Effect of nitrification inhibitors on mitigating N₂O and NO emissions from an agricultural field under drip fertigation in the North China Plain

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HIGHLIGHTS

- Drip fertigation reduced N₂O (22%) but increased NO (18%) emissions.
- Drip fertigation combined with nitrification inhibitors reduced N₂O (66%) and NO (95%) emissions.
- Drip fertigation combined with nitrification inhibitors is a good choice for reducing.
- N₂O and NO emissions, increasing the maize yields, saving water and N fertilizer in the North China Plain

GRAPHICAL ABSTRACT

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ABSTRACT

N₂O and NO emissions from a winter wheat-summer maize rotation field with five different treatments in the North China Plain (NCP) were comparably investigated from 8 October 2014 to 11 October 2015. Compared with the treatments with only flood or drip irrigation, evident emission peaks of N₂O and NO from the fertilization treatments with flood irrigation (A-Flood) and with drip fertigation (A-Drip) were observed after each fertilization event, whereas their emissions from the fertilization treatments with nitrification inhibitors under drip fertigation (A + DCD-Drip and A + Nitrapyrin-Drip) were greatly suppressed. The reduction effect of the nitrification inhibitors on N₂O and NO emissions was found to be more conspicuous during the maize season than during the wheat season, implying that the soil temperature could play an important role in the reduction effect. Compared with the A-Flood treatment, the annual cumulative emission from the A-Drip treatment reduced by 22% for N₂O and increased by 18% for NO, whereas the reductions of N₂O and NO from the treatments with nitrification inhibitors could achieve as high as 66% and 95%, respectively. The yields of the maize were significantly greater from the A-Drip and A + Nitrapyrin-Drip treatments than from the A-Flood treatment, and the yields of the wheat were almost same among the treatments of A-Flood, A-Drip and A + DCD-Drip. Considering the yields, the water saving and the reduction of N₂O and NO emissions, the application of nitrification inhibitor combined with drip fertigation is recommended in the NCP.

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1. Introduction

Nitrous oxide (N₂O) and nitric oxide (NO) are important atmospheric trace gases, strongly influencing on atmospheric environment

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(Zhu et al., 2013). N₂O is one of important greenhouse gases, contributing to the global warming (Dickinson and Cicerone, 1986) and the depletion of stratospheric ozone (Ravishankara et al., 2009). NO is a critical precursor for atmospheric photo-oxidants and significantly contributes to the tropospheric ozone production and acid rain (Crutzen, 1979).

Agricultural soil has been regarded as an important source for atmospheric N₂O, accounting for ~50% of the global anthropogenic emissions (Denman et al., 2007). Meanwhile, soil biogenic NO emissions constitute ~20% of the global emissions (Denman et al., 2007). N₂O and NO emissions from agricultural soil are primarily resulted by N fertilizer application (Bouwman et al., 2002) and are mainly produced by the microbial processes of nitrification (ammonium oxidation to nitrate) and denitrification (nitrate reduction to N₂ via NO and N₂O) (Robertson and Groffman, 2014). Therefore, reducing the emissions of N₂O and NO from agricultural soil is very important for protecting the atmospheric environment which human relies on.

The NCP is the main grain production area of China and produces 50% of wheat and 33% of maize nationally (Wang et al., 2012). To achieve high yields, the current N inputs of 550–600 kg N ha⁻¹ yr⁻¹ largely exceed crop needs of about 200 kg N ha⁻¹ yr⁻¹ (Ju et al., 2009; Cui et al., 2010), resulting in relatively high emissions of N₂O and NO (Liu et al., 2011; Zhang et al., 2011; Liu et al., 2014; Zhang et al., 2014; Zhou et al., 2016), low N utilization efficiency (Cui et al., 2010), and serious N loss via nitrate leaching (Zhang et al., 1996; Ju et al., 2006). Additionally, water consumption of 800–900 mm yr⁻¹ for maintaining the crop yield (Liu et al., 2002) greatly exceeds the regional average precipitation of 480–500 mm yr⁻¹ (Zhang et al., 2003). To offset the deficit, 71% of the cultivation lands rely on the groundwater extraction which accounts for 70% of the total water consumption (Liu et al., 2001). The excessive extraction followed by the unreasonable irrigation method (flood irrigation) for decades has exacerbated the groundwater depletion in this severe water shortage region (Hu et al., 2010).

