Paddy Water Environ (2011) 9:403–411
DOI 10.1007/s10333-011-0275-1

Nitrous oxide emissions from paddy fields under different water managements in southeast China

Shizhang Peng · Huijing Hou · Junzeng Xu · Zhi Mao · Shalamu Abudu · Yufeng Luo

Received: 26 January 2011 / Revised: 30 March 2011 / Accepted: 9 May 2011 / Published online: 2 June 2011

Abstract Water management is recognized as one of the most important factors in regulating nitrous oxide (N_2O) emissions from paddy fields. In China, controlled irrigation (CI) is widely applied because it has been proved highly effective in saving water. During the rice-growing season, the soil in CI paddy fields remains dry 60–80% of the time compared with soil irrigated by traditional methods. This study aims to assess N_2O emissions from paddy fields under CI, with traditional irrigation (TI) as the control. The cumulative N_2O emission from CI paddy fields was 2.5 kg N ha^{-1}, which was significantly greater than that from TI paddy fields (1.0 kg N ha^{-1}) ($P < 0.05$). Soil drying caused substantial N_2O emissions. The majority (73.9%) of the cumulative N_2O emission from CI paddy fields was observed during the drying phase, whereas no substantial N_2O emissions were observed when the soil was re-wetted after the drying phase. More and significantly higher peaks of N_2O emissions from CI paddy fields ($P < 0.05$) were also detected. These peaks were observed $\sim$8 days after fertilizer application at water-filled pore spaces (WFPS) ranging from 78.0 to 83.5%, soil temperature ranging from 29.1 to 29.4°C, and soil redox potential (Eh) values ranging from +207.5 to +256.7 mV. The highest N_2O emission was measured 8 days after the application of base fertilizer at a WFPS of 79.0%, soil temperature of 29.1°C, and soil Eh value of +207.5 mV. These results suggest that N_2O emissions may be reduced obviously by keeping the WFPS higher than 83.5% within 10 days after each fertilizer application, especially when the soil temperature is suitable.

Keywords Nitrous oxide emissions · Paddy field · Water management · Controlled irrigation · Traditional irrigation

S. Peng · H. Hou · J. Xu (✉) · Y. Luo
State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, 1st Xikang Road, Nanjing 210098, China
e-mail: xjz481@hhu.edu.cn

Z. Mao
College of Water Resources and Hydroelectric Engineering, Wuhan University, Wuhan, 430072, China

S. Abudu
Civil Engineering Department, New Mexico State University, MSC 3CE, Box 30001, Las Cruces, NM 88003, USA

Introduction

Nitrous oxide (N_2O) is one of the key greenhouse gases that contribute to global warming and ozone depletion. The relative global warming potential of N_2O is 298 times that of carbon dioxide in a 100-year period. Agriculture accounts for almost 60% of global anthropogenic N_2O emissions, and agricultural N_2O emissions have increased by nearly 17% from 1990 to 2005 (IPCC 2007). Rice is the staple food of nearly 50% of the world's population. Rice planting areas account for about 20% of the world total and 23% of all cultivated land in China (Frolking et al. 2002). Studies on N_2O emissions from China's paddy fields are of national and global significance for both ozone depletion and climate change issues.

Traditional irrigation (TI) of paddy fields requires the consumption of large amounts of water (Mao 1996). With decreasing water availability for agriculture and increasing demand for rice, the implementation of water-saving irrigation (WSI) programs have become one of the basic national policies in China (Li 2001). Various WSI management modes are currently practiced in the paddy fields of Southeast China; these include controlled irrigation (CI), intermittent irrigation, flooding-midseason drainage-frequent water logging with intermittent irrigation (FDF), and flooding-midseason drainage-reflooding-moist intermittent irrigation but without water logging (FDFM) (Mao 2002; Wu 1999; Zou et al. 2007). One of the major WSI practices in China is CI, initially proposed by Li and Peng (1991) and further developed by Peng (1992). During the rice-growing season, the soil in CI paddy fields remains dry 60–80% of the time, and no standing water is found after the re-greening of rice seedlings, similar to that observed in the water management strategy used in the System of Rice Intensification (Chapagain and Yamaji 2010; Miyazato et al. 2010; Sato et al. 2011). CI has been proved effective in saving water without causing yield reduction (Yu and Zhang 2002), and has been widely applied in several provinces in China, such as Jiangsu, Ningxia, and Heilongjiang. In CI paddy fields, the soil oxygen status, soil redox potential (Eh), and soil temperature are altered by varying conditions of soil moisture, unlike in TI rice paddies. These transformations consequently induce changes in N_2O emissions. The influence of water management on N_2O emissions from paddy fields under continuous flooding, FDF, and FDFM has been well documented. N_2O emissions from paddy fields are negligible in continuously flooded rice paddies (Cai et al. 1997; Smith and Patrick 1983; Zou et al. 2005a). Midseason drainage, also called sun-baking or sun-drying in China (Mao 1996), as well as alternate wetting and drying in paddy fields result in substantial N_2O emissions (Cai et al. 2001; Johnson-Beebout et al. 2009; Liu et al. 2010; Smith and Patrick 1983; Zou et al. 2005b). However, few studies have been dedicated to quantifying N_2O emissions from CI paddy fields. Hence, investigating the effects of CI on N_2O emissions from rice paddies is important.

