The influence of straw returning on N₂O emissions from a maize-wheat field in the North China Plain

Yizhen Zhou^{a,c}, Yuanyuan Zhang^{a,c}, Di Tian^{a,c}, Yujing Mu^{a,b,c,*}

^a Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

^b Center for Excellence in Regional Atmospheric Environment, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China

^c University of Chinese Academy of Sciences, Beijing 100049, China

HIGHLIGHTS

- Crop straw returning has become a prevailing cultivation practice in the NCP.
- Straw returning reduced N₂O emission under high soil moisture during the maize season.
- Straw returning reduced N₂O emission during wheat seasons were attributed to anoxic condition induced by rotting the maize straw.

GRAPHICAL ABSTRACT

ARTICLE INFO

Article history:

Received 12 December 2016

Received in revised form 20 January 2017

Accepted 21 January 2017

Available online 30 January 2017

Editor: D. Barcelo

Keywords:

Nitrous oxide
Soil moisture
Straw returning
North China Plain

ABSTRACT

Crop straw returning has become a prevailing cultivation practice in the vast area of the North China Plain (NCP), while few investigations about its influence on nitrous oxide (N₂O) emission have been conducted. In this study, N₂O emissions from an agricultural field in the NCP with and without straw returning were comparably investigated by using static chambers in two consecutive maize-wheat growing seasons from June 2010 to June 2012. Compared with the NP treatment (compound nitrogen fertilizer only), the cumulative N₂O emission from the SP treatment (compound nitrogen fertilizer plus straw) increased about 150% during the maize season in 2010, but decreased by about 35% during the maize season in 2011. The inconsistent influence of straw returning on N₂O emission from the maize field was ascribed to the evidently different soil moisture between the two years, which was further confirmed by laboratory simulation experiments. About 40% reduction of N₂O emission from the SP treatment during the two winter wheat seasons, which was mainly attributed to anoxic condition induced by rotting the maize straw.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

Nitrous oxide (N₂O) is one of important greenhouse gases and participates in the depletion of stratospheric ozone (Crutzen, 1970).

Currently, the mixing ratio of N₂O in troposphere is about 328 ppbv, and still increases at a rate of about 0.3% yr⁻¹ which is mainly attributed to the emissions from agricultural soil (IPCC, 2013). The application of nitrogen (N) fertilizer in agricultural fields for increasing crop yield

* Corresponding author.

E-mail address: yjmu@rcees.ac.cn (Y. Mu).

also provides the substrate for soil microbes to promote nitrification and denitrification processes, resulting in remarkable increment of N_2O emissions (Robertson and Groffman, 2015; Snayser et al., 2009; Wragge et al., 2001). Additionally, N_2O emissions from agricultural fields are also strongly affected by cultivation manners, e.g., tillage (Saggar, 2010; Yanai et al., 2011), irrigation (Trost et al., 2013), straw returning (Millar et al., 2004; Singh et al., 2008; Toma and Hatano, 2007) and fertilization manner (Sarkodie-Addo et al., 2003). Therefore, the change of cultivation manners should be considered for estimating N_2O emissions from agricultural fields.

The cultivation manners for the agricultural fields in China have evidently changed in recent years, especially in the North China Plain (NCP). Instead of using crop straw for cooking, crop straw returning in the NCP has become a prevailing agricultural practice for improving soil fertility and reducing air pollution induced by crop straw burning (Gao et al., 2011). However, only few studies reported the influence of straw returning on N_2O emission from the agricultural fields in the NCP and their conclusions are inconsistent. For example, Liu et al. (2011), Zhang et al. (2011, 2012) and Hu et al. (2013) pointed out that the addition of wheat straw increased N_2O emission in maize seasons, whereas the results from Pan et al. (2004) and Pei et al. (2012) showed that the addition of maize straw evidently reduced N_2O emission during the winter-wheat season. The inconsistent conclusions about the influence of crop straw returning on N_2O emissions from agricultural fields in the regions other than the NCP are also reported: some results indicated enhanced N_2O emission (e.g. Baggs et al., 2003; Cheng et al., 2012; Hu et al., 2013; Liu et al., 2011; Muhammad et al., 2011; Singh et al., 2008; Yao et al., 2010; Yang et al., 2014), whereas the others implied reduced N_2O emission (e.g. Aulakh et al., 2001; Fu et al., 2012; Hao et al., 2001; Ma et al., 2007; Shen et al., 2014; Yamulki, 2006; Zou et al., 2005). Because N_2O emissions from the vast agricultural fields in the NCP is one of the most important sources for global atmospheric N_2O (Ding et al., 2007; Zhang et al., 2012), the influence for the currently prevailing agricultural practice of straw returning on N_2O emissions should be considered.