Drip fertigation has been verified as an advanced technology for increasing crop yields, saving N inputs and reducing water usage by directly delivering water and nutrient to crop root (Singandhupe et al., 2003; Patel and Rajput, 2008; Khonok1 et al., 2014). Reduction of N₂O emissions from agricultural fields under the subsurface drip fertigation with respect to the furrow irrigation has been reported (Kallenbach et al., 2010; Kennedy, T. et al., 2013; Kennedy, T.L. et al., 2013). Our previous study indicated that the surface drip fertigation with respect to the flood irrigation could only slightly reduce the N₂O emission but significantly increase NO emission from a maize field in the NCP (Tian et al., 2016). Because the application of nitrification inhibitors has been proven to be effective for reducing N₂O and NO emissions from the agricultural field of the NCP (Ding et al., 2011; Ju et al., 2011; Ding et al., 2015; Zhou et al., 2016), the surface drip fertigation combined with nitrification inhibitors was suspected to be a good choice for solving the current problems caused by excessive N fertilizer application and over extraction of groundwater in this region. However, to our best knowledge,

there is still no investigation about the effect of the surface drip fertigation combined with nitrification inhibitors on N₂O and NO emissions in the NCP.

N₂O and NO emissions from a typical wheat-maize field under flood irrigation and surface drip fertigation (with and without nitrification inhibitor) in the NCP were comparably investigated in 2014–2015. The main objective of this study is to evaluate the effect of drip fertigation with and without nitrification inhibitors on reducing N₂O and NO emissions from the winter wheat-summer maize field.

2. Material and methods

2.1. Field experiment

The study was carried out in a winter wheat-summer maize field, located at Wangdu County (38°1'N, 115°5'E), Hebei Province, China, from 8 October 2014 to 11 October 2015. Detailed information of the experimental field has been described in our previous researches (Zhang et al., 2011; Zhang et al., 2012; Zhou et al., 2016).

During the winter wheat season, the agricultural field was divided into five treatments: a control treatment with only flood irrigation (CK-Flood); a control treatment with only drip irrigation (CK-Drip); a treatment with application of ammonium fertilizer followed by flood irrigation (A-Flood); a treatment with application of ammonium solution by drip fertigation (A-Drip); and a treatment with application of a mixture solution of ammonium and dicyandiamide by drip fertigation (A + DCD-Drip). During the summer maize season, the agricultural field was divided into four treatments: a control treatment with only flood irrigation (CK-Flood); a treatment with application of ammonium fertilizer followed by flood irrigation (A-Flood); a treatment with application of ammonium solution by drip fertigation (A-Drip); and a treatment with application of a mixture solution of ammonium and 2-chloro-6-(trichloromethyl) pyridine by drip fertigation (A + Nitrapyrin-Drip). Each treatment was separated by a sampling road with width of 1.5 m to prevent nutrient transfer among the treatments. Three plots were randomly designed in each treatment, and each plot (6 × 4 m²) was separated by a 1 m ridge.