In addition, some previous studies have confirmed that soil moisture is the most sensitive factor in regulating N_2O emissions from croplands (Zheng et al. 2000; Yan et al. 2000), and the highest N_2O emission levels were observed at a specific range of water-filled pore spaces (WFPS). In a field trial, Hansen et al. (1993) observed the highest N_2O emission levels at a WFPS ranging from 45 to 75%. In their laboratory experiment, Khalil and Baggs (2005) detected the highest N_2O emission levels at 75% WFPS soil, and that the N_2O was mostly produced during denitrification. Similarly, the laboratory incubation experiment conducted by Sey et al. (2008) revealed that the peak N_2O production was observed at 80% WFPS. Ding et al. (2007) also observed that the optimum WFPS for N_2O emissions was 50% (ranging from 45 to 60%) in a maize–wheat rotation field in the North China Plain. Under CI, the soil is unsaturated for the most part of the rice-growing season. However, few studies have been devoted to the relationship between the N_2O emissions from and soil moisture of paddy fields under CI. Hence, this phenomenon is worth studying. Moreover, it is of significant importance to study the mitigation of N_2O emissions through soil moisture regulation.

The Taihu Lake region is one of the most densely populated areas in China and adopts the most typical paddy rice–winter wheat rotation system in the country. About 75% of the arable land in this region is used for rice growth. Thus, we carried out an experiment in this region to quantify N_2O emissions from paddy fields under CI and determine the method for mitigating N_2O emissions by regulating soil moisture. The interactions between soil parameters and N_2O emissions were also investigated.

Materials and methods

Experimental site

The experiment was conducted in 2009 in drainage lysimeters at the Kunshan Irrigation and Drainage Experiment Station in the Taihu Lake region, Jiangsu Province, China (31°15′N, 120°57′E). This region has a subtropical monsoon climate with an average annual temperature of 15.5°C and a mean annual precipitation of 1097.1 mm. Soil in the experimental site is classified as dark-yellow hydromorphic paddy soil, which represents the typical soil type in this region. The main (0–20-cm depth) properties of the soil in the experiment station are described as follows: organic matter, 21.88 g/kg; total nitrogen (N), 1.03 g/kg; total phosphorus (P), 1.35 g/kg; total potassium, 20.86 g/kg; and pH, 7.4.

Experimental design

The experiment involved two irrigation treatments, CI and TI. Each irrigation mode was designed with three replications, and the replicates were established in a randomized block design in six plots with an area of about 5 m^2 (2 × 2.5 m). These replicates were designated as CI1, CI2, CI3, TI1, TI2, and TI3, and each replication was a dynamic process of soil moisture determination in the plot. For the CI paddy fields, the irrigation water layer was not maintained except in the re-greening period. Irrigations were applied under two conditions. First, the soil moisture approached the lower threshold for irrigation at a certain stage (Table 1). Second, fertilizers, herbicides, and pesticides were applied. Rainfall was deflected with a canopy to accurately control soil moisture. In the TI paddy fields, there was a 3–5 cm shallow water layer after transplanting except during the midseason drainage period and the yellow maturity stage of rice.

Rice seedlings were transplanted to the paddy fields on June 23 and harvested on October 31, 2009. In accordance

Table 1 Limits for irrigation in different stages of rice for controlled irrigation

Stages	Re-greening	Tillering			Jointing and booting		Heading and flowering	Milk maturity	Yellow maturity
		Former	Middle	Later	Former	Later			
Upper limit	25 mm	θs_1	θs_1	θs_1	θs_2	θs_2	θs_3	θs_3	Drying
Lower limit	5 mm	$0.7\theta s_1$	$0.65\theta s_1$	$0.6\theta s_1$	$0.7\theta s_2$	$0.75\theta s_2$	$0.8\theta s_3$	$0.7\theta s_3$	
Monitored soil depth (cm)	–	0–20	0–20	0–20	0–30	0–30	0–40	0–40	–

θs_1, θs_2, and θs_3 are the saturated water content of the soil in different stages of rice

with local conventional fertilizer application methods, N fertilizer was applied at a rate of 250 kg N ha^{-1}. To improve the N utilization rate, a base fertilizer consisting of a compound fertilizer (15% each of N, P_2O_5, and K_2O) and ammonium bicarbonate (17% N content) was applied two times for broadcast fertilization. The compound fertilizer with a split of 25% of the total was broadcast on June 22 prior to transplanting, and ammonium bicarbonate was used with a split of 30% of the total on June 28. Urea (46% N content) with a split of 20 and 25% of the total was used as the tillering fertilizer on July 6 and panicle fertilizer on August 12, respectively.

Sampling and measurements

N_2O emissions were monitored using the static chamber technique. The chamber, which consists of two separate parts of the same size (0.5 × 0.5 × 0.6 m), is made of polyvinyl chloride. It is equipped with a thermometer and an electric fan on top for air mixing inside. A rubber tube was inserted into the chamber from one side, and was connected outside to three stopcocks used to draw air samples every 10 min with a 60-ml syringe. The samples were then transferred into an empty sealed airbag for analysis. Plastic bases for the chambers were installed before rice transplantation in the plots, and were kept there until rice harvest.

