The response to reviewers' constructive comments and suggestions

Dear Editor,

The manuscript has been revised carefully according to constructive comments and suggestions of two reviewers. We hope this revised manuscript can fit with the acceptable standard for Biogeosciences. We would like to express our hearted gratitude to two anonymous reviewers and the editor for their constructive comments and suggestions that really improved the manuscript greatly. Our point-by-point responses are provided below, and text that has been added or modified from the original text is shown in the marked-up manuscript in red font.

Reviewer 1#:

Comments: This is a well-written paper. The research topic is scientifically sound and interesting, related to the influence of inhibitors and nitrate-based fertilizer on the N_2O emissions, crop yield and N use efficiency in the North China Plain. The authors found that the inhibitors of NBPT and DCD together with urea as basal fertilizer rather than supplemental fertilizer, and the nitrate-based fertilizer instead of urea could greatly reduce N_2O emissions during the winter wheat growth season. Meanwhile, nitrate-based fertilizer significantly increased wheat yield by 12.3% and N use efficiency from 28.8% to 35.9%. These are very interesting and valuable findings for readers and policy-makers. The experiment design is robust, data presentation is clear and the discussion section is written fully. Therefore, I would recommend its publication with a minor revision. It certainly falls within the remit of Biogeosciences.

Answer: Thank you very much for so nice comments.

Comments: A few smaller issues: 1. P13572, L10, add "kg N_2O-N ha^{-1}" following "0.49-0.12".

2. P13574, L21, change "…were drastically than…" into "…were drastically higher than…".

Answer: We have revised the sentences according to above suggestions.

Comments: 3. P13575, L22, show soil taxonomy such as UAS or FAO.

4. P13580, L3, I suggest that the analysis method for data normality test should be added.

Answer: We have added the missing information in the revised manuscript as suggested by the reviewer.

Comments: 5. P13581, L7, please delete "the".

6. P135813, L22, Change "ammonia-based" into "ammonium-based".

7. P13584, L16, Change "denitrification in general could produce more N_2O" into "denitrification could in general produce more N_2O".

8. P13586, L5, "inner Mongolia" should be "Inner Mongolia".

Answer: Thanks greatly. We improved the sentences considerably according to above suggestions.

Comments: 9. P13588 L9, "Application of urea with NBPT and/or DCD slightly increased wheat yields", I suggest adding "compared with urea alone" to this sentence.

Answer: We have revised the sentences as above suggestions.

Reviewer #2

Comments:

This manuscript reports on the changes in N_2O fluxes and NUE along with yield by the application of a nitrification inhibitor and different types of N fertilizers. The topic is within the range of the scope and the manuscript is overall well written. The authors employed a field-scale manipulation experiment and the measurements covered whole growing season. The authors employed a proper statistical test and analytical methodology is well established one. One reservation of mine is the global importance of the study to the general readers of the journal. It is obvious that Northern China is

one of the biggest agricultural sources of N_2O, but I would like to see more generalization of the results. Are there any other reports on N_2O emissions from agricultural fields in other countries with the similar climate zone? Any regional comparison or even simple literature review would benefit the quality of the manuscript.

Answer: Thank you very much for so nice comments. According to above suggestion, we have compiled data on N_2O emissions from uplands in other countries with the similar climate zone in the literature (by adding Table 6, please see below table) and make a comparison. The section of Discussion has been revised as follows:

P13586 L7, "…study. However, Zhang et al. (2014b) found that the North China Plain is a large agricultural N_2O source in China, contributing 36.3 % of the total annual N_2O emission from the China's croplands. To make a global comparison, we compiled the literature data of N_2O emissions from the temperate uplands under inorganic N fertilizer application in some countries of Asia, Europe and North America with similar latitudes to the studied region (Table 6). The emission factors of N applied in the North China Plain are generally lower than in the other countries, indicating a lower capacity of N applied being converted into N_2O in the test soil. This is probably because N_2O is predominantly produced from nitrification and denitrification is organic C-limited as discussed above. In contrast, the total N_2O emissions from the studied region are obviously higher due to the greater N fertilizer loading (Ju et al., 2009), suggesting that agricultural practices for reducing N_2O emission are urgently required. Our results confirm that N fertilizer sources …".

Comments: Other minor comments;

P13573 L1. Practice along with soil and climatic factors

P13574 L11. So -> As such

Answer: We revised the sentences according to above suggestions.

Comments: P13574L22. Drastically greater or smaller? than (something is missing)

Answer: We have added the missing word “greater”.

Comments: P13582L12. concentrations

Table 5. Pls use subscripts for chemicals (ammonium, nitrate)

Answer: We have revised the Table 5 according to above suggestions.

Table 6. Summary of N_2O emissions from uplands under inorganic fertilizer application in the countries with temperate climate.

Site	MAT (°C)	MAP (mm)	SOC (g C kg^{-1})	pH	Warm season				Cold season				Whole year			Reference
					Crop	Applied N (kg N ha^{-1})	N_2O emission (kg N ha^{-1})	N_2O EF (%)	Crop	Applied N (kg N ha^{-1})	N_2O emission (kg N ha^{-1})	N_2O EF (%)	Applied N (kg N ha^{-1})	N_2O emission (kg N ha^{-1})	N_2O EF (%)	
Fengqiu, China	14	615	7	8.7	Maize	250	3.8	1.3	Wheat	250	0.6	0.3	500	4.5	0.8	Ding et al. (2007)
Huantai, China	13	586	10	8.3	Maize	330	1.6	0.4	Wheat	270	2.4	0.8	600	4.0	0.6	Cui et al. (2012)
Baoding, China	12	555	9	8.1	Maize	173	4.5	2.2	Wheat	165	3.3	1.3	338	7.7	1.8	Zhang et al. (2014c)
Tsukuba, Japan	16	1460	19	5.7	Soybean	20	2.7	13	Wheat	100	0.5	0.5	120	3.2	2.7	Nishimura et al. (2005)
Fukushima, Japan	14	1207	14	7.4	Barley	150	3.2	2.0	–	–	–	–	–	–	–	Shoji et al. (2001)
Madrid, Spain	13	430	8	7.3	Onion	110	0.8	0.6	Fallow	0	0.25	–	110	1.2	0.7	Meijide et al. (2009)
Lavesum, Germany	10	887	18	5.3	Wheat	220	0.6	0.2	Fallow	0	1.0	–	220	1.9	0.5	Lebender et al. (2014)
Turin, Italy	12	734	10	8.1	Maize	130	0.0	0.0	Fallow	0	2.9	–	130	2.9	3.4	Alluvione et al. (2010)
Boone, USA	9	825	33	7.2	Maize	168	2.9	1.0	–	–	–	–	–	–	–	Parkin and Hatfield (2014)
Michigan, USA	8	628	20	7.0	Maize	225	3.9	1.4	–	–	–	–	–	–	–	Hoben et al. (2011)
Michigan, USA	8	628	20	7.0	Maize	180	2.5	1.2	–	–	–	–	–	–	–	Hoben et al. (2011)
Michigan, USA	8	628	20	7.0	Maize	135	1.7	0.9	–	–	–	–	–	–	–	Hoben et al. (2011)
Michigan, USA	8	628	20	7.0	Maize	90	1.1	0.7	–	–	–	–	–	–	–	Hoben et al. (2011)
Michigan, USA	8	628	20	7.0	Maize	45	0.9	1.1	–	–	–	–	–	–	–	Hoben et al. (2011)
Morris, USA	6	645	32	7.2	Maize	78	–	–	Fallow	0	–	–	78	5.2	3.0	Johnson et al. (2012)
Morris, USA	6	645	32	7.2	Wheat	78	–	–	Fallow	0	–	–	78	4.2	2.8	Johnson et al. (2012)

MAT, mean annual temperature; MAP, mean annual precipitation; EF, the N_2O emission factor of applied N.

A marked-up manuscript version

Nitrous oxide emission and nitrogen use efficiency in response to nitrophosphate, N-(n-butyl) thiophosphoric triamide and dicyandiamide of a wheat cultivated soil under sub–humid monsoon conditions

W. X. Ding[1], Z. M. Chen[1], H. Y. Yu[1], J. F. Luo[2], G. Y. Yoo[3], J. Xiang[1], H. J. Zhang[1] and J. J. Yuan[1]

[1] State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China

[2] Land and Environment, AgResearch, Hamilton 3240, New Zealand

[3] College of Engineering, Kyung Hee University, Yongin–si 446–701, Republic of Korea

Abstract

A field experiment was designed to study the effects of nitrogen (N) source and urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) or nitrification inhibitor dicyandiamide (DCD) on nitrous oxide (N_2O) emission and N use efficiency (NUE) in a sandy loam soil. Six treatments including no N fertilizer (control), N fertilizer urea alone (U), urea plus NBPT (NBPT), (4) urea plus DCD (DCD), urea plus NBPT and DCD (NBPT + DCD), and nitrate-based fertilizer nitrophosphate (NP) were designed and implemented separately during the wheat growth period. Seasonal cumulative N_2O emissions with urea alone amounted to 0.49 ± 0.12 kg N_2O-N ha^{-1}

and were significantly ($P < 0.05$) reduced to 0.28 ± 0.03, 0.31 ± 0.01 and 0.26 ± 0.01 kg N_2O-N ha^{-1} by application of DCD, NBPT and NBPT + DCD, respectively. Cumulative N_2O emissions from NP were 0.28 ± 0.01 kg N_2O-N ha^{-1}. A single N_2O flux peak was identified following basal fertilization, and DCD and/or NBPT inhibition effects mainly occurred during the peak emission period. The NP application significantly ($P < 0.05$) increased wheat yield by 12.3 % and NUE from 28.8 % (urea alone) to 35.9 %, while urease and/or nitrification inhibitors showed a slight increase effect. Our results clearly indicated that the application of urea as basal fertilizer, but not as supplemental fertilizer, together with DCD and NBPT is an effective practice to reduce N_2O emissions. The application of NP instead of urea would be an optimum agricultural strategy for reducing N_2O emissions and increasing crop yield and NUE for wheat cultivation in soils of the North China Plain.

Key words: Ammonium-based fertilizer; Inhibitors; Nitrate-based fertilizer; Nitrogen use efficiency; Nitrous oxide; Wheat yield

1 Introduction

Nitrous oxide (N_2O) is a potent and long-lived atmospheric greenhouse gas, with an annual increasing rate of 0.26 % over the past decades and a contribution of 7 % to the annual increase in radiative forcing (IPCC, 2007). Agricultural soils are identified as the major source of atmospheric N_2O, contributing 4.1 Tg N yr^{-1} (IPCC, 2013) to the global atmospheric N_2O budget of ~ 14 Tg N yr^{-1} (Fowler et al., 2009). Field management practices ~~and~~ along with soil and climatic factors are recognized as being

45 determinants of N_2O emissions from agricultural soils (Stehfest and Bouwman, 2006;
46 Gagnon et al., 2011). Among management practices, the large inputs of industrially
47 fixed N in agriculture are a major perturbation to terrestrial N cycling and a major
48 contribution to accelerating N_2O emissions (Galloway et al., 2008). During the period
49 1990–2005, agricultural N_2O emissions were globally estimated to have increased by
50 17 % (USEPA, 2006), and are projected to increase by 35–60 % by 2030 due to the
51 continuous increase of global N fertilizer consumption and animal manure production
52 (FAO, 2003).