According to the fertilization manner of local farmers, a mixture fertilizer of NH₄Cl, calcium superphosphate and KCl (N: P₂O₅: K₂O = 18%: 9%: 9%) was applied into the A-Flood treatment for two times during the wheat and maize season, respectively. Considering the growth requirement of crops, a mixture fertilizer solution of NH₄Cl and KCl (N: K₂O = 18%: 9%) was applied by fertigation in the A-Drip, A + DCD-Drip and A + Nitrapyrin-Drip treatments for three times during the wheat and maize season, respectively. Calcium superphosphate (N: P₂O₅ = 18%: 9%) was broadcasted before each fertigation. The application rates of DCD and Nitrapyrin were 5% and 1% of N amount in the fertilizer, respectively. The detailed information about the fertilization dates, N fertilization rates and irrigation amounts in each treatment are listed in Table 1. Grain yields were measured from each plot and the grain samples were dried at 65 °C until constant weight for

Table 1
The fertilization dates, N fertilization rates and irrigation amounts in each treatment.

Date	N fertilization rate (kg N ha ⁻¹)						Irrigation amount (mm)					
	CK-Flood	CK-Drip	A-Flood	A-Drip	A + DCD-Drip	A + Nitrapyrin-Drip	CK-Flood	CK-Drip	A-Flood	A-Drip	A + DCD-Drip	A + Nitrapyrin-Drip
Winter wheat season												
13 October 2014	0	0	60	42	42	–	30	18	30	18	18	–
26 November 2015	0	0	0	0	0	–	44	24	44	24	24	–
11 April 2015	0	0	105	35	35	–	76	24	76	24	24	–
15 May 2015	0	0	0	38.5	38.5	–	50	54	50	54	54	–
Summer maize season												
30 June 2015	0	–	130	18.2	–	18.2	12	–	12	7.2	–	7.2
6 August 2015	0	–	130	91	–	91	25	–	25	8	–	8
11 September 2015	0	–	0	72.8	–	72.8	0	–	0	7	–	7

determining dry matter yields. Drip pipes placed 25 cm apart for wheat and 50 cm for maize, and the dripper interval was 30 cm in each line. The precipitation, irrigation, air temperature and soil temperature at 5 cm depth are shown in Fig. 1. Precipitation and air temperature were recorded from the website (<http://www.wunderground.com/>) and the soil temperature at 5 cm depth was measured by thermometer.

2.2. Gas sampling and analyzing

N₂O emission fluxes were conducted by using opaque static chambers (each with 32 cm in diameter and 80 cm in height). Each chamber was placed on a stainless steel pedestal during the period of each flux measurement and the pedestals were inserted 10 cm into the soil and kept during the whole wheat or maize growing season. The gas samples were collected by mini-pumps (NMP 830 KNDC, Germany) at 10-min intervals (0, 10, 20 and 30 min) after the chambers were closed. N₂O flux measurements were conducted between 15:00 and 17:00, and its daily fluxes were measured for approximately two weeks after each fertilization event, one week after each irrigation event, once a month during the period of 5 December 2014 to 5 March 2015, and twice a week during the rest of the crop growing season. N₂O concentrations were analyzed by a gas chromatograph (GC, Model SP3410, Beijing Analytical Instrument Factory, China) equipped with an electron capture detector (Zhang et al., 2011, 2013).

NO fluxes were measured by using twin dynamic chambers including a reference chamber and a sample chamber (Zhou et al., 2016). The twin dynamic chambers were simultaneously flushed by the ambient air at a rate of 20 L min⁻¹. NO samples were simultaneously collected from the reference and sample chambers after flushing of 14 min when a steady state was achieved (Zhang et al., 2011). The samples were immediately analyzed by a chemiluminescent NH₃ analyzer (Model 17i, Thermo Fisher Scientific, USA). NO flux measurements were conducted from 8:00 to 12:00. Daily measurement lasted for approximately two weeks after each fertilization event and one week after each irrigation event. The NO emissions after the topdressing on

11 September 2015 were not detected due to the problem of the analyzer.

2.3. Soil sampling and analyzing

The topsoil of 0–5 cm was taken by a ring sampler (100 cm³) and gravimetrically measured after drying the soil at 105 °C for 12 h for detecting soil moisture. Water filled pore space (WFPS) was calculated by dividing the volumetric water content by total soil porosity. Total soil porosity was calculated according to the relationship: soil porosity = $(1 - \text{soil bulk density} / 2.65)$, assuming a particle density of 2.65 g cm⁻³ (Linn and Doran, 1984).