Gas samples were collected at 2–3-day intervals for 10 days after fertilizer application, then at 7-day intervals. A 7–14-day sampling interval was used during the last 2 months of rice growth. From each chamber, four gas samples were collected at 10-min intervals between 10:00 and 11:00 in the morning on every sampling day. The N_2O concentrations were analyzed using a gas chromatograph (Agilent 7890A-0468) equipped with an electron capture detector for N_2O analyses. The limit of detection of N_2O concentration was 30 nl l^{-1}. The N_2O emissions were determined from the linear increase of gas concentration at each sampling time (0, 10, 20, and 30 min) during the time of chamber closure, and calculated based on the equation of Zheng et al. (1998, 2000) and Hou et al. (2000):

$$F = \rho \times h \times \frac{273}{273 + T} \times \frac{dC}{dt}, \quad (1)$$

where F is the N_2O emission flux (μg m^{-2} h^{-1}), ρ is the N_2O density at standard state, h is the height of the chamber above the water surface (m), $\frac{dC}{dt}$ is the N_2O mixing ratio concentration (μg m^{-3} h^{-1}), and T is the mean air temperature inside the chamber during sampling (°C). The cumulative N_2O emissions during the study period were calculated by integrating the cumulative N_2O emissions on the sampling days.

During N_2O emission monitoring, the temperature inside the chamber and soil temperature at a depth of 5 cm were also measured using mercury thermometers. Soil moisture was measured directly using time domain reflectometry probes positioned vertically in the soil. Water layers were measured using rulers. Soil Eh at a 5-cm depth was measured in situ with a reduction–oxidation (redox) potential meter with Pt-tipped electrodes and a saturated calomel electrode. The soil Eh values in this study were converted to the standard H_2 reference electrode values. In this study, WFPS was adopted to describe soil moisture, and was calculated based on the following equation adopted in previous reports (Beare et al. 2009; Ding et al. 2007):

$$\mathrm{WFPS}(\%) = \frac{\text{gravimetric water content}(\%)}{\text{total soil porosity}} \times \text{soil bulk density} \times 100, \quad (2)$$

where total soil porosity = 1 − soil bulk density/2.65, with 2.65 g cm^{-3} as the assumed particle density of the soil.

Statistical analysis

Statistical analysis was performed using SPSS for Windows™. Statistically significant comparisons were identified using Fisher's least significant difference tests at an alpha level of 0.05 ($\alpha = 0.05$). Linear regression analysis was used to identify significantly positive or negative correlations among soil moisture, soil temperature, soil Eh, and N_2O emissions.

Results

Soil moisture, temperature, and redox potential

The soil moisture contents in the paddy fields under different water managements were clearly different. During the rice-growing season, the soil in the CI paddy fields remained dry 70–80% of the time (Fig. 1). A total of 11, 12, and 18 dry-wet alternations were observed in CI1, CI2, and CI3 paddy fields, respectively (Fig. 1). The first process of drying was observed 11 days after transplanting (DAT) in the former rice tillering stage. The lowest WFPS value (62.2%) was observed in CI1 24 DAT in the middle tillering stage. In the CI paddy fields, six times of irrigation were accompanied with herbicide and pesticide applications, and only one or two times of irrigation were accompanied with fertilizer application. In the TI paddy fields, the highest water layer was 6.0 cm. During the midseason drainage, soil moisture changed slowly because of the rainy weather and low temperature. At the end of the period, the WFPS values in TI1, TI2, and TI3 were 85.4%, 83.3%, and 72.5%, respectively.

Soil Eh values in the CI paddy fields were higher than those in the TI paddy fields for the most part of the rice-growing period (Fig. 2). The soil Eh values during the rice-growing season ranged from −77.9 to +489.0 mV (CI) and from −134.4 to +181.9 mV (TI). The mean Eh value in the CI fields was +216.4 mV, approximately 21 times that in the TI fields (+10.3 mV). Soil Eh values increased rapidly with time during the drying periods, and decreased rapidly following rewetting. The highest soil Eh value was observed 39 DAT at 69.5% WFPS in CI2. In the TI paddy fields, soil Eh values sharply increased from −104.1 mV (33 DAT) to +131.1 mV (39 DAT) during the midseason drainage, and rapidly decreased to −14.9 mV (46 DAT) following rewetting. Moreover, a significantly negative correlation was observed between soil Eh values and WFPS in the CI paddy fields ($P < 0.05$). However, no significant correlation was observed between soil Eh values and the water layer in the TI fields ($P > 0.05$). Soil