In this study, N_2O fluxes from a summer maize-winter wheat field with and without straw returning treatments were comparably investigated for two consecutive years, and both negative and positive influences of straw returning on N_2O emissions were also found. The inconsistent influence of straw returning on N_2O emission was mainly ascribed to the different soil moistures, which was well confirmed by laboratory simulation experiments.

2. Materials and methods

2.1. Experimental site

The experimental site is located in Wangdu Country ($38^{\circ}68'\text{N}$, $115^{\circ}25'\text{E}$), Hebei Province, China. The soil of the agricultural field is classified as aquic inceptisol with a sandy loam texture, soil pH (in a 1: 2.5 soil-to-water ratio) of 8.8, soil organic C of 8.7 g/kg and total N of 1.0 g/kg. The annual mean temperature was about 12.9°C and the annual precipitation is about 519 mm. Summer maize-winter wheat is the dominant cropping system in the field.

2.2. Field experiments

The field had been divided into three treatments (each treatment with an area of $6.4 \times 6.3 \text{ m}^2$) since 2008: One was the control treatment (designated as CK) without fertilization or straw returning; the second was applied with compound nitrogen fertilizer (designated as NP); the third was treated with straw returning plus compound nitrogen fertilizer (designated as SP). Each treatment was isolated by a 1.2 m broad zone to prevent nutrient transfer between treatments, and three opaque static chambers were set for measurements of N_2O emissions in each treatment. Maize was sown on 30 June 2010 and 30 June 2011

respectively, and harvested on 14 October 2010 and 17 October 2011. During each summer-maize season, compound fertilizer (107 kg N/ha, $\text{N:P}_2\text{O}_5:\text{K}_2\text{O} = 26\%:6\%:8\%$) was broadcast to the NP and SP treatments as basal fertilizer after seeding, and air-dried wheat straw (4.7 t/ha, $N = 0.48\%$) was simultaneously applied to the soil surface of the SP treatment. Compound fertilizer (69 kg N/ha, $N:K = 25\%:5\%$) was broadcast to the NP and SP treatments as topdressing on 6 August 2010 and 8 August 2011, respectively. Wheat was sown after tillage on 17 October 2010 and 19 October 2011, and harvested on 28 June 2011 and 15 June 2012. During the winter-wheat season, compound fertilizer (60 kg N/ha, $\text{N:P}_2\text{O}_5:\text{K}_2\text{O} = 18\%:18\%:18\%$ in 2010 and $\text{N:P}_2\text{O}_5:\text{K}_2\text{O} = 12\%:18\%:15\%$ in 2011) was broadcast to the NP and SP treatments as basal fertilizer, and air-dried maize straw (11.5 t/ha, $N = 0.6\%$) was simultaneously applied to the SP treatment, and then was tilled into the soil depth of 10 cm before sowing wheat. Urea (105 kg N/ha, $N = 46.4\%$) and compound fertilizer ($N:S = 20\%:22\%$) were broadcast to the NP and SP treatments as topdressing on 14 April 2011 and 18 April 2012, respectively. Flooding irrigation was carried out immediately after each fertilization. Additional irrigations were conducted on 21 November 2010 and 22 May 2011, and 18 November 2011 and 21 May 2012 for the wheat during two winter wheat seasons.

Three opaque static chambers were set for measurements of N_2O emissions (Zhang et al., 2011). The chambers (length $\times$ width $\times$ height: $60 \times 60 \times 90 \text{ cm}^3$) were placed on the corresponding pedestals which were inserted into soil about 8-cm depth. Four air samples from each chamber were collected into polyethylene coated aluminum bags (0.2 L, Delin, Dalian, China) by a mini-pump (NMP 830 KNDC, Germany) at 10-min intervals after the chamber being enclosed (5, 15, 25 and 35 min). The daily fluxes were measured between 9:30 a.m. and 10:30 a.m. (Local time). Soil temperature at 5 cm depth was simultaneously recorded on each sampling occasion and rainfall data was obtained from http://weather.org/weatherorg_records_and_averages.htm. The top part of the maize plant above the chamber was cut off when its height exceeded 80 cm. The measurements in 2010–2012: N_2O fluxes were measured every day within duration of >10 days after fertilization, then continuous sampling once or twice weekly during other periods of crops' growing seasons.

2.3. Simulation experiments

The soil samples collected from the agricultural field were placed into twelve plastic cylinders (ID of 20 cm and 26 cm in height) for laboratory simulation at room temperature ($\sim 25^{\circ}\text{C}$) and each cylinder was filled with about a depth of 10 cm soil ($\sim 2500 \text{ g}$ soil). The air-dried maize straw cut into segments of about 3 cm were broadcasted on the soil surfaces of six cylinders (36 g for each cylinder, which was equal to 11.5 t/ha). Based on the initial water content in the soil samples, the soil WFPS values in the twelve cylinders were firstly adjusted to be about 40% by adding distilled water for three days' incubation, and then compound fertilizer ($\text{N:P}_2\text{O}_5:\text{K}_2\text{O} = 20\%:20\%:5\%$, 1.7 g for each cylinder, which was equal to 107 kg N/ha) was evenly broadcasted on the soil surfaces of the twelve cylinders. The twelve cylinders were equally divided into two groups, and each group included three cylinders with only application of compound fertilizer (designated as treatment N1) and three cylinders with application of both the compound fertilizer and the maize straw (designated as treatment N2). The WFPS values of the soil samples were immediately adjusted to be 60% in one group and 90% in the other group just after the fertilization.