2.4. Data analysis

The cumulative N₂O and NO emissions were estimated by successive linear interpolation and assuming that the emissions followed a linear trend over the periods when no samples were taken. The emission factor (EF) was calculated as the difference between the cumulative N₂O-N emission from the fertilized and control treatments divided by the total application rate of N-fertilizer. Significance of differences in the emission factors and the cumulative emissions from different treatments were determined by LSD test ($P < 0.05$). The data was analyzed by SPSS 22.0 software (SPSS Inc., Chicago, USA) and plotted by Origin Pro 8.5 (Origin Lab Corporation, USA).

3. Results and discussions

3.1. N₂O and NO emissions from the winter wheat season

3.1.1. N₂O emissions from the winter wheat season

N₂O emission fluxes from the five treatments during the winter wheat growing season are shown in Fig. 2. Compared with the CK treatments, evident emission peaks of N₂O from the A-Flood and A-Drip treatments were observed. Whereas, N₂O emission peaks were remarkably weaker from the A + DCD-Drip treatment than from the A-Flood

Fig. 1. Precipitation (mm), irrigation (mm), air temperature (°C) and soil temperature (°C) during the period of experiment.

and A-Drip treatments. N_2O emission peaks from the A-Flood and A-Drip treatments were almost identical after the basal fertilization, however, only obvious emission peak was found from the A-Flood treatment after the topdressing I on 11 April 2015. The winter wheat seeding and the basal fertilizer application were on the same day, and hence the N nutrient in the basal fertilizer was solely used by soil microbes during the early period of the fertilization. Because the N rate of the basal fertilization was 30% lower in the A-Drip treatment than in the A-Flood treatment, the almost same N_2O emission peaks between the two treatments might be partly ascribed to the incomplete dissolution of the granular fertilizer in the A-Flood treatment (Tian et al., 2016). The residual fertilizer in the A-Flood treatment could be reflected by the relatively high N_2O emissions during the period of 26 November 2014–16 March 2015 after the irrigation on 26 November 2014. The topdressing I was conducted on 11 April 2015 when the winter wheat was at the jointing stage, and the winter wheat would compete with the microbes for utilizing the N nutrient. The remarkable higher N_2O emission peak from the A-Flood treatment than from the A-Drip treatment indicated that the rate of N fertilizer (105 kg N ha^{-1}) in the A-Flood treatment might be greatly excessive for growth of the winter wheat. The topdressing II was conducted to A-Drip treatment on 15 May 2015 when the winter wheat was at the milking stage. Although the rate of N fertilizer was only 10% greater in the topdressing II ($38.5 \text{ kg N ha}^{-1}$) than in the topdressing I (35 kg N ha^{-1}), the N_2O emission peak was a factor of 4 higher after the topdressing II than after the topdressing I. The soil WFPS of 40–60% during the topdressing I was more favorable for N_2O production via microbial activities than that of 27–37% during the topdressing II (Linn and Doran, 1984), but the effects of soil temperatures

(Fig. 1) on microbial activities during the topdressing I ($\sim 14^\circ\text{C}$) and the topdressing II ($\sim 20^\circ\text{C}$) were on the contrary (Dobbie and Smith, 2002). Therefore, it is difficult to explain the remarkable difference between the two topdressing events for N_2O emissions from the A-Drip treatment only based on the soil WFPS and temperature. The winter wheat might require more N nutrient during the jointing stage (the topdressing I) than during the milking stage (the topdressing II) (Meng et al., 2013), which was suspected to be partially responsible for the remarkable difference of N_2O emissions. Compared with the A-Drip treatment, slight reduction of N_2O emissions from the A + DCD-Drip treatment could be observed during periods of the basal fertilization and the topdressing I when the average soil temperature was about 14°C , but remarkable reduction of N_2O emissions was found after the topdressing II when the average soil temperature was about 20°C . Therefore, the effect of nitrification inhibitor (DCD) on reduction of N_2O emissions was suspected to be strongly dependent on soil temperature.