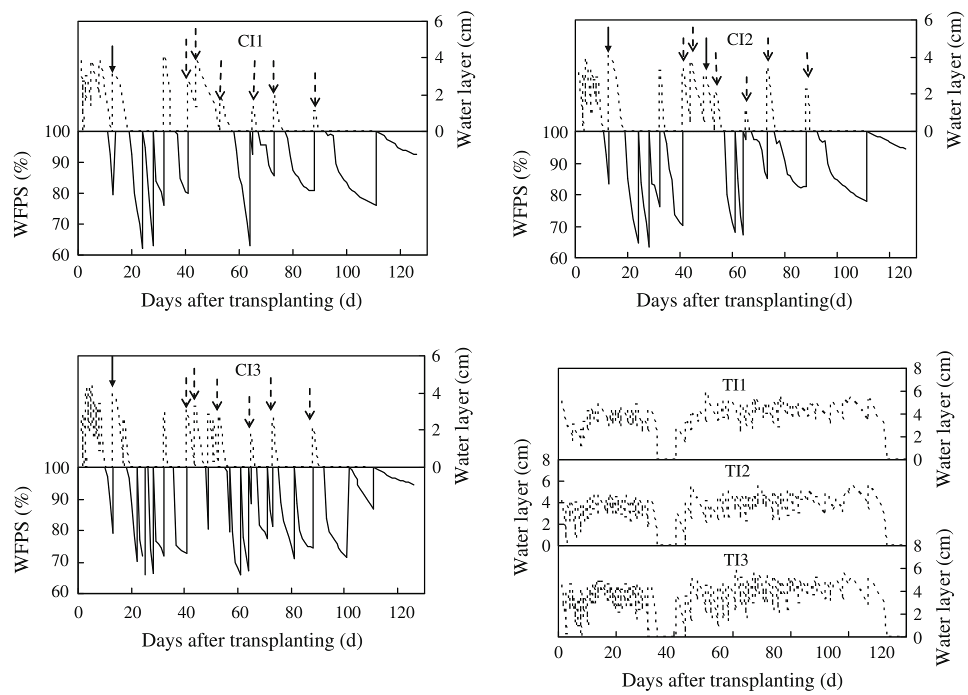

Fig. 1 Season variation of soil moisture and water layer in paddy fields under different water managements (*solid arrows* denote irrigations for fertilizer application in CI paddy fields. *Dashed arrows* denote irrigations for application of herbicides or pesticides in CI paddy fields)

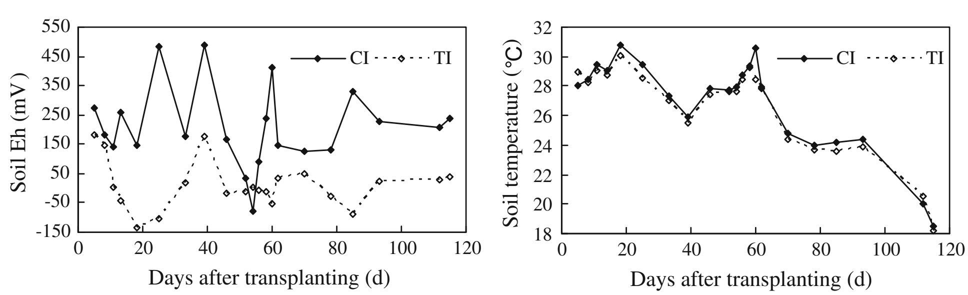

Fig. 2 Seasonal variation of soil Eh and soil temperature at 5-cm depth in paddy fields under different water managements

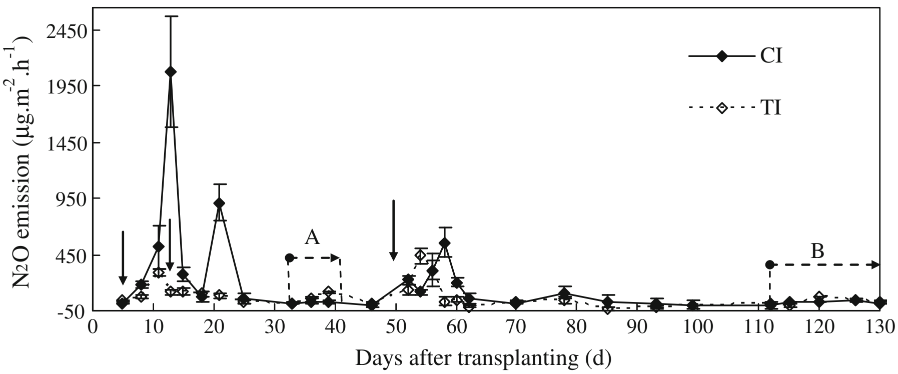

Fig. 3 Seasonal N_2O emissions (mean ± SE, $n = 3$) from paddy fields under different water managements (*vertical arrows* denote fertilizers in all treatments. *A* denotes the midseason drainage phase (34–41 DAT) in TI paddy fields, and *B* denotes the drying phase in the yellow ripeness stage of rice in TI paddy fields)

Table 2 Cumulative N_2O emission and N_2O–N loss of applied N in paddy fields under different water managements

Treatments	CI	TI
Cumulative N_2O emission (g N ha^{-1})	2535.5b*	995.1a*
N_2O emissions during the drying phases (g N ha^{-1})	1874.6b*	197.8a*
Percentage of drying phases to cumulative emission (%)	73.9	19.9
N_2O–N loss of applied N (%)	1.0	0.4

* Means in a row followed by *different small letters* were significantly different at the 5% level

temperatures at a depth of 5 cm in the CI fields were also higher than those in the TI fields for the most part of the rice-growing period (Fig. 2). Soil temperatures ranged from 18.5 to 30.8°C in the CI paddy fields, and varied from 18.2 to 30.1°C in the TI rice paddies. No significant correlation was observed between soil temperature and WFPS or water layer ($P > 0.05$).