53 China is a major agricultural producer (West et al., 2014) and the amount of
54 applied N fertilizer has increased from 7.07 to 26.21 Tg N yr^{-1} over the period from
55 1977 to 2005 (Ju et al., 2009). The North China Plain, primarily containing low
56 organic carbon (C) calcareous soils (6.40 vs. 9.60 g C kg^{-1} for national upland soils)
57 (Xie et al., 2007), is an intensive agricultural region. It covers ~ 300 000 km^2 and
58 produces up to one-fourth of the total annual grain yield in China (Liu et al., 2001). A
59 winter wheat and summer maize rotation is a commonly used cropping system, and
60 the annual application rates of synthetic N fertilizers have amounted to 600 kg N ha^{-1}
61 or more (Zhao et al., 2006; Ju et al., 2009). However, a low proportion of fertilizer N
62 is taken up by crops (< 30 %) and it is estimated that up to 41 % of N applied during
63 the growth season is subject to losses via leaching, nitrification, denitrification and
64 ammonia volatilization (Cai et al., 2002). At present, up to 33 % of fertilizer N was
65 over-applied to the fields in China, resulting in China's contribution to 28 % of the
66 global annual N_2O emissions from croplands (West et al., 2014). Hence, it is urgent to

develop optimum methods for enhancing the recycling of N in the agricultural ecosystem and reducing the fertilizer N-induced N_2O emissions.

In the past decade, a number of field measurements of N_2O emissions have been conducted in the North China Plain (Meng et al., 2005; Ding et al., 2007; Ju et al., 2011). A 3 year field measurement showed that the direct N_2O emission factors of synthetic N applied to the wheat-maize cropping systems was 0.82% (Cai et al., 2013), which was higher than the 0.6% reported from fertilizer N-treated upland soils in China (Xing, 1998). Nitrification is found to be the main process for the N_2O emission because low availability of easily degradable organic C limits denitrification in this region (Ding et al., 2007; Ju et al., 2011). Nitrification inhibitors such as DCD help to retard the oxidation of NH_4^+ to NO_3^- by inhibiting the activities of *Nitrosomonas* bacteria in soil (Prasad and Power, 1995), resulting in the reduction of N_2O emissions directly by decreasing nitrification or indirectly by reducing the availability of NO_3^- for denitrification and leaching. As a consequence, DCD can increase NUE by increasing plant growth and N uptake (Asing et al., 2008). Similarly, a urease inhibitor like NBPT can slow the conversion of urea to NH_4^+, thereby reducing N losses by NH_3 volatilization (Manunza et al., 1999; Zaman et al., 2009) and potentially reducing nitrification and subsequent denitrification rates. ~~So~~As such the use of NBPT with urea-based fertilizers may be a potential management strategy to mitigate N_2O emissions (Menéndez et al., 2009). A combined application of nitrification inhibitor and urease inhibitor with urea can maintain N as NH_4^+ for a longer time with more chance of the fertilizer-derived N being taken up by the crops

89 or immobilized by the organic or mineral component of the soil, thereby reducing the
90 gaseous loss (Xu et al., 2002). Though application of inhibitors to reduce N_2O
91 emissions has attracted more attention recently and has already been investigated in
92 many areas (Menéndez et al., 2009; Zaman et al., 2009), their effect on N_2O emissions
93 in the North China Plain has not been fully investigated.

94 Soil N_2O emissions are also influenced by the source of fertilizer N. Gagnon et al.
95 (2011) found that N_2O emissions from urea ammonium nitrate were drastically greater
96 than those from anhydrous ammonia during the maize growth season in a poorly
97 drained clay soil of Canada. In contrast, Venterea et al. (2005, 2010) reported N_2O
98 emissions from soils amended with anhydrous NH_3 to be 2- to 4-fold greater than that
99 from soils receiving urea ammonium nitrate in a silt loam of the United States. Based
100 on the analysis of published data in the literature, Stehfest and Bouwman (2006)
101 concluded that the N_2O emissions from nitrate-based fertilizers were on average lower
102 than those from ammonium-based fertilizers. During the winter wheat growth season
103 in the North China Plain, limited precipitation occurs. Therefore, it is likely that
104 applying nitrate-based fertilizer instead of urea will not accelerate the leaching of
105 NO_3^- but reduce N_2O emissions and increase NUE.

106 In this study, we hypothesize that application of urease inhibitor and/or
107 nitrification inhibitor with urea will lower N_2O emission and increase wheat yield by
108 suppressing the nitrification rate and increasing NUE in the North China Plain. We
109 also hypothesize that use of a nitrate-based fertilizer nitrophosphate by replacing urea
110 will have similar effects. The objectives of this study were: (1) to evaluate the

111 influence of application of urea with NBPT, DCD and NBPT + DCD on N_2O
112 emissions and (2) to investigate whether the use of nitrophosphate instead of urea
113 reduces N_2O emissions from an intensively cultivated calcareous soil during the wheat
114 growth season.
115
116 **2 Materials and methods**
117 **2.1 Experimental site and soil characteristics**
118 The field experiment was conducted at the Fengqiu State Key Agro-ecological
119 Experimental Station, Chinese Academy of Sciences, Henan Province, China
120 (35º00'N, 114º24'E), a typical region of the North China Plain. The region has a
121 sub-humid temperate continental monsoon climate with dry cold winters and wet hot
122 summers. A winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.)
123 rotation is selected as an intensively managed double-cropping system. The 30 year
124 mean annual temperature was 13.9 °C, with a range varying from –1.0 °C in January
125 to 27.2 °C in July. The mean annual precipitation is 615 mm, two thirds of which falls
126 between June and September. The soil is derived from alluvial sediments of the
127 Yellow River and is classified as aquic inceptisol (Soil Survey Staff, 1994). The
128 physicochemical properties of the soil are summarized in Table 1.
129
130 **2.2 Treatment and crop management**
131 The field experiment was carried out during the winter wheat growth season and
132 included six fertilization treatments: (1) no N fertilizer (control), (2) N fertilizer urea

alone (U), (3) urea plus N-(n-butyl) thiophosphoric triamide (NBPT), (4) urea plus dicyandiamide (DCD), (5) urea plus NBPT and DCD (NBPT + DCD), and (6) nitrate-based fertilizer nitrophosphate (NP). The plots were arranged in a randomized complete block with three replicates and the plot size was 5 m × 5 m. Urea and nitrophosphate (Jinkai chemical, Kaifeng, China), totaling 200 kg N ha^{-1}, were added in two applications: 120 kg N ha^{-1} as basal fertilizer and 80 kg N ha^{-1} as supplemental fertilizer. Calcium superphosphate was applied as basal fertilizer at a rate of 125 kg P_2O_5 ha^{-1} for all treatments. For the NP treatment, calcium superphosphate was added as the basal fertilizer to ensure the same application rate of phosphate between the treatments. The NBPT (Hengshuo Chemical, Wuhan, China) and DCD (Sunnyfield Chemicals, Ningxia, China) were applied at a rate of 0.2 % and 10 % of the applied N (w/w), respectively. Inhibitor(s) and urea were thoroughly mixed. All basal fertilizers were evenly spread onto the soil surface by hand and immediately incorporated into the surface soil (0–20 cm) by plowing before sowing on 15 October 2009. The supplemental urea and inhibitor(s) or nitrophosphate were surface applied by hand, then integrated into the plowed layer with irrigation water (40 mm) on 6 March 2010. The mature wheat was harvested on 10 June 2010.

2.3 N_2O flux measurement

In situ soil-surface fluxes of N_2O were measured using the static chamber-gas chromatograph (GC) method. Flux measurements were taken over the period from 16 October 2009 to 8 June 2010 (235 days) during the wheat growth season. Immediately

155 after sowing, a PVC chamber base (30 cm × 30 cm × 10 cm) was inserted into the soil
156 about 5 cm deep between wheat rows in the center of each plot. The PVC chamber
157 (30 cm × 30 cm × 15 cm) was tightly fitted to the top of the base by inserting the
158 flange of the chamber into the water trough at the upper end of the chamber base. The
159 chamber was equipped with two ports: a small, silicon-sealed vent for sampling and a
160 second port for measuring chamber temperature. Gas samples were initially taken
161 twice a week and later reduced weekly then fortnightly over the winter. Sampling was
162 done in the morning between 09:00 LT and 12:00 LT in order to minimize diurnal
163 variation in flux patterns. Each time, four samples of the chamber air were manually
164 pulled into 50 mL syringes at 0, 10, 20 and 30 min after closure, injected into 20 mL
165 pre-evacuated vials fitted with butyl rubber stoppers and taken to our laboratory for
166 analysis. The air temperature inside the chamber was simultaneously measured with a
167 mercury thermometer.

168 N_2O concentrations were analyzed on a gas chromatograph (Agilent 7890, Santa
169 Clara, CA, USA) equipped with an electron capture detector. The interfering oxygen
170 contained in the injected gas sample (1.0 mL) was separated by a pre-column (1 m) in
171 combination with an analytical column (3 m). Both columns, packed with Porapak Q
172 (80/100 mesh), were attached directly to the 6-port valve to control the backflush. The
173 temperatures of column oven, injector and detector were 40 °C, 100 °C and 300 °C,
174 respectively. The flow rate of carrier gas (95 % Argon + 5 % CH_4) was 40 mL min^{-1}.
175 The standard N_2O gas was provided by the National Institute for Agro-Environmental
176 Sciences, Japan. The N_2O fluxes were calculated using the following equation:

$$F = \rho \times (P/760) \times (V/A) \times (\Delta C/\Delta t) \times [273/(273+T)] \quad (1)$$

where F is the N_2O flux (μg N_2O-N m^{-2} h^{-1}), ρ is the density of N_2O at 0 ºC and 760 mm Hg (kg m^{-3}), V is the chamber volume (m^3), A is the area from which N_2O was emitted into the chamber (m^2), $\Delta C/\Delta t$ is the rate of N_2O accumulation in the chamber (ppbv N_2O-N h^{-1}), T is the chamber air temperature in Celsius, and P is the air pressure of the experimental site (mm Hg). The altitude of the experimental site for this study is very close to sea level, so $P/760 \approx 1$. Few sample sets were discarded when they yielded a linear regression value of R^2 greater than 0.90.

2.4 Grain yield and aboveground N uptake

After crops reached physiological maturity (10 June 2011), grain and straw were manually harvested from each plot. Grain and straw were air-dried, then further dried for 3 days at 65 °C and weighed to obtain dry matter yields. Subsamples were ground with a ball mill and analyzed for N concentration with an elemental N analyzer (VarioMax, Elementar, Hanau, Germany). Total N content in aboveground biomass was calculated from the sum of N masses harvested in grain and straw from each plot.