Four air samples from each cylinder were collected by a glass syringe (100 mL) at 10-min intervals (5, 15, 25 and 35 min) after it being enclosed with a cap. The measurements lasted 9 days from 23 to 31 January in 2015.

2.4. N₂O concentration analysis

N₂O concentration in air samples was analyzed by a gas chromatograph (Model SP3410, Beijing Analytical Instrument Factory) with an electron capture detector (ECD). The temperatures for GC oven, injector port and ECD were 72 °C, 72 °C and 390 °C, respectively (Zhang et al., 2011, 2012). High purity N₂ (99.999%) was used as carrier gas, and a makeup gas (979 ppmv CO₂ in N₂) was introduced into the downstream of the analytical column. The GC-ECD instrument precision was 0.31% (Zhang et al., 2013).

2.5. Soil sampling and analysis

Soil samples in the field experiment were collected from the topsoil of 0–5 cm depth by a ring sampler (100 cm³) for analysis of the WFPS (Lin et al., 2013), and the topsoil from 0–10 cm gathered by soil auger for detection of soil NH₄⁺-N and NO₃⁻-N concentrations. The soil NH₄⁺-N and NO₃⁻-N were extracted by the mixed fresh soils (20 g) in 100 mL of 1 mol/L KCl solution and analyzed by a colorimetric continuous flow analyzer (SANT ++, Skalar Company, the Netherlands) after the solution being filtered through filter paper. The total C and N concentrations in the soil were analyzed using Hydration potassium bichromate colorimetry and Kjeldahl boiled elimination method, respectively.

2.6. Data analysis

Statistical analyses were performed using the SPSS 13.0 software (SPSS Inc., Chicago, USA). A one-way ANOVA was used to test the differences between the NP and SP treatments in the field experiment. Cumulative N₂O emission from each treatment was calculated by a linear interpolation based on sampling date. The emission factors of N₂O (EFs) were calculated as the following (Zhang et al., 2012):

$$EF = \frac{A_{N_2O-N-F} - A_{N_2O-N-C}}{TN_{in}} \times 100\%, \quad (1)$$

where A_{N_2O-N-F} and A_{N_2O-N-C} are the amount of cumulative N₂O-N emissions from the fertilized and control treatment (kg N/ha), respectively, and TN_{in} is total N input (kg N/ha). The standard error of the emission factor was estimated using the standard errors (SE) of the cumulative emissions from the fertilized and the unfertilized plots (Cui et al., 2012).

3. Results

3.1. The variations of rainfall and the key soil parameters

The variations of rainfall and soil WFPS, NH₄⁺-N and NO₃⁻-N in the CK, NP and SP treatments from 2010 to 2011 and from 2011 to 2012 are illustrated in Figs. 1 and 2, respectively. The annual rainfalls during the growing seasons were 305.5 mm in 2010–2011 and 383 mm in 2011–2012, and the precipitation mainly concentrated in the maize seasons (194.4 mm in 2010–2011 and 302 mm in 2011–2012). Although the same flooding irrigation was conducted in the two years, the soil WFPS values were greater in 2011–2012 than in 2010–2011 (Figs. 1a and 2a), which was mainly ascribed to the excessive rainfall in 2011–2012. In addition, the soil WFPS were evidently greater in the SP treatments than in the treatments of CK and NP during the maize growing seasons.

There were no significant difference of soil NH₄⁺-N among the three treatments in each year, but it evidently increased in 2011–2012, i.e., the mean soil NH₄⁺-N concentrations in the CK, NP and SP treatments were 4.9, 4.2 and 4.7 mg/kg, respectively in 2010–2011 (Fig. 1b), and 12.9, 11.3 and 13.2 mg/kg in 2011–2012 (Fig. 2b). Soil NH₄⁺-N in the three treatments during the wheat growing seasons after the tillage

evidently increased. Compared with the CK treatment, evident increase of soil NO₃⁻-N after each fertilization was found in the NP and SP treatments (Figs. 1c and 2c).