N_2O emissions

Seasonal variations in N_2O emissions from paddy fields under different water managements were clearly different (Fig. 3). N_2O emissions from the CI paddy fields were higher than those from the TI rice paddies for the most part of the rice-growing season. The mean emission of N_2O in the CI fields (210.4 ± 82.8 μg m^{-2} h^{-1}) was 1.7 times higher than that in the TI fields (78.6 ± 20.7 μg m^{-2} h^{-1}). More and markedly higher peaks of the N_2O emissions were observed from the CI paddy fields than from the TI paddy fields. Three peaks were observed in the N_2O emissions from the CI rice paddies during the rice-growing season, whereas only two peaks were observed from the TI paddy fields. The highest peak value of the N_2O emissions from the CI paddy fields (2076.9 μg m^{-2} h^{-1}) was observed 13 DAT in the former tillering period, which was 4.8 times that from the TI paddy fields (436.9 μg m^{-2} h^{-1}). The other two peaks of the N_2O emissions from the CI fields were 911.9 and 556.9 μg m^{-2} h^{-1}, and were observed 21 DAT in the middle tillering stage and 58 DAT in the former jointing and booting stage, respectively. In the TI fields, the highest peak value of the N_2O emissions was observed 54 DAT in the former jointing and booting stage, and the lower peak (287.0 μg m^{-2} h^{-1}) was observed 11 DAT in the former tillering period of rice. In addition, only a small N_2O emission peak (114.3 μg m^{-2} h^{-1}) was observed during the midseason drainage period. The mean of N_2O emissions from the TI paddy fields during the yellow maturity period was 1.8 times that in the CI rice paddies.

Table 2 shows that the cumulative N_2O emission was significantly higher in the CI than in the TI paddy fields ($P < 0.05$) by 1.5 times. The majority (73.9%) of the cumulative N_2O emission from the CI paddy fields was observed during the drying phase. By contrast, only 19.9% of the cumulative N_2O emission from TI paddy fields was observed during the midseason drainage and yellow maturity phases. The majority (80.1%) of the cumulative N_2O emission from the TI fields was observed during the continuous flooding phase.

Discussion

Effect of water management on N_2O emissions

Seasonal variations in N_2O emissions were found dependent on the type of water management practiced in the paddy fields during the rice growing season. This finding is consistent with those of previous reports (Cai et al. 2001; Johnson-Beebout et al. 2009; Liu et al. 2010; Smith and

Patrick 1983; Zou et al. 2005b). The effects of soil drying and rewetting on N_2O emissions were highly obvious, although inconsistent with those reported in previous studies. For example, Cai et al. (1997, 2001) found that N_2O emissions peaked at the beginning of the disappearance of floodwater in rice fields, but no substantial evolution of N_2O was observed after the soil was re-flooded. By contrast, Beare et al. (2009) found that N_2O production was markedly reduced (by 93–96%) in soils during the drying phase, whereas the majority (88%) of the total N_2O production from compacted soil occurred after soil rewetting. In this study, soil drying caused substantial N_2O emissions, but no substantial N_2O emissions were observed after the soil was re-wetted. The peaks of N_2O emissions from the CI fields were observed 3–4 days after soil drying and approximately 8 days after fertilizer application. The differences between our results and those of other studies may be attributed to the soil properties. Differences in soil moisture of different soil types may affect N_2O emissions. In the TI paddy fields, N_2O emissions followed the general rule and were also increased by the midseason drainage. However, the occurrence of the majority of the cumulative N_2O emission during the continuous flooding phase was inconsistent with the findings of Cai et al. (1997) and Zou et al. (2005a). They found that the majority of the cumulative N_2O emission occurred during the midseason drainage. Our N_2O emission data during the midseason drainage were much lower than that obtained by Zou et al. (2005a). The major reason for this difference was the unobvious effect of midseason drainage on N_2O emissions in this study. During the midseason drainage, soil moisture changed slowly because of the rainy weather and low temperature, and did not reach the range that suitable for high emissions of N_2O. Therefore, the N_2O emissions caused by the midseason drainage depended on the extent of soil drying.

The N_2O–N loss was used to measure the amount of N_2O emissions from the paddy fields. The mean N_2O–N loss accounted for 1.0% (CI) and 0.4% (TI) of the applied N (Table 2). These values fall in the range 0.001–6.8% that was observed in cultivated soils (Bouwman 1990; Eichner 1990). The TI result is higher than that reported by Kumar et al. (2000) who found that the total N_2O–N emissions of applied N ranged from 0.08 to 0.14% through urea and $(NH_4)_2SO_4$ in paddy fields. However, it is lower than the results in most previous studies on paddy fields under the FDF water management (Table 3). Moreover, it is close to that reported by Akiyama et al. (2005) who observed an average emission factor of 0.37% for fertilized paddies with midseason drainage, although the authors used emission factor instead of N_2O–N loss of applied N. Total N_2O–N emissions of applied N from CI paddy fields are higher than the results of Suzhou and Wuxi, who studied paddy fields in China under the FDFM water management, and those in Nanjing and Jurong in China under the FDF water management (Table 3). However, it is lower than those in Nanjing paddy fields under the FDFM water management (Table 3). The differences are caused considerably by the kind of fertilizer and water management.

Factors regulating N_2O emissions

The change of WFPS affected N_2O emissions from CI paddy fields obviously during the drying phase. There was a narrow range of WFPS for high emissions of N_2O. The peaks of N_2O emissions were observed at a WFPS range of 78.0–83.5%, and the highest N_2O emission was measured at a WFPS of 79.0% (Fig. 4). The result is similar to the laboratory reports of Sey et al. (2008), who observed the peak N_2O production at 80% WFPS, but is slightly higher than the results of Khalil and Baggs (2005), who observed the highest N_2O emission at 75% WFPS. In addition, a significantly positive relationship was observed between N_2O emissions and the WFPS values ranging from 62.2 to 83.5% ($P < 0.05$). A significantly negative relationship was observed between N_2O emissions and WFPS values higher than 83.5% ($P < 0.05$). Thus, keeping WFPS higher than 83.5% may be an effective measure in reducing N_2O emissions.