2.5 Auxiliary variables

Soil temperatures were measured, simultaneously with gas sampling, at vertical depths of 5, 10 and 15 cm with a digital thermometer (Model 2455, Yokogawa, Japan). Soil moisture was measured at 5 cm depth at three different positions in the vicinity of each chamber using time domain reflectometry probes and was expressed as

water-filled pore space (WFPS) by the equation:

WFPS [%] = (volumetric water content [%]/total soil porosity [%]) × 100 (2)

where total soil porosity = 1 – (soil bulk density/2.65), with 2.65 [g cm^{-3}] being the assumed particle density of the soil. The precipitation and air temperature were monitored at a neighboring meteorological station 100 m away from the experimental field.

During the growth season, six soil samples were taken from the 0–20 cm soil layer at different positions in each plot just after flux measurement using a 5- cm diameter stainless steel soil sampler and then all samples from each plot were thoroughly mixed to form a composite. After visible roots and litter materials were removed, soil samples were passed through a 2 mm sieve and then extracted with 2 M KCl (soil/KCl suspension of 30:100 ratio) for 1 h on a rotary shaker. The extracted solutions were filtered and stored in a deep freezer (−18 °C) until analysis. The NH_4^+-N and NO_3^--N concentrations were measured using a colorimetric method on a Skalar segmented flow analyzer (SAN^{++}, the Netherlands).

2.6 Data analysis and statistics

Average fluxes and standard errors of the N_2O fluxes were calculated from triplicate plots. Seasonal cumulative N_2O emissions were calculated using the following equation:

$$\text{Cumulative } N_2O \text{ emission} = \sum_{i=1}^{n} (F_i + F_{i+1})/2 \times (t_{i+1} - t_i) \times 24 \quad (3)$$

where F is the N_2O flux (μg N_2O-N m^{-2} h^{-1}), i is the ith measurement, the term of

221 ($t_{i+1} - t_i$) is the number of days between two measurements, and n is the total number
222 of the measurements. The N_2O direct emission factor (%) of fertilizer N applied to the
223 soil with background adjustment was calculated as follows:

224 $$\text{Emission factor} = ((N_2O\text{-}N_{fertilizer} - N_2O\text{-}N_{control})/N_{fertilizer}) \times 100 \quad (4)$$

225 where $N_2O\text{-}N_{fertilizer}$ and $N_2O\text{-}N_{control}$ are the cumulative N_2O emissions (kg N_2O-N
226 ha^{-1}) in the N-fertilized treatment and the control treatment, respectively, and $N_{fertilizer}$
227 is the amount of fertilizer N applied (kg N ha^{-1}). Yield-scaled N_2O emissions were
228 calculated by dividing cumulative N_2O emission by grain yield for each plot. NUE
229 was calculated by dividing differences of the N amount in the aboveground biomass
230 between N-fertilized plots and control plots within the same block by the N
231 application rate (200 kg N ha^{-1}). Soil inorganic N intensities were calculated
232 separately for NH_4^+ (NH_4I), NO_3^- (NO_3I) and the sum of NO_3^- + NH_4^+ (IONI) as the
233 summation of daily NH_4^+-N, NO_3^--N or (NO_3^- + NH_4^+)-N concentrations in the 0–20
234 cm layer over the same period as for cumulative N_2O emissions using linear
235 interpolation between sampling dates, and presented in units of g d kg^{-1}, the index
236 being what is commonly reported (Zebarth et al., 2008; Engel et al., 2010).

237 All data were statistically analyzed using the SPSS software package for
238 Windows (Version 13.0, SPSS inc, Chicago, IL, USA). The effects of fertilization
239 management on N_2O emissions, emission factor, and grain yields were evaluated
240 using one-way ANOVA, followed by the least significant difference (LSD) test at $P <$
241 0.05. All dependent variables were evaluated for normality using the
242 Kolmogorov-Smirnov test and were log-transformed to normalize the distributions if

necessary prior to statistical analysis. Correlation and nonlinear regression analyses were used to test relationships between N_2O fluxes and other factors.

3 Results

3.1 Wheat yield and nitrogen use efficiency

Grain yield in the urea alone treatment was 4652 kg ha^{-1} and this was increased by 1.3 %, 1.8 % or 1.8 % when NBPT, DCD or both were added with urea fertilizer (Table 2). Compared with the urea alone, the increase in the grain yield in the NP treatment was 12.3 % (Table 2). The N process inhibitors, NBPT, DCD or the combination of both, slightly increased the amount of N uptake by wheat plants. However, this increase was not statistically significant ($P > 0.05$). A significant increase in the plant N uptake was observed in the NP treatment compared with urea only treatment ($P < 0.05$). The NUE was calculated at 28.8 % for the urea alone treatment and this was slightly increased to 29.2–31.2 % when urea was applied with NBPT, DCD or the combination of NBPT and DCD. However, the NUE was increased to 35.9% for the NP treatment, which was significantly higher than that for all the urea treatments ($P < 0.05$).

3.2 Soil temperature and moisture

Temporal variations of air temperature, precipitation, and soil WFPS and soil temperature at 5 cm depth over the experimental period are presented in Fig. 1. The cumulative rainfall over the wheat growth season was 97.6 mm which was lower than

the long-term average. Soil moisture levels were highly variable, with WFPS values varying from 10.7 % to 80.4 %. Periods with high soil moisture (> 75 % WFPS) were observed following heavy rainfall or irrigation events. Soil temperature at 5 cm depth was below zero in early January and increased to 23 °C in early June.

3.3 N_2O emissions

Variations of the N_2O fluxes over the wheat growth season are illustrated in Fig. 2. N_2O fluxes from all fertilizer-incorporated treatments showed almost the same pattern with peak N_2O fluxes being observed soon after application of basal fertilizers. The fluxes from all ~~the~~ N fertilizer treatments were generally low on most of the other sampling dates and these fluxes were not significantly different from those from the control. On several occasions in the winter the fluxes were negative. No significant increases in the N_2O fluxes were found following the supplemental fertilization coupled with irrigation. N_2O fluxes did not increase after heavy rainfall events either.

The peak N_2O flux was 120.4 μg N_2O-N m^{-2} h^{-1} in the urea alone treatment. Compared with the urea only, application of NBPT, DCD or the combination of both reduced the peak fluxes by 41.1 %, 75.0 % and 61.2 %, respectively. Application of NP reduced peak fluxes by 69.1 % compared with application of urea alone. Analysis showed that the natural logarithms of the N_2O fluxes were weakly, but not significantly, correlated with soil WFPS in all treatments except the DCD treatment, but significantly ($P < 0.05$) correlated with soil temperature in all treatments except the NBPT + DCD treatment (Table 3).

Cumulative N_2O emissions from the different treatments are listed in Table 4. Total N_2O emissions from the control, urea alone, urea + NBPT, urea + DCD, urea + NBPT + DCD and NP treatments were 0.16 ± 0.02, 0.49 ± 0.12, 0.31 ± 0.01, 0.28 ± 0.01, 0.26 ± 0.01 and 0.28 ± 0.03 kg N_2O-N ha^{-1}, respectively, over the wheat growth season. The highest total N_2O emission was found from the plot which only received urea. These emissions mainly occurred during the 18 day peak emission period following basal fertilizer application from 16 October to 3 November. Application of NBPT, DCD or the combination of both significantly reduced the seasonal N_2O emissions from urea by 36.7 %, 42.9 % or 46.9 %, respectively ($P < 0.05$). Compared with the emissions from the urea alone treatment, significantly lower N_2O emissions were also observed from the NP treatment ($P < 0.05$) (42.9 % less than those from the urea alone treatment). The direct N_2O emission factor for urea application alone was 0.17 %, and the addition of NBPT, DCD or the combination of both reduced the emission factor for urea to 0.05–0.08 %. These reductions were statistically significant ($P < 0.05$). The direct N_2O emission factor for NP was 0.06 %, which was also significantly lower than that for urea application alone ($P < 0.05$).

The grain yield-scaled N_2O emission from the NP treatment was significantly lower than that from the urea alone treatment ($P < 0.05$), but not different from those from the NBPT, DCD or NBPT + DCD treatments during the wheat growth season (Table 4).

3.4 Soil NH_4^+ and NO_3^- concentrations

309 Soil NH_4^+ and NO_3^- concentrations drastically increased after application of basal N
310 fertilizers compared with the control. The levels of NO_3^- in the NBPT and NBPT +
311 DCD treatments were relatively low for one week after basal fertilizer application
312 compared with those in the other treatments. However, the levels of NO_3^- in the
313 NBPT and NBPT + DCD treatments gradually increased, this was probably due to
314 degradation of NBPT and its subsequent loss of effectiveness. Following application
315 of supplemental fertilizer urea, no apparent increase in soil NO_3^- levels was observed,
316 and NO_3^- concentration kept at a relatively constant level. In contrast, soil NO_3^-
317 concentration following application of supplemental fertilizer NP showed a rapidly
318 decreasing trend. In all urea-added treatments, soil NO_3^- concentration sharply
319 decreased to less than 10 mg N kg^{-1} from 15 April onwards.

320 Soil NH_4^+ concentration increased from 2 to 10 mg N kg^{-1} after application of
321 basal fertilizer; however it sharply decreased soon afterwards. Application of DCD or
322 NBPT + DCD sustained soil NH_4^+ concentrations at higher levels compared with urea
323 application alone. In the NP treatment, soil NH_4^+ concentrations were always at low
324 levels. The natural logarithms of the N_2O fluxes were more correlated with NH_4^+
325 concentrations than with NO_3^- concentrations in the soil, despite the fact that a
326 significant relationship was only observed in the urea alone treatment.

327 Mean soil NH_4I levels in the NP treatment were the lowest among all N-added
328 treatments and tended to be higher in the DCD and NBPT + DCD treatments
329 compared with urea alone (Table 5). Mean soil NO_3I levels showed a similar trend
330 among the treatments and were ranked in the order of NBPT, NBPT + DCD > DCD >

331 urea alone, NP > control. Mean soil IONI levels were also similar among the
332 treatments and were ranked as NBPT + DCD > NBPT, DCD > urea alone, NP >
333 control.
334
335 **4 Discussion**
336 **4.1 Nitrous oxide emissions as affected by nitrogen sources**
337 Compared with the urea alone, application of NP significantly reduced N_2O emissions
338 by 42.9 % during the wheat growth season (Table 4), and increased wheat yield by
339 12.3 % and NUE by 24.7 % (Table 2). Ju et al. (2011) obtained a similar result in the
340 North China Plain, finding that emissions of N_2O derived from $Ca(NO_3)_2$ were lower
341 than those from $NH_4(SO_4)_2$ during the maize growth season (0.38–0.81 vs. 1.31–3.52
342 kg N_2O-N ha^{-1}). A lower N_2O emission for urea ammonium nitrate than for
343 anhydrous ammonia was also reported in a silt loam of the United States (Venterea et
344 al., 2005). In contrast, Gagnon et al. (2011) measured a significantly higher N_2O
345 emission following application of urea ammonium nitrate or calcium ammonium
346 nitrate compared with anhydrous ammonia in a poorly drained clay soil of Canada. In
347 a German grassland ecosystem, Müller and Sherlock (2004) found that the emissions
348 for ammonium-based fertilizer were lower than those for nitrate-based fertilizer.
349 These researchers suggested that higher emissions from nitrate-based fertilizers were
350 because of the propensity of the fine-textured clay soil to become anaerobic following
351 rainfall and a strong fixation of NH_4^+ in clay lattices reducing NH_4^+ available for N_2O
352 production (Chantigny et al., 2004). In this study, mean soil NO_3^- intensities (NO_3I)

were not significantly different between the NP and urea alone treatments (Table 5), and mean NO_3^- concentrations (Fig. 3) were higher than the suggested threshold value for denitrification of 5 mg N kg^{-1} (Dobbie and Smith, 2003) during the growth season except for the period from 24 April to 10 June. These results imply that soil NO_3^- concentration was not the only limiting factor affecting denitrification and N_2O emission in the test soil.