3.1.2. NO emissions from the winter wheat season

NO emission fluxes from the five treatments during the winter wheat growing season are illustrated in Fig. 3. Similar to the N_2O emissions (Fig. 2), evident NO emission peaks from the three fertilization treatments could be also observed after each fertilization event. In contrast to the slight different N_2O emission peaks from the three fertilization treatments after the basal fertilization (Fig. 2), NO emission peak from the A-Drip treatment was about a factor of 1.6 and 4.7 higher than from the A-Flood treatment and from the A + DCD-Drip treatment, respectively. Besides the incomplete dissolution of fertilizer for the A-

Fig. 2. N_2O emissions from the CK-Flood, CK-Drip, A-Flood, A-Drip and A + DCD-Drip treatments during the wheat growing season. Solid arrows indicate fertilization and irrigation, and dot arrows indicate irrigation only. Error bars represent the standard deviation.

Fig. 3. Variations of the NO emissions from the CK-Flood, CK-Drip, A-Flood, A-Drip and A + DCD-Drip treatments during the wheat growing season. Solid arrows show fertilizer application and irrigation, and dot arrows indicate irrigation only. Error bars represent the standard deviation.

Flood treatment (as mentioned in the Section 3.1.1), the relatively lower soil moisture (Fig. 6a) in the A-Drip treatment was suspected to be responsible for the remarkably higher NO emission peak from the A-Drip treatment than from the A-Flood treatment (Tian et al., 2016). Compared with the A-Drip treatment, the reduction of NO was more pronounced than that of N₂O from the A + DCD-Drip treatment (Fig. 2), implying that DCD might have different effect on N₂O and NO emissions. Similar phenomenon has been observed in our previous study (Zhou et al., 2016), for example, N₂O emission was only reduced by 31%, whereas NO emission was reduced by 100% in the same field with application of DCD during the maize growing season. In contrast to the basal fertilization, NO emission peak from the A-Flood treatment after the topdressing was the highest among the treatments, which was mainly ascribed to the surplus fertilization. Although the NO emission peak from the A-Flood treatment was about a factor of 1.8 higher after the topdressing than after the basal fertilization, the evidently narrower NO emission peak after the topdressing than after the basal fertilization provided circumstantial evidence that the N nutrient applied might be quickly consumed by the winter wheat during the jointing stage. Similar to the N₂O emissions, the higher NO emission peak from the A-Drip treatment after the topdressing II than after the topdressing I was also partly ascribed to the different N nutrient requirement between the jointing stage and the milking stage. Our previous study revealed that NO emission peaks could not be observed from the DCD treatment during the maize growing season when the soil temperature was usually above 25 °C (Zhou et al., 2016). However, the evident NO emission

peak from the A + DCD-Drip treatment was observed after each fertilization event during the wheat growing season, implying that the effect of DCD on nitrification for NO production might be also dependent on soil temperature.

3.2. N₂O and NO emissions from the summer maize season

3.2.1. N₂O from the summer maize season

N₂O emission fluxes from the four treatments during the summer maize growing season are illustrated in Fig. 4. Compared with the CK-Flood treatment, evident N₂O emission peaks from the A-Flood and A-Drip treatments but only slight N₂O emission peak from the A + Nitrpyrin-Drip treatment were found after each fertilization event. Our previous studies (Zhang et al., 2014; Tian et al., 2016; Zhou et al., 2016) revealed that N₂O emission peaks from the same field with the fertilization treatments were usually much higher after the basal fertilization events than after the topdressing events, however, the result in this study was on the contrary. The inconsistent results between our previous studies and this study were mainly ascribed to the remarkable difference of the soil moisture. The soil moisture in this year was extremely low (WFPS < 20%, Fig. 6b) before the basal fertilization due to the low rainfall (Fig. 1), whereas the soil moistures in the previous years were usually >40% (Zhang et al., 2014; Tian et al., 2016; Zhou et al., 2016). Therefore, the lowest N₂O emission peak after the basal fertilization during the maize growing season in this year further supported the conclusion that N₂O emission from the agricultural field