There was a close relationship between N_2O emissions and soil temperatures, because the high emissions of N_2O were detected at high soil temperatures (Fig. 4). This observation consists with the result of Granli and Bøckman (1994) who suggested that N_2O emission increased with soil temperature for cultivated soil at temperatures between 25 and 40°C. As shown in Fig. 4, the peaks of N_2O emissions were observed at soil temperatures ranging from 29.1 to 29.4°C in the CI paddy fields, and from 27.6 to 29.1°C in the TI rice paddies. The highest N_2O emission was measured at a soil temperature of 29.1°C in the CI fields, and at 27.6°C in the TI fields. However, no significant correlation was found between soil temperature and N_2O emissions ($P > 0.05$), indicating that soil temperature is not a critical factor in N_2O emission. The temperature effect might be masked due to existence of other factors (Hou et al. 2000), such as soil moisture, soil mineral nitrogen, soil redox potential, and microbial activity.

Soil Eh is also an important factor affecting N_2O emissions from paddy fields. N_2O peaks were observed at soil Eh values ranging from +207.5 to +256.7 mV in CI paddy fields. No significant N_2O emission occurred at Eh values higher than +300 mV or lower than +120 mV (Fig. 4). This is similar to the results of Hou et al. (2000) and Yu et al. (2001). Hou et al. (2000) found significant N_2O emissions that occurred only at soil redox potentials above approximately +200 mV. As soil redox potential

Table 3 Cumulative N_2O emission and N_2O–N loss of applied N in paddy fields under different water managements reported by the previous studies

Water management	Site	Year	Chemical fertilizer		N_2O emission (kg N ha^{-1})	N_2O–N loss of applied N (%)	References
			Type	Amount (kg N ha^{-1})			
F-D-F	Nanjing 32°00′N, 118°48′E	1994	U	100	0.17	0.17	Cai et al. (1997)
		1994	AS	100	0.17	0.17	
		1994	U	300	0.62	0.21	
		1994	AS	300	0.98	0.33	
		2000	U	277	1.55	0.56	Zou et al. (2005a)
F-D-F	Jurong 31°58′N, 119°10′E	1995	U	100	0.86	0.86	Cao et al. (1999)
		1995	U	200	0.82	0.41	
		1995	U	200	0.74	0.37	
		1995	U	300	0.93	0.31	
F-D-F-M	Suzhou 31°16′N, 120°38′E	1994	U	310	2.82	0.91	Zheng et al. (2000)
		1994	AB	191	1.24	0.65	
		1994	AB	191	1.72	0.90	
		1996	U	191	1.92	1.01	
		1996	AB	191	1.52	0.80	
F-D-F-M	Wuxi 31°37′N, 120°28′E	2001	U	150	1.5	1.00	Zheng et al. (2004)
		2001	U	250	2.31	0.92	
		2001	U	250	1.21	0.48	
		2002	U	150	1.71	1.14	
		2002	U	250	1.99	0.80	
		2002	U	250	2.99	1.20	
F-D-F-M	Nanjing 32°00′N, 118°48′E	2001	CF + AB	333	4.11	1.23	Zou et al. (2005a)
		2002	U	150	2.67	1.78	Zou et al. (2005b)
		2002	U	300	4.44	1.48	
		2002	U	450	6.17	1.37	

Type of chemical fertilizer: *AS* ammonium sulfate, *U* urea, *AB* ammonium bicarbonate, *CF* compound fertilizer, *F-D-F* flooding-midseason drainage-frequent water logging with intermittent irrigation, *F-D-F-M* flooding- midseason drainage-reflooding-moist intermittent irrigation but without water logging

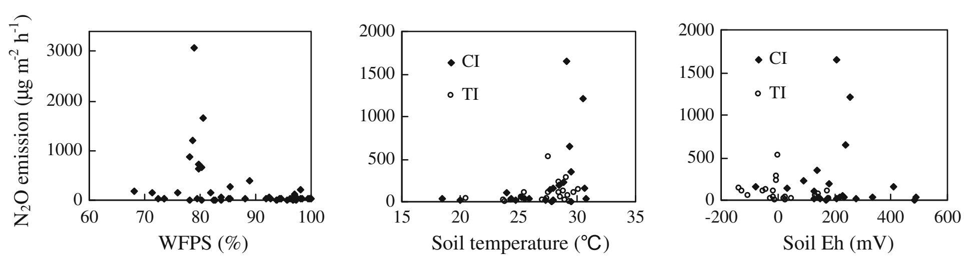

Fig. 4 Relationship between soil moisture, temperature, Eh values, and N_2O emissions from paddy fields under different water managements

decreased, less N_2O was emitted. In a laboratory experiment, Yu et al. (2001) found that N_2O emission was regulated within the narrow redox potential range of +120 to +250 mV, due to the balance of N_2O production and its further reduction to N_2. In the TI paddy fields, N_2O peaks appeared at soil Eh values of 0 mV approximately (Fig. 4). No significant correlation between soil Eh values and N_2O emissions was observed ($P > 0.05$).