3.2. N₂O fluxes from the field experiments

The N₂O fluxes from the three treatments during the whole crop growing season in 2010–2011 and 2011–2012 are illustrated in Figs. 3 and 4, respectively. As shown in Figs. 3a and 4a, the N₂O fluxes from the CK treatment varied in relatively narrow range, from –4.8 ng N/(m²·s) to 39.5 ng N/(m²·s) in 2010–2011 and from –37.3 ng N/(m²·s) to 51.4 ng N/(m²·s) in 2011–2012, and the small spiking emissions of N₂O only occasionally occurred after the events of irrigation or rainfall.

Compared with the CK treatment, large variations of N₂O fluxes were found in the NP and SP treatments. N₂O fluxes from the NP and SP treatments quickly increased around 2–3 days after fertilization, and relative high N₂O fluxes could last about 10 days (Figs. 3b, c and 4b, c). With the exception of the 10 day's period after fertilization, N₂O fluxes from the NP and SP treatments always remained at almost the same level as those from the CK treatment.

During the maize season in 2010, N₂O emission peaks were found remarkably greater from the SP treatment than from the NP treatment: N₂O emission peaks from the NP and SP treatments were 503 ± 123 ng N/(m²·s) and 1269 ± 384 ng N/(m²·s), respectively after the basal fertilization, and 81 ± 15 ng N/(m²·s) and 114 ± 91 ng N/(m²·s), respectively after the topdressing. During the maize season in 2011, however, N₂O emission peaks were found evidently smaller from the SP treatment than from the NP treatment: N₂O emission peaks from the NP treatment were 558 ± 188 ng N/(m²·s) after the basal fertilization and 229 ± 15 ng N/(m²·s) after the topdressing, whereas from the SP treatment were 253 ± 36 ng N/(m²·s) and 94 ± 17 ng N/(m²·s) after the basal fertilization and topdressing, respectively. Compared with the NP treatment, evident reduction of N₂O emission peaks from the SP treatment was found during the two winter wheat seasons. In 2010–2011, N₂O emission peaks from the NP treatment were 134 ± 39 ng N/(m²·s) after the basal fertilization and 147 ± 41 ng N/(m²·s) after the topdressing, whereas from SP treatment were 39 ± 17 ng N/(m²·s) after the basal fertilizer application and 78 ± 24 ng N/(m²·s) after the topdressing. In 2011–2012, N₂O emission peaks from the NP treatment and the SP treatment after the basal fertilization were 248 ± 194 ng N/(m²·s) and 236 ± 110 ng N/(m²·s), and after the topdressing were 624 ± 280 ng N/(m²·s) and 289 ± 76 ng N/(m²·s), respectively.

The cumulative N₂O emissions from the three treatments and the N₂O-N emission factors (EFs) from the NP and SP treatments are listed in Table 1. Compared with the NP treatment, the cumulative N₂O flux as well as the EF from the SP treatment during the maize season significantly ($p < 0.05$) increased by 146% in 2010, but remarkably ($p < 0.05$) reduced by 34% in 2011. During the winter wheat seasons, the cumulative N₂O fluxes from the SP treatment in 2010–2011 and 2011–2012 were reduced by 48% and 37%, respectively.

3.3. N₂O emissions in the laboratory simulation experiments

The N₂O emissions from the N1 and N2 treatments under WFPS values of 60% and 90% are illustrated in Fig. 5. Similar to the field measurements, N₂O emissions from the two treatments in the laboratory simulation sharply increased just after the fertilization. N₂O emissions were remarkably higher from the N2 treatment than from the N1 treatment under WFPS of 60% (Fig. 5a), but evidently lower under WFPS of 90% (Fig. 5b). N₂O emissions from the N1 treatment were much less under WFPS of 60% than under WFPS of 90%, whereas N₂O emissions from the N2 treatment were on the contrary.

Fig. 1. Variations of rainfall and soil WFPS (a), $\text{NH}_4^+\text{-N}$ (b) and $\text{NO}_3^-\text{-N}$ (c) in CK, NP and SP treatments from June 2010 to June 2011. Arrows show the date of fertilizer application and irrigation. Dash arrows show the date of only irrigation.

4. Discussions

4.1. The source of N_2O from the agricultural field

N_2O emissions from soil have been commonly considered as the results of soil nitrification and denitrification processes, however the relative contribution of each process to N_2O emission is still unclear for

various soils (Anderson and Levine, 1986; Bremner, 1997; Shaw et al., 2006; Wrage et al., 2001). The relationship between N_2O emissions and the concentrations of $\text{NO}_3^-\text{-N}$ and $\text{NH}_4^+\text{-N}$ in soils may be a useful indicator for distinguishing the contribution of nitrification from that of denitrification. The immediate increase of soil $\text{NO}_3^-\text{-N}$ but no increment of soil $\text{NH}_4^+\text{-N}$ in the NP and SP treatments after the each fertilization implied that the $\text{NH}_4^+\text{-N}$ applied could be fast converted to $\text{NO}_3^-\text{-N}$

Fig. 2. Variations of rainfall and soil WFPS (a), $\text{NH}_4^+\text{-N}$ (b) and $\text{NO}_3^-\text{-N}$ (c) in CK, NP and SP treatments from June 2011 to June 2012. Arrows show the date of fertilizer application and irrigation. Dash arrows show the date of only irrigation.