The notable difference in the seasonal N_2O emissions between the NP and urea alone treatments occurred mainly during the 18 day peak emission period following the basal fertilizer application and concurrent irrigation from 16 October to 3 November. It has been reported that application of ammonium-based fertilizers emitted more N_2O than nitrate-based fertilizers under aerobic soil conditions, while application of nitrate-based fertilizers induced a greater increase in N_2O production when soil conditions were anoxic (Pathak and Nedwell, 2001; Tenuta and Beauchamp, 2003). For cultivated soils, the primary mechanism of N_2O production is generally believed to be the nitrification process when soil WFPS levels are between 30 % and 70 % and the denitrification process when soil WFPS levels were between 70 % and 90 % (Granli and Bøckman, 1994). Some other studies also suggest that denitrification could in general produce more N_2O compared with nitrification (eg. Dobbie et al., 1999). According to the studies of Ding et al. (2007) and Wan et al. (2009), N_2O in sandy loam soils of the North China Plain was primarily produced by nitrification unless soil WFPS reached 75 % or more. Pihlatie et al. (2004) reported that even at 100 % WFPS in a loamy sand soil with 24 g organic C kg^{-1}, nitrification

375 was still the dominant N_2O production process. In this study, the highest soil WFPS
376 measured during the peak emission period was ~65 %; thus we suggest that low soil
377 moisture limited denitrification and N_2O production from the nitrate-based fertilizer in
378 the test soil.

379 In the North China Plain, the addition of starch to soil treated with nitrate-based
380 fertilizers in the field stimulated N_2O production through denitrification, but wheat
381 straw amendment did not do so (Wan et al., 2009; Ju et al., 2011). Previous studies
382 demonstrated that denitrification was not only controlled by soil moisture and nitrate,
383 but also by organic C supply, and increasing organic C availability could reduce the
384 minimum soil moisture threshold for denitrification (van Groenigen et al., 2004;
385 Chantigny et al., 2013). Yu et al. (2012) found that the mass proportion of
386 macroaggregates in a NPK-treated soil with 6.0 g organic C kg^{-1} only accounted for
387 8.8 %, while this proportion amounted to 30.8 % in an 18 year compost-added soil
388 with 10.0 g organic C kg^{-1} in the North China Plain. This change significantly
389 increased the proportion of pores with a neck diameter < 4 μm by reducing the
390 proportion of pores with a neck diameter of 15–60 μm, which in turn lowered the
391 effective diffusion coefficient of oxygen in the soils and the ratio of monounsaturated
392 to branched phospholipid fatty acids (PLFAs) i.e. aerobic to anaerobic
393 microorganisms (Zhang et al., 2014a). According to results found by Myrold and
394 Tiedje (1984), only large aggregates have anaerobic microsites. Thus, it is likely that
395 the relatively low organic C concentration in the test soil retards macroaggregation
396 and slows formation of anaerobic microsites, which in turn results in rise of the

minimum moisture threshold required for denitrification. Consequently, the denitrification process is of much less importance than nitrification for N_2O production and emissions in soils of the North China Plain.

In a German silt loam soil, similar to that tested in this study, Rover et al. (1998) reported that winter was a key period for N_2O emissions from arable crops in the temperate climate zone, contributing ~ 70 % of the annual N_2O losses during the thawing from December to February. Wolf et al. (2010) also verified that N_2O pulses due to spring thaw dominated total annual N_2O emission in a steppe grassland of Inner Mongolia, China. At our site, spring thawing of the soil at the fertilized plots only caused minor N_2O emission pulses, which were considerably lower than those reported earlier for other arable soils (Syväsalo et al., 2004; Teepe et al., 2000). It is suggested that reduced oxygen supply through alteration of pore structure during thawing, and high soil water contents in the winter, would promote microbial denitrification (Edwards and Killham, 1986; Mørkved et al., 2006). Our present study, together with previous measurements (Ding et al., 2007; Ju et al., 2010; Cui et al., 2012; Cai et al., ~~2012~~2013~~; Cui et al., 2012~~), showed that the highest soil WFPS was no more than 70 % during the spring thawing period, a value that was lower than the threshold value of 80 % for thawing N_2O pulses in a silt loam found by Rover et al. (1998). The cumulative rainfall during the winter period from December 2009 to February 2010 was only 4.4 mm and no apparent snow cover was observed at our study site. So the warm temperate monsoon zone, with cold and dry winter in the North China Plain, which is distinctly different from other climatic zones such as

419 western Europe (Dobbie and Smith 2003) and Inner Mongolia of China (Wolf et al.,
420 2010), would not induce thawing N_2O pulses from arable soils, as found in our study.
421 However, Zhang et al. (2014b) found that the North China Plain is a large agricultural
422 N_2O source in China, contributing 36.3 % of the total annual N_2O emission from the
423 China's croplands. To make a global comparison, we compiled the literature data of
424 N_2O emissions from the temperate uplands under inorganic N fertilizer application in
425 some countries of Asia, Europe and North America with similar latitudes to the
426 studied region (Table 6). The emission factors of N applied in the North China Plain
427 are generally lower than in the other countries, indicating a lower capacity of N
428 applied being converted into N_2O in the test soil. This is probably because N_2O is
429 predominantly produced from nitrification and denitrification is organic C-limited as
430 discussed above. In contrast, the total N_2O emissions from the studied region are
431 obviously higher due to the greater N fertilizer loading (Ju et al., 2009), suggesting
432 that agricultural practices for reducing N_2O emission are urgently required. Our
433 results confirm that N fertilizer sources influence soil N_2O emissions, but that this
434 effect probably depends on soil properties and especially climate conditions. Our
435 study also suggests that, compared with urea or ammonium-based fertilizer, applying
436 nitrate-based fertilizer is an effective management strategy to mitigate N_2O emissions
437 and to increase NUE and wheat yield in the North China Plain.
438
439 **4.2 Nitrous oxide emissions as affected by inhibitors**
440 The application of basal fertilizer urea followed by flooding irrigation resulted in N_2O
441 emission pulses for 18 days. This finding is in agreement with those of other studies

for arable fields (Bouwman et al., 2002; Ding et al., 2007; Cui et al., 2012). The presence of inhibitors NBPT and/or DCD significantly lowered N_2O peak fluxes, and cumulative N_2O emissions during the 18 day peak emission period were reduced by 50.0 % by NBPT, 78.6 % by DCD and 67.9 % by NBPT + DCD, compared with application of urea alone. Our results indicate that the addition of DCD alone or in combination with NBTP effectively reduced N_2O emissions from application of urea. In other sites of the North China Plain, Liu et al. (2013) also reported that nitrification inhibitors DCD and DMPP (3,4-dimethylpyrazole phosphate) could reduce N_2O emissions from application of N fertilizers by 30 % and 21 %, respectively, during the wheat growth season. Ju et al. (2011) observed no apparent differences in cumulative N_2O emissions between zero N control and urea with DMPP during the maize growth season, suggesting strong nitrification inhibition effectiveness of DMPP.

N_2O emission is directly related to the amount of mineral N available in the soil and application of inhibitors with urea can effectively regulate the NO_3^- and NH_4^+ concentrations (Li et al., 2009; Zaman et al., 2009). Recently, Maharjan and Venterea (2013) demonstrated that N_2O emissions were more correlated with soil NO_2^- intensity rather than NO_3^- or NH_4^+ intensity, and that inhibitors controlled N_2O production by adjusting soil NO_2^- intensity. In this study, soil NH_4^+ concentration slightly increased in the presence of DCD and, in contrast, relatively low NH_4^+ concentration was found after NBPT application following application of basal fertilizer. NBPT delays urea hydrolysis, thereby lowering soil pH elevation and NH_4^+ production, which can in turn reduce NH_3 toxicity effects on nitrite-oxidizing bacteria

464 (NOB). DCD slows oxidation of NH_4^+ to NO_2^- mainly by inhibiting activities of
465 ammonia-oxidizing bacteria (AOB), which allows NOB to use NO_2^- at the rate closely
466 matched to its production rate (Zaman et al., 2008; Maharjan and Venterea, 2013).
467 Both NBPT and DCD could additively attenuate formation of N_2O from urea in the
468 soil. Thus, the reduction of N_2O emissions by inhibitors is probably due to both low
469 oxidation rate of NH_4^+ and low NO_2^- concentration, thereby reducing N_2O "leaking"
470 as a by-product of nitrification (Firestone and Davidson, 1989).

471 Following supplemental fertilization with or without inhibitors, no distinct N_2O
472 flux peaks were found in our study. This may be attributable to no significant increase
473 of soil NH_4^+ and NO_3^- concentrations after urea top-dressing. Cui et al. (2012)
474 ascribed low increases in mineral N concentrations to large losses of urea-derived
475 ammonia via volatilization. However, a field measurement at our study site showed
476 that < 1 % of the N applied was lost via volatilization following urea top-dressing in
477 March (Ni et al., 2009); so a large amount of NH_3 loss would not occur at our site.
478 Milchunas et al. (1988) suggested that urea hydrolysis is primarily affected by soil
479 moisture. An incubation at 13 °C demonstrated that lowering soil moisture level from
480 60 % to below 40 % water holding capacity produced a longer lag before ammonia
481 evolution and considerably retarded urea hydrolysis (Foster et al., 1980). The range of
482 soil WFPS between 40 and 60 % during the period following urea top-dressing with
483 subsequent irrigation suggested that soil moisture could partly have affected N_2O
484 production. Suter et al. (2011) observed that lowering incubation temperature from 25
485 °C to 5 °C greatly retarded the hydrolysis of urea when WFPS was below 60%,

especially for an alkaline soil with low urease activity. In contrast, the temperature decrease increased the inhibitory effectiveness of NBPT on urea hydrolysis. In this study, soil temperature measured in the field after urea top-dressing varied from 2 °C to 9 °C, close to or just above the thresholds for nitrification (above 5.0 °C) (Anderson et al., 1971) and urea hydrolysis (~ 2 °C) (Xu et al., 1993; Yadav et al., 1987). It is obvious that low soil temperature led to the absence of fertilizer N-induced N_2O flux peaks following the supplemental fertilization and urease or nitrification inhibitors should not necessarily be applied with supplemental fertilizers during the wheat growth season.

