropped soil also enhances N_2O flux (Scheer et al., 2008). The variation of soil N_2O flux with ecosystem type and fertilization practices can be explained by changes in soil C/N ratio which is negatively related with N_2O flux (Klemedtsson et al., 2005). Generally, top soils in forests and grasslands have larger C/N ratios than do farmland soils, and the soils with large C/N ratios have lower N_2O fluxes. The application of mineral N fertilizer to soil reduces the C/N ratio, and thus increases N_2O flux. Soil C/N ratios of the farmland in our site are larger than those observed by Scheer et al. (2008) and smaller than those by Wagner-Riddle et al. (2007) and Barton et al. (2008), and our flux in CK and mineral N fertilized treatment are smaller than Scheer et al. (2008) and larger than Wagner-Riddle et al. (2007) and Barton et al. (2008). The application of manure fertilizer often increases the C/N ratio and consequently decreases the N_2O flux. For all treatments the top soil C/N ratios followed the order of M>NPM>N while the fluxes followed the order of M<NPM<N.

Although several studies demonstrated that P promotes N_2O flux (Minami and Fukushi, 1983; Falkiner et al., 1993; Zhang and Han, 2008), we observed 24% and 27% lower fluxes in the NP treatment than in the N treatment in 2006–2007 and 2007-2008, indicating that P could alleviate single N fertilizer increase of N_2O flux. We assume that this effect be due to the fact that the NP treatment accelerated the uptake of soil mineral N and caused a low level of nitrate and ammonium in the soils compared with the N treatment. The lower N in soils provides less substrate for N_2O production. The uptake of N by winter wheat in 2006–2007 and 2007–2008 were 109% and 67% higher in NP than in N, while the residual nitrate and ammonium in the top soil (0–10 cm) were 23% and 13%, and 35% and 6% less in NP than in N treatment.

4.2 Seasonal patterns

The fertilization significantly affected the seasonal pattern of soil N_2O flux, which was characterized by a peak flux within 30 days following fertilization, consistent with other findings (Hall and Matson, 1999). For the whole wheat season and fallow season, the flux was significantly related with soil temperature for each treatment. Except for the seedling period, the seasonal patterns of N_2O flux in all treatments were closely related with WFPS (Table 4), indicating that N_2O fluxes in the winter wheat fields of the study area were somewhat temperature and water dependent.

The dependence of N_2O production on soil temperature has been reported in many ecosystems (Dobbie and Smith, 2003a; Flynn et al., 2005; Wagner-Riddle et al., 2007; Zhang and Han, 2008). A threshold of 5 °C for N_2O production has been reported (Dobbie & Smith, 2003b). According to this threshold, it hence should be little N_2O flux in the littering stage. However, winter and spring thaw could magnify N_2O flux because freeze/thaw cycles have been related to enhanced microbial activity due to increased available carbon from freezing lysis (Christensen and Tiedje, 1990), and disintegrating aggregates (van Bochove et al., 2000), combined with higher water content in the soil during thawing (Lemke et al., 1998). Combined these conditions can result in a relatively large flux in the littering stage. Wagner-Riddle et al. (2007) also observed increased N_2O in cold season, agreeing with our measurements. Additionally, large available N in soils during the stage following the seedling stage (when the fertilizer was applied) might be another reason for the higher fluxes in the nitrogen fertilized treatment.

In our study, 93% of the observed WFPS values were lower than 70%, which is the threshold for denitrification dominance (Davidson, 1992), suggesting that nitrification is likely the main source of N_2O in our study. The seasonal patterns of winter wheat growth and WFPS differed significantly with fertilization, indicating that the effects of fertilization on temporal N_2O flux in the growing season was mainly associated with wheat root activities and WFPS changes, which alter soil microorganism's role in N_2O production together with soil C and N conditions. The effects in the fallow season were dominated by the WFPS and soil C and N conditions.