Fig. 4. N_2O emissions from the CK-Flood, A-Flood, A-Drip and A + Nitrapyrin-Drip treatments during the maize growing season. Solid arrows indicate fertilization and irrigation, and dot arrows indicate irrigation only. Error bars represent the standard deviation.

positively correlated with soil moisture (Zhang et al., 2014). Although the N fertilization rate (130 kg N ha^{-1}) in the A-Flood treatment was a factor of 7 greater than that ($18.2 \text{ kg N ha}^{-1}$) in the A-Drip treatment,

the N_2O emission peaks from the two treatments were almost same after the basal fertilization. Under the extremely low soil moisture before the basal fertilization, the community of the nitrifying bacteria for

Fig. 5. NO emissions from the CK-Flood, A-Flood, A-Drip and A + Nitrapyrin-Drip treatments during the maize growing season. Solid arrows indicate fertilization and irrigation, and dot arrows indicate irrigation only. Error bars represent the standard deviation.

N_2O production (as discussed in the Section 3.3) might greatly decline and its recovery after the fertilization with irrigation might less depend on N fertilization rates. As for the topdressing, the evidently lower N_2O emission peaks from the A-Drip treatment than from the A-Flood treatment were mainly ascribed to the less N fertilization rates (91 kg N ha^{-1} for topdressing I and $72.8 \text{ kg N ha}^{-1}$ for topdressing II) in the A-Drip treatment than that (130 kg N ha^{-1}) in the A-Flood treatment. The evident N_2O emission peaks could appear from the fertilization treatment with application of DCD during the maize growing season in our previous study (Zhou et al., 2016), whereas inconspicuous N_2O emission peaks from the A + Nitrapyrin-Drip treatment were observed, implying that the effect of Nitrapyrin might be more effective than DCD on reduction of N_2O emission from the field.

3.2.2. NO emissions from the summer maize season

NO emission fluxes from the four treatments during the summer maize growing season are shown in Fig. 5. Similar to the N_2O emissions (Fig. 4), evident NO emission peaks from the A-Flood and A-Drip treatments but almost no NO emission peak from the A + Nitrapyrin-Drip treatment were found after each fertilization event. Same as the N_2O emissions, the almost same NO emission peaks from both the A-Flood and A-Drip treatments after the basal fertilization were also ascribed to the extremely low soil moisture, and the evidently higher NO emission peak after the topdressing on 6 August 2015 from the A-Flood treatment than from the A-Drip treatment was attributed to the greater N application rate in the A-Flood treatment. The nearly 100% reduction of NO emission peak from the A + Nitrapyrin-Drip treatment was in good agreement with our previous study in the same maize field by using DCD as nitrification inhibitor (Zhou et al., 2016).

3.3. The origin of N_2O and NO from the agricultural field

Nitrification is usually considered as the dominant source for emissions of N_2O and NO from soils when the molar ratio of $\text{NO}/\text{N}_2\text{O}$ is >0.11 (Meijide et al., 2007). As shown in Fig. 7, the molar ratios of $\text{NO}/\text{N}_2\text{O}$ after each fertilization event during both the wheat and maize growing seasons were usually >0.11 , confirming that nitrification was the dominant source for N_2O and NO emissions from the agricultural field (Zhang et al., 2011; Zhang et al., 2016). The remarkably higher molar ratios from the A-Flood and A-Drip treatments after the basal fertilization during the maize season were probably ascribed to the extremely low soil moisture which favored for NO emission and suppressed N_2O production through NO reduction by denitrification of nitrifying bacteria (Russow et al., 2009; Kool et al., 2011). Except for the two topdressing events for the winter wheat, the molar ratios of $\text{NO}/\text{N}_2\text{O}$ from the A + DCD-Drip treatment and A + Nitrapyrin-Drip treatment were evidently lower than those from the A-Flood and A-Drip treatments, indicating that the application of the nitrification inhibitors greatly suppressed nitrification process for production of N_2O and NO.