Application of urea with NBPT and/or DCD compared with urea alone slightly increased wheat yields, which differs from application of NP. Similar results were also obtained by Ju et al. (2011) and Liu et al. (2013) in the North China Plain. A meta-analysis of data measured in Germany showed that N fertilizers with nitrification inhibitors did not significantly influence the yields of all investigated crops (Hu et al., 2014). The absence of inhibitor effects on crop yields might have been ascribed to the following three reasons. Firstly, low precipitation during the wheat growth season reduced the risk of N leaching and resulted in low N losses. This is evidenced by the significant stimulation of NP on wheat yields. Secondly, it is well known that the application rate of N fertilizers is far above optimum for crops (West et al., 2014). The overloading of N fertilizer might mask the influence on crop yields of increased mineral N in soils caused by inhibitors. The result of Sharma and Prasad (1996) supported the hypothesis that application of DCD significantly increased

maize yield when the application rate of fertilizer N was as low as 60 kg N ha^{-1}. It should be noted that the increase in NH_4^+ concentration in the test soil due to DCD application alone following the basal fertilization may stimulate NH_3 volatilization, resulting in higher N losses compared with urea alone, since NH_3 volatilization accounted for ~ 13 % of N applied (Ni et al., 2009). Mahmood et al. (2011) demonstrated that application of DCD to an alkaline calcareous soil increased fertilizer N losses. Finally, also more importantly, application of DCD with supplemental fertilizer slowed the nitrification rate and then lowered NO_3^- supply for wheat growth when it was at the rapid growth stage. A lower soil NO_3^- concentration in the NP treatment than in the urea-added treatments following the supplemental fertilizer in this study supports this speculation. Based on this study, it is not necessary to apply DCD with supplemental fertilizer urea and a combination of urease and nitrification inhibitors would be a better approach to reduce N_2O emission than urease or nitrification inhibitor application alone with basal fertilizer urea for wheat cultivation.

5 Conclusions

The present field study provided an insight into N_2O emissions from a calcareous soil during the wheat growth season in the North China Plain, as affected by application of urease or nitrification inhibitors and nitrate-based fertilizer nitrophosphate. A single N_2O flux peak was found following basal fertilization during the wheat growth period. Application of urea with NBPT, DCD or NBPT + DCD significantly reduced N_2O

emissions from urea by 36.7 %, 42.9 % or 46.9 %, respectively. Application of nitrophosphate also resulted in reduction of total N_2O emissions by 42.9 %, compared with application of urea alone. NBPT and/or DCD were effective in reducing N_2O emissions following basal fertilization. Compared with urea application alone, application of inhibitors with urea, either individually or combined together, slightly increased wheat yield and NUE, while nitrophosphate significantly increased wheat yield by 12.3 % and increased NUE from 28.8 % (urea alone) to 35.9 %. N_2O flux was primarily affected by soil temperature and low temperature at the study site minimized fertilizer N-induced N_2O peaks following application of supplemental fertilizer. Based on our findings, the combination of NBPT and DCD with basal fertilizer urea would be an effective practice for reducing N_2O emission. As well, this study suggests that application of nitrophosphate, instead of urea, is an optimum agricultural strategy for reducing N_2O emission and for increasing crop yield and NUE for wheat cultivation in the soils of the North China Plain.

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Reference

Alluvione, F., Bertora, C., Zavattaro, L., and Grignani, C.: Nitrous oxide and carbon

552 dioxide emissions following green manure and compost fertilization in corn, Soil
553 Sci. Soc. Am. J., 74, 384–395, 2010.
554 Anderson, O. E., Boswell, F. C., and Harrison, R. M.: Variations in low temperature
555 adaptability of nitrifiers in acid soils, Soil Sci. Soc. Am. Pro., 35, 68–71, 1971.
556 Asing, J., Saggar, S., Singh, J., and Bolan, N. S.: Assessment of nitrogen losses from
557 urea and organic manure with and without nitrification inhibitor, dicyandiamide,
558 applied to lettuce under glasshouse conditions, Aust. J. Soil Res., 46, 535–541,
559 2008.
560 Bouwman, A. F., Boumans, L. J. M., and Batjes, N. H.: Emissions of N_2O and NO
561 from fertilized fields: summary of available measurement data, Global
562 Biogeochem. Cy., 16, 1058, 2002..
563 Cai, G., Chen, D., White, R. E., Fan, X. H., Pacholski, A., Zhu, Z. L., and Ding, H.:
564 Gaseous nitrogen losses from urea applied to maize on a calcareous fluvo-aquic
565 soil in the North China Plain, Aust. J. Soil Res., 40, 737–748, 2002.
566 Cai, Y. J., Ding, W. X., and Luo, J. F.: Nitrous oxide emissions from Chinese
567 maize-wheat rotation systems: a 3 year field measurement, Atmos. Environ.,
568 65:112–122, 2013.
569 Chantigny, M. H., Angers, D. A., Morvan, T., and Pomar, C.: Dynamics of pig slurry
570 nitrogen in soil and plant as determined with ^{15}N, Soil Sci. Soc. Am. J. 68,
571 637–643, 2004.
572 Chantigny, M. H., Pelster, D. E., Perron, M. H., Rochette, P., Angers, D. A., Parent, L.
573 E., Massé, D., and Ziadi, N.: Nitrous oxide emissions from clayey soils amended

574 with paper sludges and biosolids of separated pig slurry, J. Environ. Qual., 42,
575 30–39, 2013.
576 Cui, F., Yan, G. X., Zhou, Z. X., Zheng, X. H., and Deng, J.: Annual emissions of
577 nitrous oxide and nitric oxide from a wheat-maize cropping system on a silt loam
578 calcareous soil in the North China Plain, Soil Biol. Biochem., 48, 10–19, 2012.
579 Ding, W. X., Cai, Y., Cai, Z. C., Yagi, K., and Zheng, X. H.: Nitrous oxide emissions
580 from an intensively cultivated maize-wheat rotation soil in the North China Plain,
581 Sci. Total Environ., 373, 501–511, 2007.
582 Dobbie, K. E., and Smith, K. A.: Impact of different forms of N fertilizer on N_2O
583 emissions from intensive grassland, Nutr. Cycl. Agroecosys., 67, 37–46, 2003.
584 Dobbie, K. E., McTaggart, I. P., and Smith, K. A.: Nitrous oxide emissions from
585 intensive agricultural systems: variations between crops and seasons, key driving
586 variables and mean emission factors, J. Geophys. Res. 104, 26891–26899, 1999.
587 Edwards, A. C., and Killham, K.: The effect of freeze/thaw on gaseous nitrogen loss
588 from upland soils. Soil Use Manage., 3, 86–91, 1986.
589 Engel, R., Liang, D. L., Wallander, R., and Bembenek, A.: Influence of urea fertilizer
590 placement on nitrous oxide production from a silt loam soil, J. Environ. Qual., 39,
591 115–125, 2010.
592 FAO: World Agriculture: Towards 2015/2030. An FAO Perspective. FAO, Rome. 97,
593 2003.
594 Firestone, M. K., and Davidson, E. A.: Microbiological basis of NO and N_2O
595 production and consumption in soil, in: Exchange of trace gases between

596 terrestrial ecosystems and the atmosphere, edited by: Andreae, M. O., and
597 Schimel, D. S., John Wiley & Sons, New York, 7–21, 1989.
598 Foster, N. W., Beauchamp, E. G., and Corke, C. T.: The influence of soil moisture on
599 urea hydrolysis and microbial respiration in jack pine humus, Can. J. Soil Sci.,
600 60, 675–684, 1980.
601 Fowler, D., Pilegaard, K., Sutton, M., Ambus, P., Raivonen, M., Duyzer, J., Simpson,
602 D., Fagerli, H., Fuzzi, S., and Schjrring, J. K.: Atmospheric composition change:
603 ecosystems – atmosphere interactions, Atmos. Environ., 43, 5193–5267, 2009.
604 Gagnon, B., Ziadi, N., Rochette. P., Chantigny, M. H., and Angers, D. A.: Fertilizer
605 source influenced nitrous oxide emissions from a clay soil under corn, Soil Sci.
606 Soc. Am. J., 75, 595–604, 2011.
607 Galloway, J. N., Townsend, A. R., Erisman, J. W., Bekunda, M., Cai, Z. C., Freney, J.
608 R., Martinelli, L. A., Seitzinger, S. P., and Sutton, M. A.: Transformation of the
609 nitrogen cycle: recent trends, questions, and potential solutions, Science, 320,
610 889–892, 2008.
611 Granli, T., and Bøckman, O.C.: Nitrous oxide from agriculture, Nor. J. Agric. Sci., 12,
612 1–128, 1994.
613 Hoben, J. P., Gehl, R. J., Millar, N., Grace, P. R., and Robertson, G. P.: Nonlinear
614 nitrous oxide (N_2O) response to nitrogen fertilizer in on-farm corn crops of the
615 US Midwest, Glob. Change Biol., 17, 1140–1152, 2011.
616 Hu, Y., Schraml, M., von Tucher, S., Li, F., and Schmidhalter, U.: Influence of
617 nitrification inhibitors on yields of arable crops: A meta–analysis of recent

studies in Germany, Int. J. Plant Prod., 8, 1735–6814, 2014.

IPCC: Climate Change 2007, The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007.

IPCC: Climate Change 2013, The Physical Science Basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2013.

Johnson, J. M. F., Weyers, S. L., Archer, D. W., and Barbour, N. W.: Nitrous oxide, methane emission, and yield-scaled emission from organically and conventionally managed systems, Soil Sci. Soc. Am. J., 76, 1347–1357, 2012.

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., and Zhang, F. S.: Reducing environmental risk by improving N management in intensive Chinese agricultural systems, P. Natl. Acad. Sci. USA, 106, 3041–3046, 2009.

Ju, X. T., Lu, X., Gao, Z. L., Chen, X. P., Su, F., Kogge, M., Römheld, V., Christie, P., and Zhang, F. S.: Processes and factors controlling N_2O production in an intensively managed low carbon calcareous soil under sub-humid monsoon conditions, Environ. Pollut., 159, 1007–1016, 2011.

Lebender, U., Senbayram, M., Lammel, J., and Kuhlmann, H.: Effect of mineral nitrogen fertilizer forms on N_2O emissions from arable soils in winter wheat production, J. Plant Nutr. Soil Sci., 177, 722–732, 2014.