Research prospects

The cumulative N_2O emissions from paddy fields under different water managements were obviously different. The cumulative N_2O emission from the CI paddy fields was 1.5 times greater than that from the TI paddy fields. Nevertheless, the assumption that TI fields are more environment-friendly than CI fields is misleading. The environment-friendliness of CI cannot be evaluated only by these N_2O emission results in view of the other environmental benefits of CI. Four explanations are provided for this issue. First, it may be an effective measure to reduce N_2O emissions from CI paddy fields by monitoring WFPS higher than 83.5%, because the majority (73.9%) of the cumulative N_2O emission from CI paddy fields was observed during the drying phase and the peaks of N_2O emissions were observed at the WFPS ranging from 78.0 to 83.5%. The effect of this measure on mitigating N_2O emission requires further verification. Second, N_2O emissions have been confirmed to be strongly influenced by the historical conditions of soil moisture (Akiyama et al. 2005; Liu et al. 2010; Yan et al. 2003; Zheng et al. 2004), especially in the rice–winter wheat rotation system (Liu et al. 2010). The water status of paddy fields during the rice growth period affects the N_2O emissions during the subsequent non-rice season. Continuous flooding during the rice-growing season in an annual rice-upland rotation system results in increased N_2O emissions during the follow non-rice season. Therefore, N_2O emissions during the following non-rice season are likely to be higher in the fields managed by TI than by CI during the rice-growing season. This issue needs further investigation. Third, Peng et al. (2007) confirmed that methane (CH_4) emissions from CI were significantly less than those from TI paddy fields. Thus, the integrated greenhouse effect caused by CH_4 and N_2O emissions from CI fields is likely to be less than that from TI fields, another compelling research direction. Finally, the N and P losses from paddy fields through ammonia volatilization, leaching and runoff are more effectively reduced by CI than by TI (Peng et al. 2011; Yang et al. 2010). Therefore, the application of CI increases the efficiency of fertilizer use and protects the water surrounding the paddy fields. Investigating the integrated environmental benefits of CI is also a worthwhile endeavor.

Conclusion

This study investigated the effects of water management types on N_2O emissions from paddy fields. CI reflected significantly higher N_2O emissions from the paddy fields in Southeast China. Cumulative N_2O emission was 1.5 times greater in the CI than in TI paddy fields. More and significantly higher peaks of N_2O emissions were observed in CI paddy fields. However, the environment-friendliness of CI cannot be evaluated only by the N_2O emission results in view of the other environmental benefits of CI.

Soil drying resulted in substantial N_2O emissions from the paddy fields. The majority (73.9%) of the cumulative N_2O emission from the CI paddy fields was observed during the drying phase. N_2O emissions from the CI paddy fields peaked only at about 8 days after fertilizer application when the WFPS ranged from 78.0 to 83.5%. There was also no substantial N_2O emission after rewetting of the soil following the drying phase. Keeping WFPS higher than 83.5% within 10 days after each fertilizer application is likely to reduce N_2O emissions effectively, especially at suitable soil temperatures.

Acknowledgments We appreciate the various helps of Mao Zhi, an academician of the Chinese Academy of Engineering. In addition, this study was financially supported by the National Natural Science of China (Grant Nos 50839002, 50809022) and the Foundation for the Author of National Excellent Doctoral Dissertation of PR China (No. 200546).

References

Akiyama H, Yagi K, Yan XY (2005) Direct N_2O emissions from rice paddy fields: summary of available data. Glob Biogeochem Cycle 19(1):GB1005.1001–GB1005.1010

Beare MH, Gregorich EG, St-Georges P (2009) Compaction effects on CO_2 and N_2O production during drying and rewetting of soil. Soil Biol Biochem 41(3):611–621

Bouwman AF (1990) Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. In: Bouwman AF (ed) Soils and the greenhouse effect. Wiley, New York, pp 61–127

Cai ZC, Xing GX, Yan XY, Xu H, Tsuruta H, Yagi K, Minami K (1997) Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilisers and water management. Plant Soil 196(1):7–14

Cai ZC, Laughlin RJ, Stevens RJ (2001) Nitrous oxide and dinitrogen emissions from soil under different water regimes and straw amendment. Chemosphere 42(2):113–121

Cao JL, Ren LQ, Yang BL, Xu H, Xing GX, Zhang HK (1999) Characteristics of N_2O emission from rice fields in the hilly area of southern Jiangsu province. Chin J Ecol 18:6–9 (in Chinese)

Chapagain T, Yamaji E (2010) The effects of irrigation method, age of seedling and spacing on crop performance, productivity and water-wise rice production in Japan. Paddy Water Environ 8(1):81–90

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

Eichner MJ (1990) Nitrous oxide emissions from fertilized soils: summary of available data. J Environ Qual 19(2):272–280

Frolking S, Qiu J, Boles S, Xiao X, Liu J, Zhuang Y, Li C, Qin X (2002) Combining remote sensing and ground census data to develop new maps of the distribution of rice agriculture in China. Glob Biogeochem Cycle 16(4):1091–1101

Granli T, Bøckman OC (1994) Nitrous oxide from agriculture. Nor J Agric Sci 8(Suppl 12):1–128

Hansen S, Maehlum JE, Bakken LR (1993) N_2O and CH_4 fluxes in soil influenced by fertilization and tractor traffic. Soil Biol Biochem 25(5):621–630