4.3 Implications for N_2O emission and fertilization

At the global scale, annual N_2O emissions from cropped mineral soils ranged from 0.3 to 16.8 kg N_2O ha^{-1} yr^{-1} (Stehfest and Bouwman, 2006). For wheat soils, the emission ranged from 0.8 to 5.8 kg N_2O ha^{-1} yr^{-1} regardless of irrigation or not, while more than 75% of these observations were less than 2.5 kg N_2O ha^{-1} yr^{-1} (Roelandt et al., 2005). The background emission (CK treatment) in our rain-fed winter wheat field were 2.6 and 2.3 kg N_2O ha^{-1} yr^{-1}, while our fertilized emissions were 3.3–5.3 and 3.2–7.5 kg N_2O ha^{-1} yr^{-1} for 2006–2007 and 2007–2008 observation years, which were at relatively large emission levels.

The annual N_2O emission from fertilized treatments was in the following order N>NPM and NP>>M, suggesting that the contribution of single N fertilizer was larger than that of NP and NPM, this agrees with many other findings (Flynn et al., 2005;

Dambreville et al., 2008; Alluvione et al., 2010). This result implies that the present assessment might be larger because manure and phosphorous fertilizers are widely used in agriculture together with mineral N fertilizer while its role in offsetting mineral N fertilizers induced N_2O emissions are usually neglected. Barton et al. (2007) also suggested that the observed emission factor in semiarid cropped soil is 60 times less than the values suggested by IPCC. Many estimations separate fertilizer N as mineral N and organic N (from manure fertilizer) (Flynn et al., 2005, Davidson, 2009) without considering the fact that organic N and mineral N and mineral N and P are often used together. These estimations often ignore the offsetting role of manure when it is applied together with mineral N fertilizers.

Our results further show that M treatment has relatively large biomass and grain yield and less N_2O flux and annual emission. The biomass and grain yield in M are −14%∼70% and −10%∼66% higher than those in N, NP, NPM treatments in 2006–2008 (Fig.4), yet the annual N_2O emissions were 27–58% lower than those of N, NP, and NPM. From the point of agricultural production and N_2O emission, M should be recommended while single N fertilization avoided for highland winter wheat when all of the fertilizers are applied at the time of planting.

Acknowledgements. This study was supported by the National Key Basic Research Special Foundation Project (2005CB121101, 2009CB118604), the Knowledge Innovation Program of Chinese Academy of Sciences (KZCX2-YW-424-3, KSCX-YW-09-07), National Natural Science Foundation of China (40801111), the Program for Youthful Talents in Northwest A & F University and the Chinese Academy of Sciences Visiting Professorship for Senior International Scientists (2009Z2-37).

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Table 1. Soil fertility after 22 years of fertilization management (0–20 cm).

Treatments	Organic C ($\mathrm{Mg\,ha^{-1}}$)	Total N ($\mathrm{Mg\,ha^{-1}}$)	Total P ($\mathrm{Mg\,ha^{-1}}$)	Available N ($\mathrm{kg\,ha^{-1}}$)	Available P ($\mathrm{kg\,ha^{-1}}$)	Available K ($\mathrm{kg\,ha^{-1}}$)	C/N
CK	16.5	2.3	1.3	110	13	368	7.3
M	24.1	2.6	1.5	158	65	1024	9.0
N	17.8	2.4	1.6	136	14	371	7.4
NP	20.1	2.3	2.0	148	36	624	8.8
NPM	24.9	2.9	2.2	182	102	849	8.9

Table 2. Mean N_2O fluxes during the first 30 days after fertilization and during the most of the year (the later period).