640 Li, X. L., Zhang, G. B., Xu, H., Cai, Z. C., and Yagi, K.: Effect of timing of joint
641 application of hydroquinone and dicyandiamide on nitrous oxide emission from
642 irrigated lowland rice paddy field, Chemosphere, 75, 1417–1422, 2009.
643 Liu, C., Yu, J., and Kendy, E.: Groundwater exploitation and its impact on the
644 environment in the North China Plain. Water Int., 26, 265–272, 2001.
645 Liu, C., Wang, K., and Zheng, X.: Effects of nitrification inhibitors (DCD and DMPP)
646 on nitrous oxide emission, crop yield and nitrogen uptake in a wheat–maize
647 cropping system, Biogeosciences, 10, 2427–2437, doi:10.5194/bg-10-2427-2013,
648 2013.
649 Maharjan, B., and Venterea, R. T.: Nitrite intensity explains N management effects on
650 N_2O emissions in maize, Soil Biol. Biochem. 66, 229–238, 2013.
651 Mahmood, T., Ali, R., Latif, Z., and Ishaque, W.: Dicyandiamide increases the
652 fertilizer N loss from an alkaline calcareous soil treated with ^{15}N-labelled urea
653 under warm climate and under different crops, Biol. Fert. Soils, 47, 619–631,
654 2011.
655 Manunza, B., Deiana, S., Pintore, M., and Gessa, C.: The binding mechanism of urea,
656 hydroxamic acid and N-(n-butyl)-phosphoric triamide to the urease active site: a
657 comparative molecular dynamics study, Soil Biol. Biochem., 31, 789–796, 1999.
658 Meijide, A., Garcia-Torres, L., Arce, A., and Vallejo, A.: Nitrogen oxide emissions
659 affected by organic fertilization in a non-irrigated Mediterranean barley field, Agric.
660 Ecosyst. Environ., 132, 106–115, 2009.
661 Menéndez, S., Merino, P., Pinto, M., González-Murua, G., and Estavillo, J. M.: Effect

662 of N–(n–butyl) thiophosphoric triamide and 3, 4–dimethylpyrazole phosphate on
663 gaseous emissions from grasslands under different soil water contents, J. Environ.
664 Qual. 38, 27–35, 2009.
665 Meng, L., Ding, W. X., and Ca, Z. C.: Long-term application of organic manure and
666 nitrogen fertilizer on N_2O emissions, soil quality and crop production in a sandy
667 loam soil, Soil Biol. Biochem., 37, 2037–2045, 2005.
668 Milchunas, D. G., Parton, W. J., Bigelow, D. S., and Schimel, D. S.: Factors
669 influencing ammonia volatilization from urea in soils of the shortgrass steppe, J.
670 Atmos. Chem., 6, 323–340, 1988.
671 Mørkved, P. T., Dörsch, P., Henriksen, T. M., and Bakken, L. R.: N_2O emissions and
672 product ratios of nitrification and denitrification as affected by freezing and
673 thawing, Soil Biol. Biochem., 38, 3411–3420, 2006.
674 Müller, C., and Sherlock, R. R.: Nitrous oxide emissions from temperate grassland
675 ecosystems in the Northern and Southern Hemispheres, Global Biogeochem. Cy.,
676 18, GB1045, doi:10.1029/2003GB002175, 2004.
677 Myrold, D. D., and Tiedje, J. M.: Diffusional constraints on denitrification in soil,
678 Soil Sci. Soc. Am. J., 49, 651–657, 1984.
679 Ni, K., Ding, W. X., and Cai, Z. C.: Ammonia volatilization from soil as affected by
680 long-term application of organic manure and chemical fertilizers during wheat
681 growing season, J. Agro-Environ. Sci., 28, 2614–2622, 2009.
682 Nishimura, S., Sawamoto, T., Akiyama, H., Sudo, S., Cheng, W. G., and Yagi, K.:
683 Continuous, automated nitrous oxide measurements from paddy soils converted

684 to upland crops, Soil Sci. Soc. Am. J., 69, 1977–1986, 2005.
685 Parkin, T. B., and Hatfield, J. L.: Enhanced efficiency fertilizers: effect on nitrous
686 oxide emissions in Iowa, Agron. J., 106, 694–702, 2014.
687 Pathak, H., and Nedwell, D. B.: Nitrous oxide emission from soil with different
688 fertilizers, water levels and nitrification inhibitors, Water Air Soil Poll., 129,
689 217–228, 2001.
690 Pihlatie, M., Syväsalo, E., Simojoki, A., Esala, M., and Regina, K.: Contribution of
691 nitrification and denitrification to N_2O production in peat, clay and loamy sand
692 soils under different soil moisture conditions, Nutr. Cycl. Agroecosys., 70,
693 35–141, 2004.
694 Prasad, R., and Power, J. F.: Nitrification inhibitors for agriculture, health and the
695 environment, Adv. Agron., 54, 233–281, 1995.
696 Rover, M., Heinemeyer, O., and Kaiser, E. A.: Microbial induced nitrous oxide
697 emissions from an arable soil during winter, Soil Biol. Biochem., 30, 1859–1865,
698 1998.
699 Sharma, S. N., and Prasad, R.: Use of nitrification inhibitors (neem and DCD) to
700 increase N efficiency in maize-wheat cropping system, Fertil. Res., 44, 169–175,
701 1996.
702 Shoji, S., Delgado, J., Mosier, A., and Miura, Y.: Use of controlled release fertilizers
703 and nitrification inhibitors to increase nitrogen use efficiency and to conserve air
704 andwater quality, Commun. Soil Sci. Plant Anal., 32, 1051–1070, 2001.
705 Soil Survey Staff: Keys to soil taxonomy, 6th edn. United States Department of

706 Agriculture, Natural Resources Conservation Service, Washington, DC, 1994.
707 Stehfest, E., and Bouwman, L.: N_2O and NO emission from agricultural fields and
708 soils under natural vegetation: summarizing available measurement data and
709 modeling of global annual emissions, Nutr. Cycl. Agroecosys., 74, 207–228,
710 2006.
711 Suter, H. C., Pengthamkeerati, P., Walker, C., and Chen, D.: Influence of temperature
712 and soil type on inhibition of urea hydrolysis by N-(n-butyl) thiophosphoric
713 triamide in wheat and pasture soils in south-eastern Australia, Soil Res., 49,
714 315–319, 2011.
715 Syväsalo, E., Regina, K., Pihlatie, M., and Esala, M.: Emissions of nitrous oxide from
716 boreal agricultural clay and loamy sand soils, Nutr. Cycl. Agroecosys., 69,
717 155–165, 2004.
718 Teepe. R., Brumme, R., and Beese, F.: Nitrous oxide emissions from frozen soils
719 under agricultural, fallow and forest land, Soil Biol. Biochem., 32, 1807–1810,
720 2000.
721 Tenuta, M., and Beauchamp, E. G.: Nitrous oxide production from granular nitrogen
722 fertilizers applied to a silt loam soil, Can. J. Soil Sci., 83, 521–532, 2003.
723 United States Environmental Protection Agency (USEPA): Global Anthropogenic
724 Non-CO_2 Greenhouse Gas Emissions: 1990–2020, EPA 430-R-06-003, United
725 States Environmental Protection Agency, Washington, DC, 2006.
726 Van Groenigen, J. W., Kasper, G. J., Velthof, G. L., Dasselaar, Pol-van van den A.,
727 and Kuikman, P. J.: Nitrous oxide emissions from silage maize fields under

different mineral nitrogen fertilizer and slurry application, Plant Soil, 263, 101–111, 2004.

Venterea, R. T., Burger, M., and Spokas, K. A.: Nitrogen oxide and methane emissions under varying tillage and fertilizer management, J. Environ. Qual., 34, 1467–1477, 2005.

Venterea, R. T., Dolan, M. S., and Ochsner, T. E.: Urea decreases nitrous oxide emissions compared with anhydrous ammonia in a Minnesota corn cropping system, Soil Sci. Soc. Am. J., 74, 407–418, 2010.

Wan, Y. J., Ju, X. T., Ingwersen, J., Schwarz, U., Stange, C. F., Zhang, F. S., and Streck, T.: Gross nitrogen transformations and related nitrous oxide emissions in an intensively used calcareous soil, Soil Sci. Soc. Am. J., 73, 102–112, 2009.

West, P. C., Gerber, J. S., Engstrom, P. M., Mueller, N. D., Brauman, K. A., Carlson, K. M., Cassidy, E. S., Johnston, M., MacDonald, G. R. D. K., and Siebert, S.: Leverage points for improving global food security and the environment, Science, 345, 325–327, 2014..

Wolf, B., Zheng, X., Brüggemann, N., Chen, W., Dannenmann, M., Han, X., Sutton, M. A., Wu, H., Yao, Z., and Butterbach-Bahl, K.: Grazing-induced reduction of natural nitrous oxide release from continental steppe, Nature, 464, 881–884, 2010.

Xie, Z. B., Zhu, J. G., Liu, G., Georg, C., Toshihiro, H., Chen, C. M., Sun, H. F., Tang, H. Y., and Zeng, Q.: Soil organic carbon stocks in China and changes from 1980s to 2000s, Glob. Change Biol., 13, 1989–2007, 2007.

750 Xing, G. X.: N_2O emission from cropland in China, Nutr. Cycl. Agroecosys., 52,
751 249–254, 1998.
752 Xu, J. G., Heeraman, D. A., and Wang, Y.: Fertilizer and temperature effects on urea
753 hydrolysis in undisturbed soil, Biol. Fert. Soils, 16, 63–65, 1993.
754 Xu, X. K., Boeckx, P., van Cleemput, O., and Zhou, L. K.: Urease and nitrification
755 inhibitors to reduce emissions of CH_4 and N_2O in rice production, Nutr. Cycl.
756 Agroecosys., 64, 203–211, 2002..
757 Yadav, D. S., Kumar, V., Singh, M., and Relan, P. S.: Effect of temperature and
758 moisture on kinetics of urea hydrolysis and nitrification, Aust. J. Soil Res., 25,
759 185–191, 1987.
760 Yu, H. Y., Ding, W. X., Luo, J. F., Geng, R. L., and Cai, Z. C.: Long-term application
761 of compost and mineral fertilizers on aggregation and aggregate-associated
762 carbon in a sandy loam soil, Soil Till. Res., 124, 170–177, 2012.
763 Zaman, M., Nguyen, M. L., Blennerhassett, J. D., and Quin, B. F.: Reducing NH_3,
764 N_2O and NO_3-N losses from a pasture soil with urease or nitrification inhibitors
765 and elemental S-amended nitrogenous fertilizers, Biol. Fert. Soils, 44, 693–705,
766 2008.
767 Zaman, M., Saggar, S., Blennerhassett, J. D., and Singh, J.: Effect of urea and
768 nitrification inhibitors on N transformation, gaseous emissions of ammonia and
769 nitrous oxide, pasture yield and N uptake in grazed pasture system, Soil Biol.
770 Biochem., 41, 1270–1280, 2009.
771 Zebarth, B. J., Rochette, P., and Burton, D. L.: N_2O emissions from spring barley

772 production as influenced by fertilizer nitrogen rate, Can. J. Soil Sci., 88, 197–205,
773 2008.
774 Zhang, H. J., Ding, W. X., He, X. H., Yu, H. Y., Fan, J. L., and Liu, D. Y.: Influence of
775 20 year organic and inorganic fertilization on organic carbon accumulation and
776 microbial community structure of aggregates in an intensively cultivated sandy
777 loam soil, Plos One, 9, e92733, doi:10.1371/journal.pone.0092733, 2014a.
778 Zhang, W., Yu, Y. Q., Li, T. T., Sun, W. J., and Huang, Y.: Net greenhouse gas balance
779 in China's croplands over the last three decades and its mitigation potential,
780 Environ. Sci. Technol., 48, 2589–2597, 2014b.
781 Zhang, Y., Mu, Y., Zhou, Y., Liu, J., and Zhang, C.: Nitrous oxide emissions from
782 maize-wheat field during 4 successive years in the North China Plain,
783 Biogeosciences, 11, 1717–1726, 2014c.
784 Zhao, R. F., Chen, X. P., Zhang, F. S., Zhang, H., Schroder, J., And Romheld. V.:
785 Fertilization and nitrogen balance in a wheat maize rotation system in North
786 China, Agron. J., 98, 938–945, 2006.