Fig. 3. N_2O fluxes in the CK (a), NP (b) and SP (c) treatments from June 2010 to June 2011. N_2O fluxes are means $\pm$ standard deviation for three replicates. Arrows show the date of fertilizer application and irrigation. Dash arrows show the date of only irrigation.

Fig. 4. N_2O fluxes in the CK (a), NP (b) and SP (c) treatments from June 2011 to June 2012. N_2O fluxes are means $\pm$ standard deviation for three replicates. Arrows show the date of fertilizer application and irrigation. Dash arrows show the date of only irrigation.

Table 1

Cumulative N₂O fluxes and emission factors of 2010–2011 and 2011–2012. Data shown are means $\pm$ standard errors (SE) of the replicates.

Seasons	Cumulative N ₂ O fluxes (kg N/ha)			EF (%)	
	CK	NP	SP	NP	SP
2010–2011					
Maize season	0.4 $\pm$ 0.02	2.8 $\pm$ 0.1	6.9 $\pm$ 1.2	1.4 $\pm$ 0.06	3.3 $\pm$ 0.14
Wheat season	0.9 $\pm$ 0.03	2.1 $\pm$ 0.1	1.1 $\pm$ 0.09	0.7 $\pm$ 0.06	0.09 $\pm$ 0.07
Whole year	1.3 $\pm$ 0.2	4.8 $\pm$ 0.3	8.0 $\pm$ 1.1	1.1 $\pm$ 0.09	1.5 $\pm$ 0.24
2011–2012					
Maize season	0.5 $\pm$ 0.3	4.7 $\pm$ 0.3	3.1 $\pm$ 0.02	2.4 $\pm$ 0.23	1.5 $\pm$ 0.13
Wheat season	2.3 $\pm$ 0.3	7.8 $\pm$ 0.4	4.9 $\pm$ 0.4	3.4 $\pm$ 0.32	1.6 $\pm$ 0.23
Whole year	2.7 $\pm$ 0.6	12.5 $\pm$ 0.1	8.0 $\pm$ 0.5	2.9 $\pm$ 0.18	1.6 $\pm$ 0.17

into the soil through nitrification process. The accumulation and gradual decrease of soil NO₃⁻-N in the NP and SP treatments after the fertilization indicated the rate of soil denitrification was much slower than that of nitrification. Compared with the CK treatment, although remarkably high concentrations of NO₃⁻-N in the NP and SP treatments usually lasted >30 days after each fertilization, N₂O emission fluxes from the NP and SP treatments after 10 days of each fertilization always remained at the same levels as those from the CK treatment. Our previous study (Zhang et al., 2012) also revealed that the application of NO₃⁻-N in the agricultural soil made negligible contribution to N₂O emission. Therefore, the sharp N₂O emission peaks and the short duration of relatively high N₂O emission after the each fertilization of NH₄⁺-N were mainly ascribed to the fast nitrification process in the soil.

4.2. The influence of straw returning on N₂O emission

The amount of N fertilizer application and the flooding irrigation for the NP and SP treatments was identical in each year, and thus the remarkable differences of N₂O emission peaks (Figs. 3b, c and 4b, c) and the cumulative N₂O emissions (Table 1) between the NP and SP treatments in each year should be ascribed to the influence of straw returning. As shown in Figs. 3, 4 and Table 1, positive influence of straw returning on N₂O emission was found in the maize season in 2010, whereas negative influence concurred during the maize season in 2011 and during the two winter wheat seasons. Compared with the maize season in 2010, the soil WFPS during the maize season in 2011 remarkably increased due to the intensive rainfall (Figs. 1a and 2a). As soil moisture strongly affects soil anoxic condition which influences on soil nitrification and denitrification for N₂O production (Bateman and Baggs, 2005; Luo et al., 2013; Zhang et al., 2014), the evident difference of the soil moisture between the two maize seasons was suspected to be responsible for inconsistent influence of straw returning on N₂O emission. Compared with the NP treatment, the wheat straw returning on the