		Whole year			First 30 days after fertilization			Latter period (31–365 days)		
		2006-2007	2007-2008	2006-2008	2006-2007	2007-2008	2006-2008	2006-2007	2007-2008	2006-2008
Rainfall (mm)	358	509	456	57	100	90	300	409	366	
Temp (°C)	10.8	9.6	10.1	13.9	10.6	12.1	10.8	9.5	9.9	
	CK	33	28	31	34	37	36	33	26	30
	M	41	37	41	40	55	47	41	34	38
Flux	N	100	103	127	338	443	432	42	40	42
(ug N_2O m^{-1} h^{-1})	NP	76	76	93	221	310	288	41	32	37
	NPM	76	78	92	204	277	265	45	40	43
F	4.50	3.69	11.38	7.03	8.07	14.37	1.65	8.29	5.98	
p	0.0015	0.0060	< 0.0001	< 0.0001	0.0002	< 0.0001	0.1621	< 0.0001	0.0001	

Table 3. N_2O fluxes in growing season and fallow season as affected by fertilization.

		Seedling	Tillering	Jointing	Booting Maturity	Heading to season	Fallow	*F*	*p*
2006-2007									
Rainfall (mm)		59	39	21	11	68	160		
Temp (˚C)		14.0	1.4	8.7	16.6	19.9	20.2		
	CK	34	24	27	24	40	41	2.48	0.0413
	M	42	32	37	34	45	51	1.68	0.1536
Flux	N	365	24	23	36	46	62	12.88	< 0.0001
(ug $N_2O\,m^{-1}\,h^{-1}$)	NP	234	32	39	34	45	50	10.13	< 0.0001
	NPM	219	25	23	35	49	67	6.97	< 0.0001
F		7.03	5.47	11.40	2.54	0.15	1.68		
P		0.0001	0.0006	0.0002	0.0603	0.9610	0.1626		
2007–2008									
Rainfall (mm)		110	46	21	16	88	239		
Temp (˚C)		10.6	−0.7	10.0	15.0	19.1	19.7		
	CK	38	25	25	29	19	29	2.49	0.0432
	M	57	35	35	33	32	36	3.50	0.0087
Flux	N	546	54	31	33	32	41	29.14	< 0.0001
(ug $N_2O\,m^{-1}\,h^{-1}$)	NP	382	34	30	29	21	40	26.71	< 0.0001
	NPM	345	30	40	42	47	49	12.11	< 0.0001
F		8.07	9.29	0.75	0.85	4.34	3.61		
P		0.0002	< 0.0001	0.5671	0.5049	0.0069	0.0110		

Table 4. Correlationships between N_2O fluxes and soil temperature and water-filled pore space (WFPS).

		CK	M	N	NP	NPM	All treatments
	The whole observation period						
Soil temperature	*r*	0.2386	0.2058	0.0750	0.0839	0.1412	0.0833
	p	0.0076	0.0217	0.4080	0.3544	0.1177	0.0381
WFPS	*r*	0.1693	0.1243	0.3710	0.3163	0.3667	0.2760
	p	0.0602	0.1691	< 0.0001	0.0003	< 0.0001	< 0.0001
	The whole observation period except seedling stage						
Soil temperature	*r*	0.2515	0.2243	0.2170	0.2610	0.5171	0.2865
	p	0.0097	0.0214	0.0260	0.0072	< 0.0001	< 0.0001
WFPS	*r*	0.1489	0.0776	0.1562	0.1318	0.0224	0.0903
	p	0.1294	0.4315	0.1117	0.1801	0.8208	0.0386