787 **Table 1.** Soil properties.

Soil depth	pH	Bulk density	Organic C	Total N	C/N	NO_3^--N	NH_4^+-N	Particle size distrubution (%)		
(cm)	(H_2O)	(Mg m^{-3})	(g C kg^{-1})	(g N kg^{-1})		(mg N kg^{-1})	(mg N kg^{-1})	Sand	Silt	Clay
0-20	8.60	1.40	12.0	1.50	8.0	14.70	2.48	17.0	72.0	11.0

788

789 **Table 2.** Effects of urease and/or nitrification inhibitors and nitrophosphate on wheat biomass, amount of N uptake by crops and N use

790 efficiency.

Treatment	Biomass (kg ha^{-1})			Amount of N uptake (kg N ha^{-1})			N use efficiency (%)
	Grain	Straw	Total	Grain	Straw	Total	
Control	2297±150 c	2215±134 b	4513±283 c	24.4±1.6 c	11.9±0.7 b	36.4±2.3 c	–
U	4652±11 b	4075±81 a	8727±85 b	59.6±0.1 b	34.2±0.7 a	93.9±0.7 b	28.8 ±0.8 b
NBPT	4711±126 b	4098±356 a	8809±472 b	60.4±1.6 b	34.4±3.0 a	94.8±4.5 b	29.2 ±1.0 b
DCD	4736±103 ab	4080±52 a	8816±86 b	60.7±1.3 b	34.3±0.4 a	95.0±1.1 b	29.3 ±0.9 b
NBPT + DCD	4735±290 ab	4535±503 a	9271±764 ab	60.7±3.7 b	38.1±4.2 a	98.8±7.6 ab	31.2 ±1.2 b
NP	5225±142 a	4906±251 a	10131±370 a	67.0±1.8 a	41.2±2.1 a	108.2±3.7 a	35.9 ±1.1 a

791 Mean ± standard error (n = 3).

792 Different letters within the column indicate significantly difference between treatments at $P < 0.05$.

793 **Table 3.** Correlation between ln [N_2O flux + 1] and soil WFPS, soil temperature at depths of 5 (T_{5cm}), 10 (T_{10cm}) and 15 cm (T_{15cm}), ammonium

794 (NH_4^+-N), nitrate (NO_3^--N) or inorganic nitrogen (NH_4^+-N plus NO_3^--N) concentration.

Treatment	WFPS	T_{5cm}	T_{10cm}	T_{15cm}	NH_4^+-N	NO_3^--N	Inorganic N
Control	0.095	0.413**	0.376*	0.392*	–0.153	0.140	0.109
U	0.023	0.381**	0.340*	0.346*	0.274*	0.365**	0.380**
NBPT	0.118	0.275*	0.264	0.274	0.215	0.206	0.222
DCD	0.323*	0.282*	0.180	0.189	0.104	–0.127	–0.092
NBPT + DCD	0.021	0.216	0.252	0.272	0.074	0.155	0.156
NP	0.084	0.301*	0.370*	0.403**	0.105	–0.056	–0.037

795 * $P < 0.05$, ** $P < 0.01$.

Table 4. Effects of urease and/or nitrification inhibitors and nitrophosphate on cumulative N_2O emissions, fertilizer N-induced N_2O emission factors and yield-scaled N_2O emissions.

Treatment	Cumulative N_2O emission (kg N_2O-N ha^{-1})		Ratio of peak to total emissions (%)	Emission factor (% of applied N)	Yield-scaled N_2O emission (g N_2O-N kg^{-1} grain)
	Total	Peak			
Control	0.16±0.02 c	0.03±0.00 d	18.8±2.3 d	−	0.068±0.006 b
U	0.49±0.12 a	0.28±0.10 a	57.1±4.2 a	0.17±0.05 a	0.105±0.026 a
NBPT	0.31±0.01 b	0.14±0.01 b	45.2±3.9 b	0.08±0.00 b	0.065±0.003 b
DCD	0.28±0.01 b	0.06±0.01 c	21.4±2.1 d	0.06±0.00 b	0.060±0.004 b
NBPT + DCD	0.26±0.01 b	0.09±0.00 bc	34.6±3.2 c	0.05±0.00 b	0.056±0.003 b
NP	0.28±0.03 b	0.11±0.03 bc	39.3±3.7 c	0.06±0.01 b	0.053±0.008 b

Mean ± standard error (n = 3).

Peak emission denotes cumulative emissions during the 18 days' period following the basal fertilizer application from 16 October to 3 November.

Different letters within the column indicate significantly difference between treatments at $P < 0.05$.

Table 5. Effects of urease and/or nitrification inhibitors and nitrophosphate on soil ammonium (NH_4I), nitrate (NO_3I) and inorganic N (IONI) intensities.

Treatment	NH_4I (g N d kg^{-1})	NO_3I (g N d kg^{-1})	IONI (g N d kg^{-1})
Control	0.24±0.01 e	2.58±0.01 d	2.82±0.00 d
U	0.40±0.03 d	4.75±0.13 c	5.15±0.16 c
NBPT	0.61±0.02 c	6.18±0.08 a	6.79±0.08 b
DCD	0.96±0.01 b	5.74±0.01 b	6.70±0.01 b
NBPT + DCD	1.07±0.01 a	6.11±0.16 a	7.17±0.16 a
NP	0.36±0.02 d	4.69±0.09 c	5.05±0.07 c

Mean±standard error (n = 3). Different letters within the column indicate significantly difference between treatments at $P < 0.05$.

806 **Table 6.** Summary of N_2O emissions from uplands under inorganic fertilizer application in the countries with temperate climate.

Site	MAT (°C)	MAP (mm)	SOC (g C kg^{-1})	pH	Warm season				Cold season				Whole year			Reference
					Crop	Applied N (kg N ha^{-1})	N_2O emission (kg N ha^{-1})	N_2O EF (%)	Crop	Applied N (kg N ha^{-1})	N_2O emission (kg N ha^{-1})	N_2O EF (%)	Applied N (kg N ha^{-1})	N_2O emission (kg N ha^{-1})	N_2O EF (%)	
Fengqiu, China	14	615	7	8.7	Maize	250	3.8	1.3	Wheat	250	0.6	0.3	500	4.5	0.8	Ding et al. (2007)
Huantai, China	13	586	10	8.3	Maize	330	1.6	0.4	Wheat	270	2.4	0.8	600	4.0	0.6	Cui et al. (2012)
Baoding, China	12	555	9	8.1	Maize	173	4.5	2.2	Wheat	165	3.3	1.3	338	7.7	1.8	Zhang et al. (2014c)
Tsukuba, Japan	16	1460	19	5.7	Soybean	20	2.7	13	Wheat	100	0.5	0.5	120	3.2	2.7	Nishimura et al. (2005)
Fukushima, Japan	14	1207	14	7.4	Barley	150	3.2	2.0	–	–	–	–	–	–	–	Shoji et al. (2001)
Madrid, Spain	13	430	8	7.3	Onion	110	0.8	0.6	Fallow	0	0.25	–	110	1.2	0.7	Meijide et al. (2009)
Lavesum, Germany	10	887	18	5.3	Wheat	220	0.6	0.2	Fallow	0	1.0	–	220	1.9	0.5	Lebender et al. (2014)
Turin, Italy	12	734	10	8.1	Maize	130	0.0	0.0	Fallow	0	2.9	–	130	2.9	3.4	Alluvione et al. (2010)
Boone, USA	9	825	33	7.2	Maize	168	2.9	1.0	–	–	–	–	–	–	–	Parkin and Hatfield (2014)
Michigan, USA	8	628	20	7.0	Maize	225	3.9	1.4	–	–	–	–	–	–	–	Hoben et al. (2011)
Michigan, USA	8	628	20	7.0	Maize	180	2.5	1.2	–	–	–	–	–	–	–	Hoben et al. (2011)
Michigan, USA	8	628	20	7.0	Maize	135	1.7	0.9	–	–	–	–	–	–	–	Hoben et al. (2011)
Michigan, USA	8	628	20	7.0	Maize	90	1.1	0.7	–	–	–	–	–	–	–	Hoben et al. (2011)
Michigan, USA	8	628	20	7.0	Maize	45	0.9	1.1	–	–	–	–	–	–	–	Hoben et al. (2011)
Morris, USA	6	645	32	7.2	Maize	78	–	–	Fallow	0	–	–	78	5.2	3.0	Johnson et al. (2012)
Morris, USA	6	645	32	7.2	Wheat	78	–	–	Fallow	0	–	–	78	4.2	2.8	Johnson et al. (2012)