3.4. The emission factors and the cumulative emissions of N_2O and NO

The emission factors and the cumulative emissions of N_2O and NO from the fertilization treatments are listed in Table 2. N_2O emission factor during the wheat season was significantly greater from the A-Flood treatment than from the A-Drip treatment, whereas it was slightly less from the A-Flood treatment during the maize season. The slightly less N_2O emission factor from the A-Flood treatment with respect to the A-

Fig. 6. Soil water-filled pore space (WFPS, %) of 0–5 cm depth during the experimental period. Arrows indicate irrigation only.

Fig. 7. Molar ratios of NO/N₂O after each N fertilization event from the fertilization treatments in this experiment. Solid arrows indicate fertilization and irrigation.

Drip treatment for the maize growing season was in good agreement with our previous study (Tian et al., 2016). The annual cumulative N₂O emission from the A-Drip treatment was significantly lower (22%) than from the A-Flood treatment, which was mainly ascribed to the significantly lower N₂O emission factor from the A-drip treatment during the wheat season. The N₂O emission factors and cumulative emissions from the A + DCD-Drip and A + Nitrapyrin-Drip treatments were significantly lower than those from the A-Flood and A-Drip treatments, implying that application of the nitrification inhibitors greatly suppressed nitrification process for N₂O production.

NO emission factor during the wheat season was slightly less from the A-Flood treatment than from the A-Drip treatment, whereas it was significantly less from the A-Flood treatment during the maize season. Apparent enhancement of NO emission factor from the same field under drip fertigation with respect to the flood irrigation for the maize growing season in 2013 was also reported in our previous study (Tian et al., 2016). Although the N fertilization rate was reduced by 58% in the A-drip treatment during the maize season (only the basal fertilization and topdressing I were considered) and 30% during the wheat season, the annual cumulative NO emission was slightly higher from the A-Drip treatment than from the A-Flood treatment, which was in line with

Table 2

The emission factors and the cumulative emissions (mean ± SE) of N₂O and NO during the wheat and maize growing seasons.

		CK-Flood	CK-Drip	A-Flood	A-Drip	A + DCD-Drip	A + Nitrapyrin-Drip
N ₂ O EF (%)	Annual	—	—	0.51 ± 0.02b	0.51 ± 0.07b	—	0.07 ± 0.01a
	Wheat	—	—	0.36 ± 0.02b	0.16 ± 0.05a	0.04 ± 0.02a	—
	Maize	—	—	0.60 ± 0.04b	0.74 ± 0.10b	—	0.10 ± 0.01a
Cumulative emission ^d (kg N ₂ O-N ha ⁻¹)	Annual	0.78 ± 0.04a	—	2.95 ± 0.10c	2.30 ± 0.21b	—	1.00 ± 0.03a
	Wheat	0.41 ± 0.04a	0.39 ± 0.03a	1.00 ± 0.04c	0.58 ± 0.06b	0.44 ± 0.02a	—
	Maize	0.37 ± 0.01a	—	1.94 ± 0.10b	1.72 ± 0.18b	—	0.56 ± 0.02a
NO EF (%)	Annual	—	—	0.57 ± 0.09b	1.27 ± 0.03c	—	0.03 ± 0.00a
	Wheat	—	—	0.17 ± 0.03b	0.22 ± 0.03b	−0.01 ± 0.01a	—
	Maize ^f	—	—	0.82 ± 0.14b	2.40 ± 0.10c	—	0.08 ± 0.02a
Cumulative emission ^e (kg NO-N ha ⁻¹)	Annual	0.05 ± 0.06a	—	2.47 ± 0.39b	2.91 ± 0.06b	—	0.12 ± 0.00a
	Wheat	0.08 ± 0.12a	0.07 ± 0.03a	0.37 ± 0.05b	0.33 ± 0.03b	0.07 ± 0.01a	—
	Maize ^f	−0.03 ± 0.05a	—	2.10 ± 0.37b	2.58 ± 0.11b	—	0.05 ± 0.02a