surface of the agricultural field for the SP treatment during the maize seasons could result in relatively high soil moisture due to shielding the soil from direct sunlight irradiation, e.g. the soil WFPS in the SP treatment during the two maize growing season was evidently higher than that in the NP treatment (Figs. 1a and 2a). On the other hand, the wheat straw rotting at the interface of the straw and the soil could consume a quantity of oxygen. Both the relative high soil moisture and the additional oxygen consumption in the SP treatment resulted in more severe soil anoxic condition. The initial NO gas product formed through soil nitrification or denitrification can act as an electron acceptor under typical anoxic condition to be reduced to N₂O or N₂ (NO₂⁻ → NO → N₂O → N₂). Our previous study (Zhang et al., 2012) revealed that NO emission from the SP treatment was evidently smaller than that from the NP treatment. N₂O would be the dominant product if the soil anoxic condition was moderate, and N₂ would become the dominant product under extremely anoxic condition because N₂O could be further used by soil microbes as an electron acceptor (Wrage et al., 2001). The N₂O emission peaks (Figs. 3b and 4b) and the cumulative N₂O emission (Table 1) from the NP treatment were evidently greater in 2011–2012 than in 2010–2011, indicating that the relatively high soil moisture favored N₂O emission from the soil. Therefore, the remarkably positive influence of the SP treatment on N₂O emission during the maize season in 2010 could be easily understood. During the maize season in 2011, because the agricultural soil was almost saturated with water, the more severe soil anoxic condition caused by straw returning in the SP treatment might accelerate further reduction of N₂O via nitrifier denitrification, resulting in evident negative influence of the SP treatment on N₂O emission. The two soil moistures in laboratory simulation experiments were similar to those of the agricultural field during the two maize seasons in 2010 and 2011, respectively. The evidently positive influence of straw returning on N₂O emission under soil WFPS of ~60% (Fig. 5a) and remarkably negative influence under soil WFPS of ~90% (Fig. 5b) were in good agreement with the results of the field measurements.

During the winter wheat growing season, the maize straw was returned into the field with tillage for seeding. The soils of both the SP and NP treatments were equally exposed to the air and sunlight irradiation, and hence there was no significant difference of the soil moisture between the two treatments. The anoxic condition induced by rotting the maize straw underneath the soil might be in favor of reduction of N₂O emission from the SP treatment.

5. Conclusions

Both negative and positive influences of straw returning on N₂O emission from the agricultural field were found during the two consecutive years. The laboratory simulation experiments confirmed that the inconsistent influence of straw returning on N₂O emission was mainly

Fig. 5. N₂O emissions from the N1 (only application of the compound fertilizer) and N2 (application of both the compound fertilizer and the maize straw) treatments under (a) WFPS 60% and (b) WFPS 90%. N₂O emission values are means $\pm$ standard deviation for three replicates. Arrows show the days of fertilizer applications.

ascribed to the different soil moistures. Negative influence of straw returning on N₂O emission from the agricultural field would occur in relatively wet year with intensive rainfall, whereas positive influence could be found in relative dry year with less rainfall. The negative influences of straw returning on N₂O emission from the agricultural field during the two winter wheat seasons were attributed to anoxic condition induced by incorporating the maize straw into the soil.

Because crop straw returning in the vast area of the NCP has become a prevailing agricultural practice, the significantly negative and positive influences of straw returning on N₂O emission in different years should be considered for estimating N₂O emission from this region.

Acknowledgement

This work was supported by the National Key Technology R&D Program of China (2013BAD11B03-3), the National Natural Science Foundation of China (91544211, 21477142 and 41203070), the Special Fund for Environmental Research in the Public Interest (201509002), and the “Strategic Priority Research Program” of the Chinese Academy of Sciences (XDB05010100).