807 MAT, mean annual temperature; MAP, mean annual precipitation; EF, the N_2O emission factor of applied N.

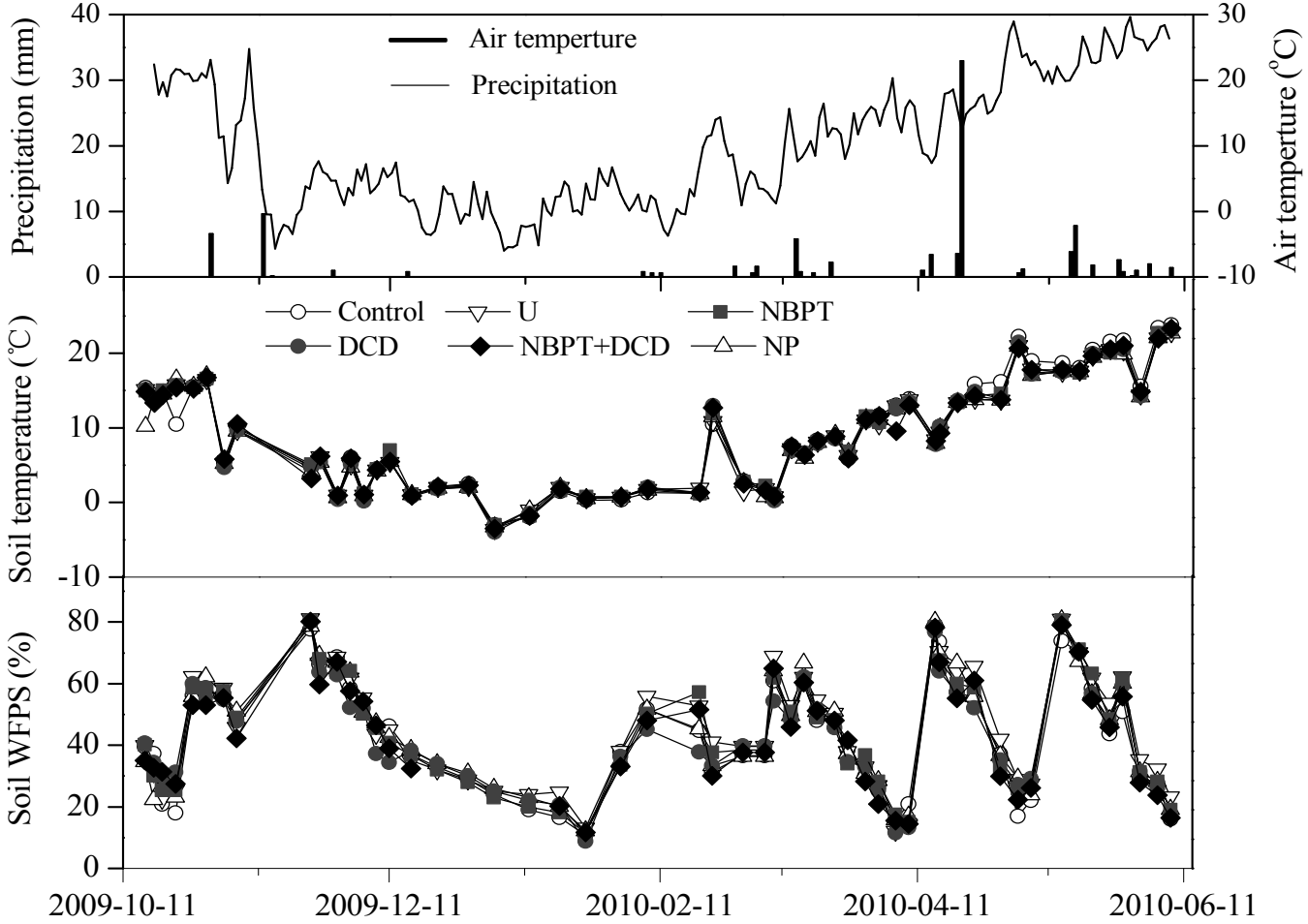
Figure caption

Figure 1. Temporal variation of daily precipitation and air temperature, and mean soil moisture and water-filled pore space (WFPS) at time of N_2O sampling in the control, urea alone (U), urea with NBPT (NBPT), urea with DCD (DCD), urea with NBPT + DCD (NBPT + DCD) and nitrophosphate (NP) treatments during the wheat growth season. The standard errors of soil temperature and moisture were not shown for figure clarity.

Figure 2. Temporal variation of nitrous oxide fluxes in the control, urea alone (U), urea with NBPT (NBPT), urea with DCD (DCD), urea with NBPT + DCD (NBPT + DCD) and nitrophosphate (NP) treatments during the wheat growth season. Flux values are mean values ± standard errors for three replicates. Arrows indicate date of fertilizer application.

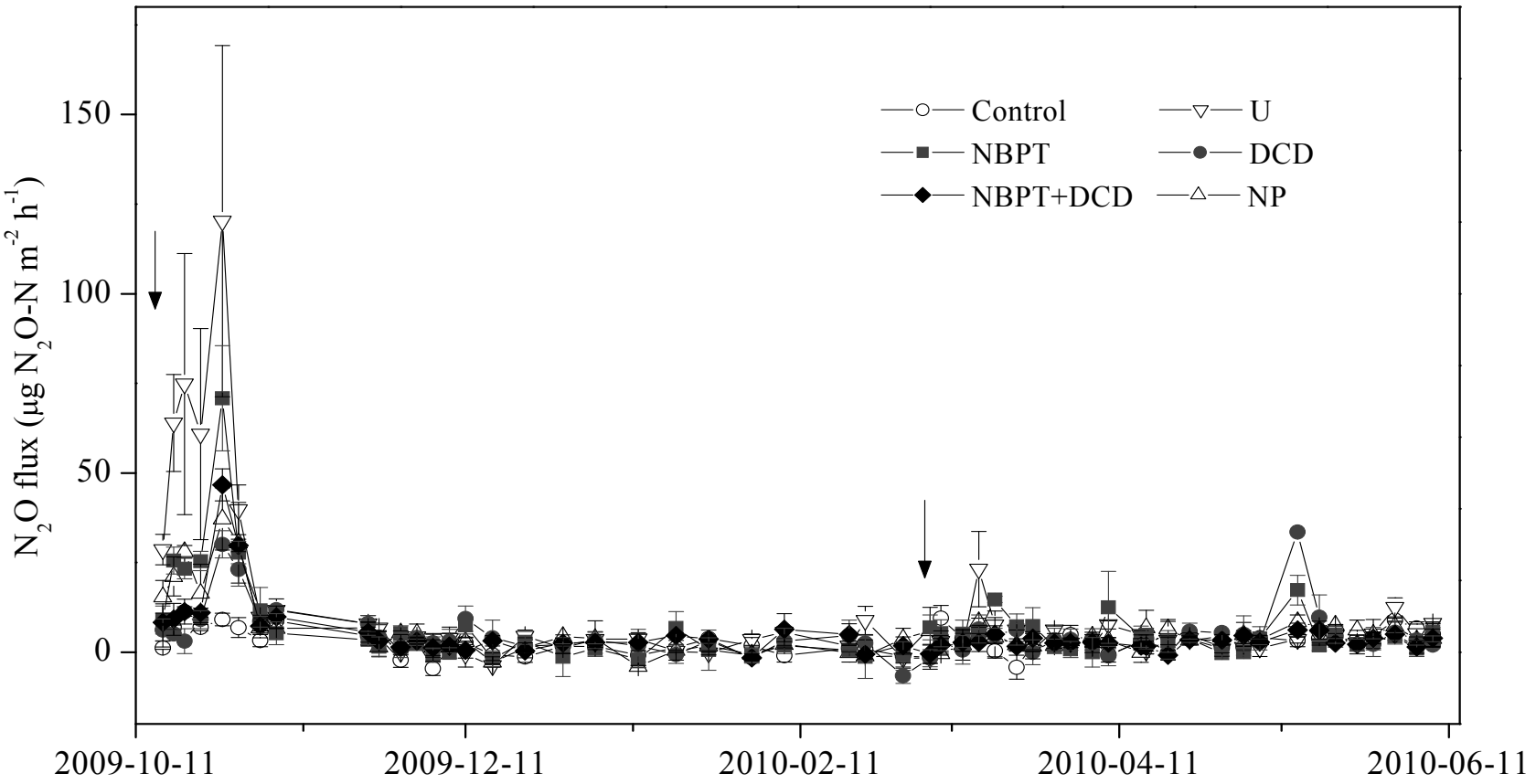
Figure 3. Temporal variation of ammonium and nitrate concentrations in samples from the 0–20 cm depth in the control, urea alone (U), urea with NBPT (NBPT), urea with DCD (DCD), urea with NBPT + DCD (NBPT + DCD) and nitrophosphate (NP) treatments during the wheat growth season. Vertical bars denote the standard error of the means (n = 3).

827 **Figure 1**



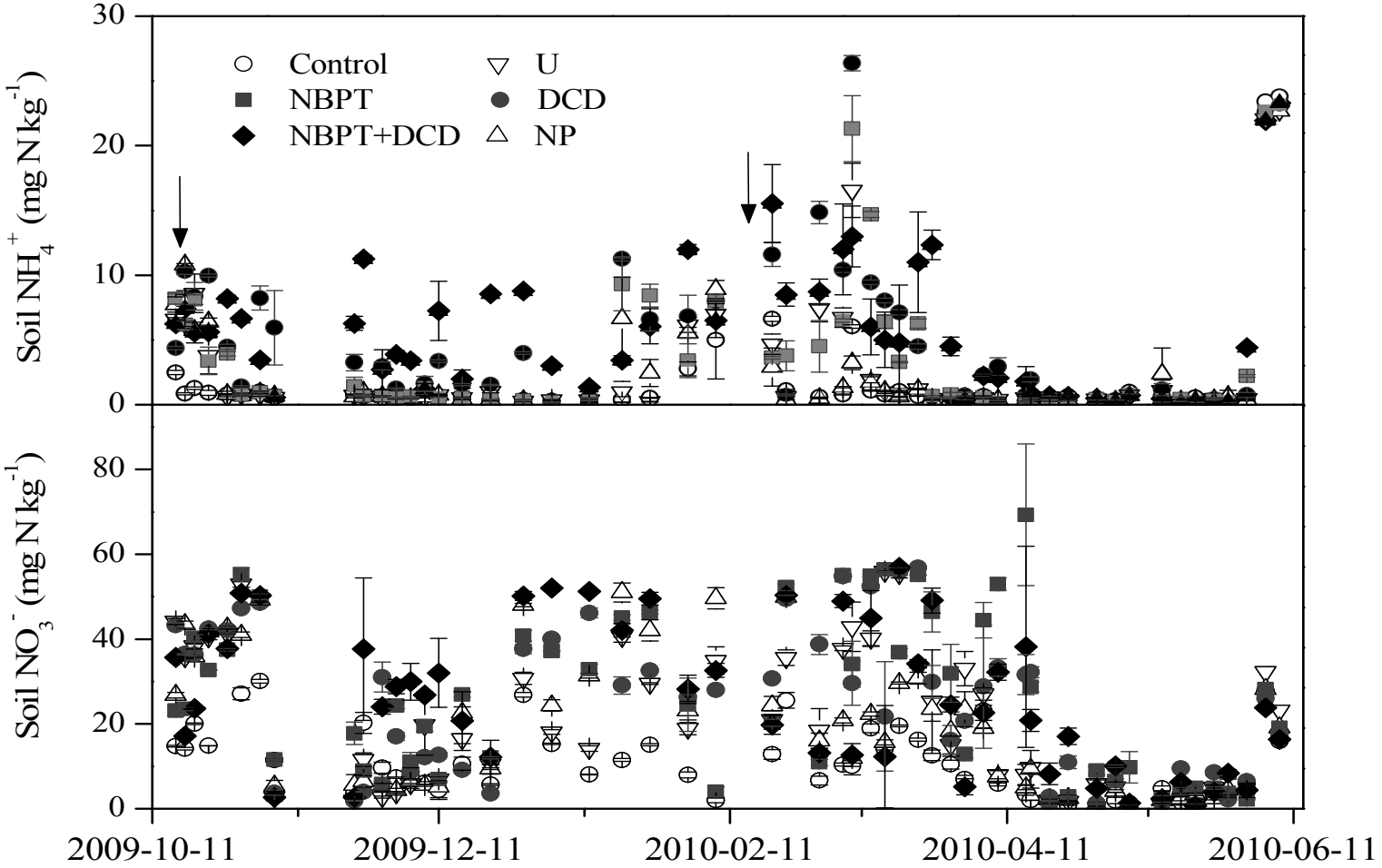
828

829 **Figure 2**



830

831 **Figure 3**



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