The letters of a, b, c denotes the sequence of the values from the lowest to the highest in each line; the same letter (or different letters) in different columns within the same line represents no significant difference (or significant difference) among different treatments by LSD test at $P < 0.05$.

^d N₂O cumulative emissions are the emissions during the entire crop growing season.

^e Only the emissions after the basal fertilization (30 June 2015) and topdressing I (6 August 2015) were considered in the A-Drip and A + Nitrapyrin-Drip treatments, and the total N fertilizer amount during the two fertigation events was 109.2 kg N ha⁻¹.

^f NO cumulative emissions are the emissions within approximately 10 days after each fertilization event.

the results of our previous study (Tian et al., 2016). The NO emission factors and cumulative emissions from the A + DCD-Drip and A + Nitrapyrin-Drip treatments were significantly lower than those from the A-Flood and A-Drip treatments, implying that application of the nitrification inhibitors also greatly suppressed nitrification process for NO production.

The N₂O emission factors from the A-Flood treatment for the wheat and maize growing seasons were within the ranges of 0.09–3.3% and 0.08–3.8%, respectively, reported by previous studies in the NCP (Zhang et al., 2004; Meng et al., 2005; Ding et al., 2007; Cui et al., 2012; Hu et al., 2013; Zhang et al., 2014), whereas the emission factors for the maize season was lower than the range of 1.1–3.8% reported by our previous studies in the same field (Zhang et al., 2012; Zhang et al., 2014; Tian et al., 2016; Zhou et al., 2016). The NO emission factor from the A-Flood treatment during the wheat season was lower than 0.33% reported by Cui et al. (2012), and during the maize season was within the range of 0.24–1.93% reported by previous studies in the NCP (Zhang et al., 2011; Cui et al., 2012; Tian et al., 2016).

Compared with the yield ($7750 \pm 828 \text{ kg ha}^{-1}$) from the A-Flood treatment, the maize yields from the A-Drip ($9483 \pm 243 \text{ kg ha}^{-1}$) and A + Nitrapyrin-Drip ($9767 \pm 206 \text{ kg ha}^{-1}$) treatments were significantly increased by 22% and 26%, respectively. Whereas the yields from the A-Drip ($7775 \pm 586 \text{ kg ha}^{-1}$), A + DCD-Drip ($7600 \pm 471 \text{ kg ha}^{-1}$) and A-Flood ($7825 \pm 526 \text{ kg ha}^{-1}$) treatments for the wheat season were almost the same. Considering the yields, the water saving and the reduction of N₂O and NO emissions, the application of nitrification inhibitor combined with drip fertigation is a good choice in the agricultural field of the NCP.

4. Conclusions

The replacement of the current flood irrigation by the drip fertigation in the agricultural field only reduced annual N₂O emission by 22%, but increased NO emission by 18%. In contrast, the replacement by the drip fertigation combined with nitrification inhibitors could reduce the annual emissions of N₂O and NO by 66% and 95%, respectively. Besides the remarkable reduction of N₂O and NO emission, the treatment of drip fertigation combined with nitrification inhibitors could increase 26% maize yield, reduce 30% N fertilization rate and 40% irrigation amount, and thereby is a good cultivation manner in the agricultural field of NCP.

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