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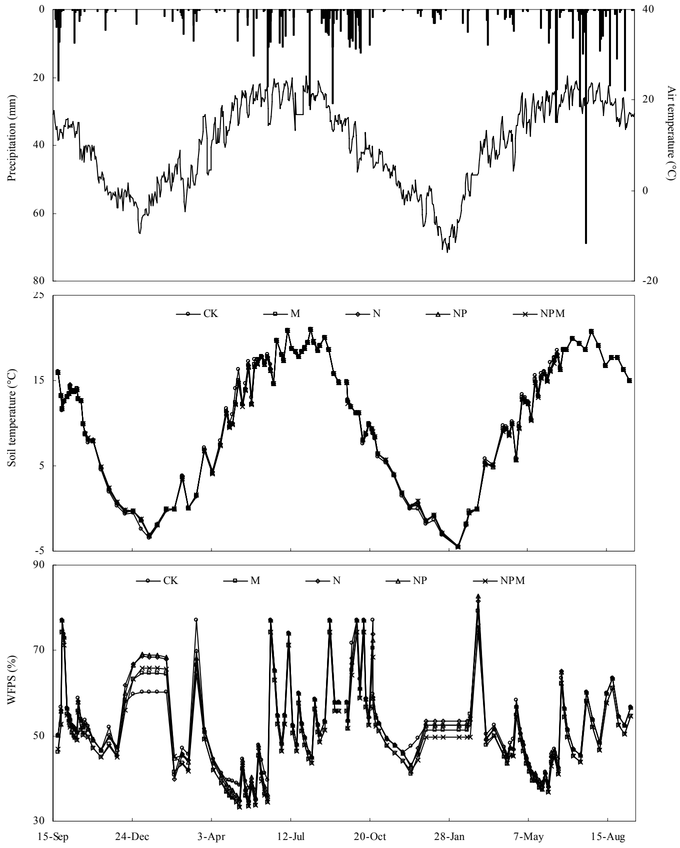

Fig. 1. Precipitation and air temperature **(a)**, 5 cm depth soil temperature **(b)** and WFPS **(c)** at different fertilization treatments during the experimental period (September 2006–September 2008).

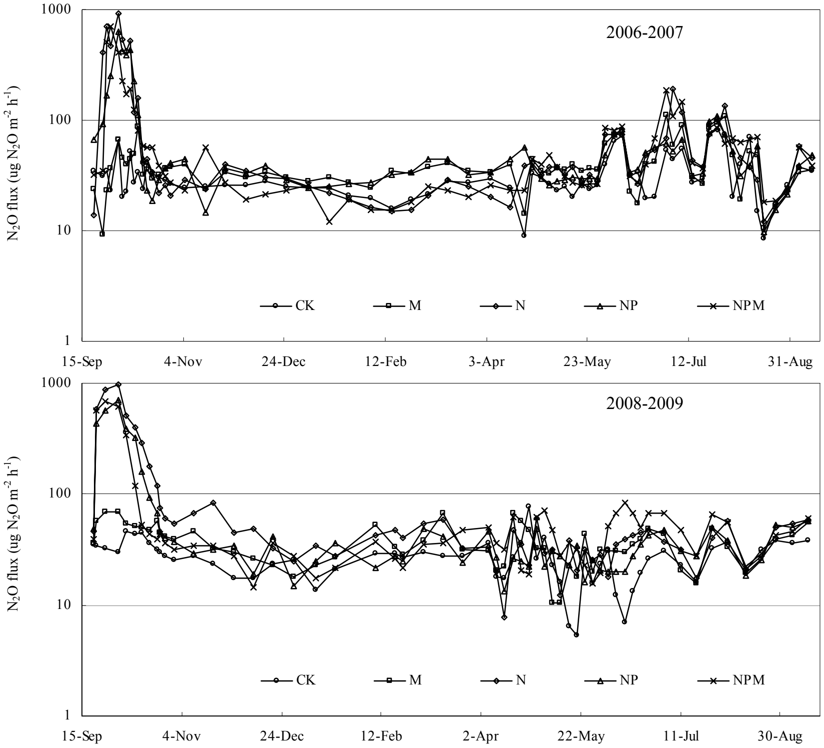

Fig. 2. N_2O flux at different fertilization treatments during the experimental period (September 2006–September 2008).