References

- Anderson, I.C., Levine, J.S., 1986. Relative rates of nitric-oxide and nitrous-oxide production by nitrifiers, denitrifiers, and nitrate respirers. *Appl. Environ. Microbiol.* 51 (5), 938–945.
- Aulakh, M.S., Khera, T.S., Doran, J.W., Bronson, K.F., 2001. Denitrification, N₂O and CO₂ fluxes in rice-wheat cropping system as affected by crop residues, fertilizer N and legume green manure. *Biol. Fertil. Soils* 34, 375–389.
- Baggs, E.M., Stevenson, M., Pihlatie, M., Regar, A., Cook, H., Cadisch, G., 2003. Nitrous oxide emissions following application of residues and fertilizer under zero and conventional tillage. *Plant Soil* 254, 361–370.
- Bateman, E.J., Baggs, E.M., 2005. Contributions of nitrification and denitrification to N₂O emissions from soils at different water-filled pore space. *Biol. Fert. Soils* 3.
- Bremner, J.M., 1997. Sources of nitrous oxide in soils. *Nutr. Cycl. Agroecosys.* 49, 7–16.
- Cheng, Y., Cai, Z.C., Chang, S.X., Wang, J., Zhang, J.B., 2012. Wheat straw and its biochar have contrasting effects on inorganic N retention and N₂O production in a cultivated Black Chernozem. *Biol. Fertil. Soils* 48 (8), 941–946.
- Crutzen, P.J., 1970. The influence of nitrogen oxides on the atmospheric ozone content. *Quart. J. Roy. Meteorol. Soc.* 96 (408):320–325. <http://dx.doi.org/10.1002/qj.49709640815>.
- Cui, F., Yan, G., Zhou, Z., Zheng, X., Deng, J., 2012. Annual emissions of nitrous oxide and nitric oxide from a wheat-maize cropping system on a silt loam calcareous soil in the North China Plain. *Soil Biol. Biochem.* 48:10–19. <http://dx.doi.org/10.1016/j.soilbio.2012.01.007>.
- Ding, W., Cai, Y., Cai, Z., Yagi, K., Zheng, X., 2007. Nitrous oxide emissions from an intensively cultivated maize-wheat rotation soil in the North China Plain. *Sci. Total. Environ.* 373 (2–3):501–511. <http://dx.doi.org/10.1016/j.scitotenv.2006.12.026>.
- Gao, B., Ju, X.T., Zhang, Q., Christie, P., Zhang, F.S., 2011. New estimates of direct N₂O emissions from Chinese croplands from 1980 to 2007 using localized emission factors. *Biogeosciences* 8, 3011–3024.
- Hao, X., Chang, C., Carefoot, J.M., Janzen, H.H., Ellert, B.H., 2001. Nitrous oxide emissions from an irrigated soil as affected by fertilizer and straw management. *Nutr. Cycl. Agroecosys.* 60 (1–3):1–8. <http://dx.doi.org/10.1023/a:1012603732435>.
- Hu, X.K., Su, F., Ju, X.T., Gao, B., Oenema, O., Christie, P., Huang, B.X., Jiang, R.F., Zhang, F.S., 2013. Greenhouse gas emissions from a wheat-maize double cropping system with different nitrogen fertilization regimes. *Environ. Pollut.* 176, 198–207.
- IPCC, 2013. Summary for policymakers. In: Stocker, T.F., Qin, D., Plattner, G.K., et al. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Lin, S., Iqbal, J., Hu, R., Shaaban, M., Cai, J., Chen, X., 2013. Nitrous oxide emissions from yellow brown soil as affected by incorporation of crop residues with different carbon-to-nitrogen ratios: a case study in central China. *Arch. Environ. Contam. Toxicol.* 65 (2):183–192. <http://dx.doi.org/10.1007/s00244-013-9903-7>.
- Liu, C., Wang, K., Meng, S., Zheng, X., Zhou, Z., Han, S., Chen, D., Yang, Z., 2011. Effects of irrigation, fertilization and crop straw management on nitrous oxide and nitric oxide emissions from a wheat-maize rotation field in northern China. *Agr. Ecosyst. Environ.* 140 (1–2):226–233. <http://dx.doi.org/10.1016/j.agee.2010.12.009>.
- Luo, G.J., Kiese, R., Wolf, B., Butterbach-Bahl, K., 2013. Effects of soil temperature and moisture on methane uptake and nitrous oxide emissions across three different ecosystem types. *Biogeosci. Discuss.* 10, 927–965.
- Ma, J., Li, X.L., Xu, H., Han, Y., Cai, Z.C., Yagi, K., 2007. Effects of nitrogen fertilizer and wheat straw application on CH₄ and N₂O emissions from a paddy rice field. *Aust. J. Soil Res.* 45, 359–367.
- Millar, N., Ndafa, J.K., Cadisch, G., Baggs, E.M., 2004. Nitrous oxide emissions following incorporation of improved-fallow residues in the humid tropics. *Global. Biogeochem. Cy.* 18. <http://dx.doi.org/10.1029/2003GB002114> (GB 1032).
- Muhammad, W., Vaughan, S.M., Dalal, R.C., Menzies, N.W., 2011. Crop residues and fertilizer nitrogen influence residue decomposition and nitrous oxide emission from a Vertisol. *Biol. Fertil. Soils* 47, 15–23.
- Pan, Z., Wu, W., Liu, G., Gao, X., 2004. Effect of straw return and nitrogen fertilizer application on the N₂O emission of soil. *Soils Fertil.* 0, 6–8 (in Chinese).