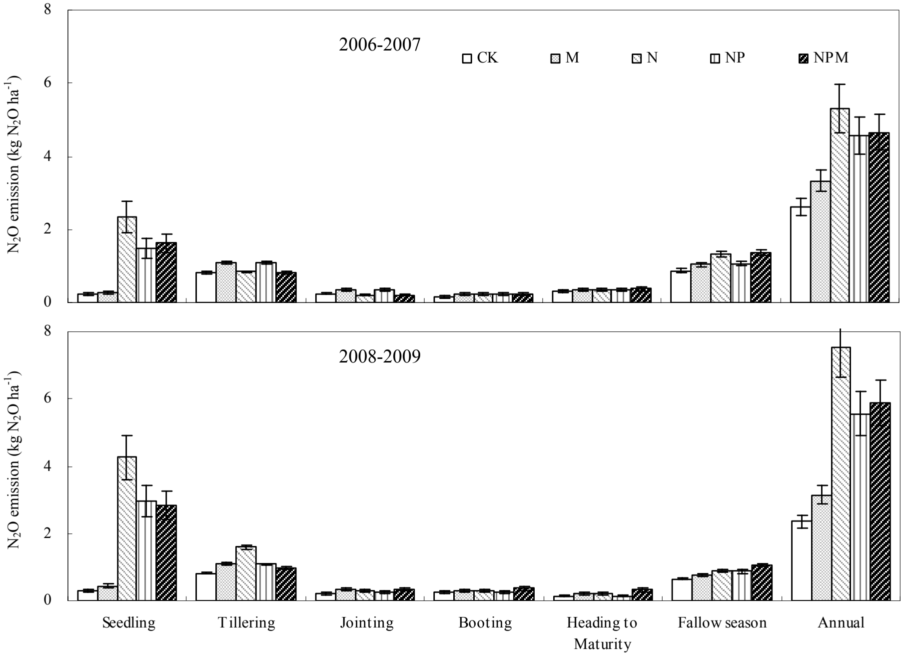

Fig. 3. Changes in N_2O emissions with winter wheat growth at different fertilization treatments during the experimental period.

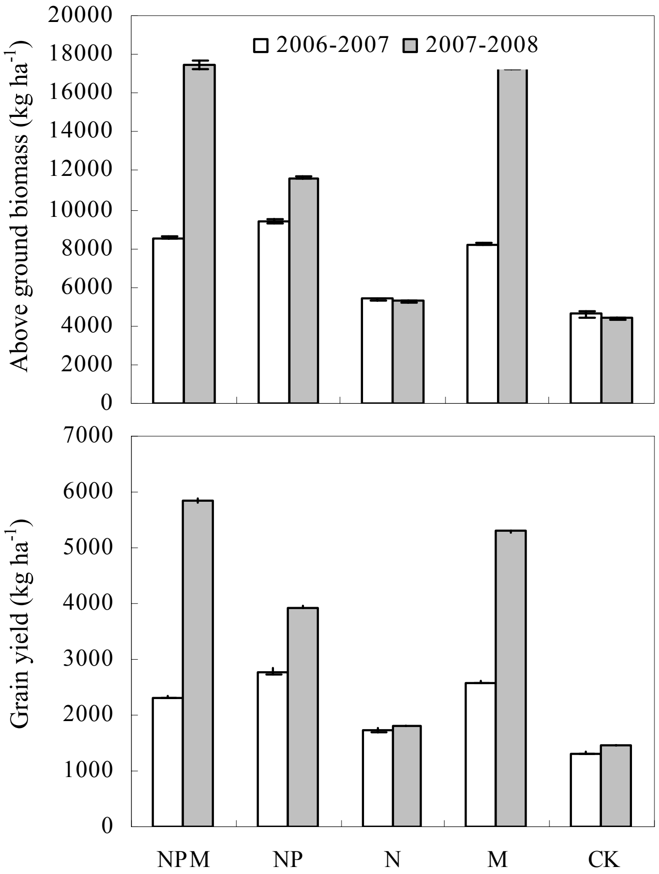

Fig. 4. Above ground biomass and grain yield of winter wheat at different fertilization treatments during the experimental period.