- Pei, S., Zhang, Y., Liu, J., Lun, X., Mu, Y., 2012. N₂O exchange fluxes from wheat-maize crop rotation system in the North China Plain. *Huanjing Kexue* 33 (10), 3641–3646 (in Chinese).
- Robertson, D.S., Groffman, P.M., 2015. Nitrogen transformations. In: Paul, E.A. (Ed.), *Soil Microbiology, Ecology and Biochemistry*. Academic Press, Burlington, MA, pp. 421–446.
- Saggar, S., 2010. Estimation of nitrous oxide emission from ecosystems and its mitigation technologies. *Agric. Ecosyst. Environ.* 136, 189–191.
- Sarkodie-Addo, J., Lee, H.C., Baggs, E.M., 2003. Nitrous oxide emissions after application of inorganic fertilizer and incorporation of green manure residues. *Soil Use Manag.* 19, 331–339.
- Shaw, L.J., Nicol, G.W., Smith, Z., Fear, J., Prosser, J.I., Baggs, E.M., 2006. *Nitrosospira* spp. can produce nitrous oxide via a nitrifier denitrification pathway. *Environ. Microbiol.* 8, 214–222.
- Shen, J.L., Tang, H., Liu, J.Y., Wang, C., Li, Y., Ge, T.D., Jones, D.L., Wu, J.S., 2014. Contrasting effects of straw and straw-derived biochar amendments on greenhouse gas emissions within double rice cropping systems. *Agric. Ecosyst. Environ.* 188, 264–274.
- Singh, B., Shan, Y.H., Johnson-Beebout, S.E., Singh, Y., Buresh, R.J., 2008. In: Sparks, D.L. (Ed.), *Crop residue management for lowland rice-based cropping systems in Asia*. *Advan. Agron.* Vol. 98:pp. 117–199. [http://dx.doi.org/10.1016/s0065-2113\(08\)00203-4](http://dx.doi.org/10.1016/s0065-2113(08)00203-4).
- Snyser, C.S., Bruulsema, T.W., Jensen, T.L., Fixen, P.E., 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agric. Ecosyst. Environ.* 133, 247–266.
- Toma, Y., Hatano, R., 2007. Effect of crop residue C:N ratio on N₂O emissions from Gray Lowland soil in Mikasa, Hokkaido, Japan. *Soil Sci. Plant Nutr.* 53, 198–205.
- Trost, B., Prochnow, A., Drastig, K., Meyer-Aurich, A., Ellmer, F., Baumecker, M., 2013. Irrigation, soil organic carbon and N₂O emissions. A review. *Agron. Sustain. Dev.* 33, 733–749.
- Wrage, N., Velthof, G.L., van Beusichem, M.L., Oenema, O., 2001. Role of nitrifier denitrification in the production of nitrous oxide. *Soil Biol. Biochem.* 33, 1723–1732.
- Yang, L., Wang, L.G., Li, H., Qiu, J.J., Liu, H.Y., 2014. Impacts of fertilization alternatives and crop straw incorporation on N₂O emissions from a spring maize field in northeastern China. *J. Integr. Agric.* 13, 881–892.
- Yamulki, S., 2006. Effect of straw addition on nitrous oxide and methane emissions from stored farmyard manures. *Agr. Ecosyst. Environ.* 112, 140–145.
- Yanai, Y., Hirota, T., Iwata, Y., Nemoto, M., Nagata, O., Koga, N., 2011. Accumulation of nitrous oxide and depletion of oxygen in seasonally frozen soils in northern Japan — snow cover manipulation experiments. *Soil Biol. Biochem.* 43 (9):1779–1786. <http://dx.doi.org/10.1016/j.soilbio.2010.06.009>.
- Yao, Z.S., Zhou, Z.X., Zheng, X.H., Xie, B.H., Mei, B.L., Wang, R., Butterbach-Bahl, K., Zhu, J.G., 2010. Effects of organic matter incorporation on nitrous oxide emissions from rice-wheat rotation ecosystems in China. *Plant Soil* 327 (1–2):315–330. <http://dx.doi.org/10.1007/s11104-009-0056-4>.
- Zhang, Y., Liu, J., Mu, Y., Pei, S., Lun, X., Chai, F., 2011. Emissions of nitrous oxide, nitrogen oxides and ammonia from a maize field in the North China Plain. *Atmos. Environ.* 45 (17):2956–2961. <http://dx.doi.org/10.1016/j.atmosenv.2010.10.052>.
- Zhang, Y., Liu, J., Mu, Y., Xu, Z., Pei, S., Lun, X., Zhang, Y., 2012. Nitrous oxide emissions from a maize field during two consecutive growing seasons in the North China Plain. *J. Environ. Sci.* 24 (1):160–168. [http://dx.doi.org/10.1016/s1001-0742\(10\)60594-3](http://dx.doi.org/10.1016/s1001-0742(10)60594-3).
- Zhang, Y., Mu, Y., Fang, S., Liu, J., 2013. An improved GC-ECD method for measuring atmospheric N₂O. *J. Environ. Sci.* 25 (3):547–553. [http://dx.doi.org/10.1016/s1001-0742\(12\)60090-4](http://dx.doi.org/10.1016/s1001-0742(12)60090-4).
- Zhang, Y., Mu, Y., Zhou, Y., Liu, J., Zhang, C., 2014. Nitrous oxide emissions from maize-wheat field during 4 successive years in the North China Plain. *Biogeosciences* 11, 1717–1726.
- Zou, J., Huang, Y., Jiang, J., Zheng, X., Sass, R.L., 2005. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: effects of water regime, crop residue, and fertilizer application. *Glob. Biogeochem. Cycle* 19 (2):9. <http://dx.doi.org/10.1029/2004gb002401>.