Hou AX, Chen GX, Wang ZP, Van Cleemput O, Patrick WH (2000) Methane and nitrous oxide emissions from a rice field in relation to soil redox and microbiological processes. Soil Sci Soc Am J 64(6):2180–2186

IPCC (2007) Agriculture. In: Metz B, Davidson OR, Bosch PR (eds) Climate change 2007: mitigation, contribution of Working Group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Johnson-Beebout SE, Angeles OR, Alberto MCR, Buresh RJ (2009) Simultaneous minimization of nitrous oxide and methane emission from rice paddy soils is improbable due to redox potential changes with depth in a greenhouse experiment without plants. Geoderma 149(1–2):45–53

Khalil MI, Baggs EM (2005) CH_4 oxidation and N_2O emissions at varied soil water-filled pore spaces and headspace CH_4 concentrations. Soil Biol Biochem 37(10):1785–1794

Kumar U, Jain MC, Pathak H, Kumar S, Majumdar D (2000) Nitrous oxide emission from different fertilizers and its mitigation by nitrification inhibitors in irrigated rice. Biol Fert Soils 32(6):474–478

Li YH (2001) Research and practice of water-saving irrigation for rice in China. In: Barker R. Loeve R, Li YH, Tuong TP (eds) Water saving irrigation for rice: proceedings of an international workshop, Wuhan, China. International Water Management Institute, pp 1–9

Li SS, Peng SZ (1991) Rice controlled irrigation. Paper presented at the Proceedings of international commission on irrigation and drainage, special technical session, Beijing, pp 77–84

Liu SW, Qin YM, Zou JW, Liu QH (2010) Effects of water regime during rice-growing season on annual direct N_2O emission in a paddy rice-winter wheat rotation system in southeast China. Sci Total Environ 408(4):906–913

Mao Z (1996) Environmental impact of water-saving irrigation for rice. In: ICID/FAO Workshop on Irrigation Scheduling Rome (Italy), FAO/ICID, pp 141–145

Mao Z (2002) Water saving irrigation for rice and its effect on environment. Eng Sci 4(7):8–16 (in Chinese)

Miyazato T, Mohammed RA, Lazaro RC (2010) Irrigation management transfer (IMT) and system of rice intensification (SRI) practice in the Philippines. Paddy Water Environ 8(1):91–97

Peng SZ (1992) The new characters of rice water requirement in water-saving irrigation. Chin Rural Water Hydropower 10(3): 401–412 (in Chinese)

Peng SZ, Li DX, Xu JZ, Ding JL, He Y, Yu JY (2007) Effect of water-saving irrigation on the law of CH_4 emission from paddy field. Environ Sci 28(1):9–13 (in Chinese)

Peng SZ, Yang SH, Xu JZ, Luo YF, Hou HJ (2011) Nitrogen and phosphorus leaching losses from paddy fields with different water and nitrogen managements. Paddy Water Environ. doi: 10.1007/s10333-010-0246-y

Sato S, Yamaji E, Kuroda T (2011) Strategies and engineering adaptions to disseminate SRI methods in large-scale irrigation systems in Eastern Indonesia. Paddy Water Environ. doi: 10.1007/s10333-010-0242-2

Sey B, Manceur A, Whalen J, Gregorich E, Rochette P (2008) Small-scale heterogeneity in carbon dioxide, nitrous oxide and methane production from aggregates of a cultivated sandy-loam soil. Soil Biol Biochem 40(9):2468–2473

Smith CJ, Patrick WH (1983) Nitrous oxide emission as affected by alternate anaerobic and aerobic conditions from soil suspensions enriched with ammonium sulfate. Soil Biol Biochem 15(6): 693–697

Wu X (1999) Popularization of water saving irrigation technique to farmers. In: Xu Z (ed) Proceedings of the international symposium on water-saving irrigation for paddy rice, Guilin, China, pp 41–46

Yan X, Shi S, Du L, Xing G (2000) Pathways of N_2O emission from rice paddy soil. Soil Biol Biochem 32(3):437–440

Yan XY, Akimoto H, Ohara T (2003) Estimation of nitrous oxide, nitric oxide and ammonia emissions from croplands in East, Southeast and South Asia. Glob Change Biol 9(7):1080–1096

Yang SH, Peng SZ, Xu JZ, Wang PF (2010) Influences of different water and fertilizer treatments on distribution of nitrogen profiles and loss of ammonia volatilization in soils of paddy fields. Adv Sci Technol Water Resour 30(1):40–44 (in Chinese)

Yu SE, Zhang ZY (2002) Technical system of water saving irrigation for rice planting in Jiangsu Province. J Hohai Univ (Nat Sci) 30(6):30–34

Yu KW, Wang ZP, Vermoesen A, Patrick WH, Van Cleemput O (2001) Nitrous oxide and methane emissions from different soil suspensions: effect of soil redox status. Biol Fert Soils 34(1):25–30

Zheng XH, Wang MX, Wang YS, Shen RX, Li J (1998) Comparison of manual and automatic methods for measurement of methane emission from rice paddy fields. Adv Atmos Sci 15:569–579

Zheng XH, Wang MX, Wang YS, Shen RX, Li J, Jin J, Li L (2000) Impacts of soil moisture on nitrous oxide emission from croplands: a case study on the rice-based agro-ecosystem in Southeast China. Chemosphere Glob Change Sci 2(2):207–224

Zheng XH, Han SH, Huang Y, Wang YS, Wang MX (2004) Re-quantifying the emission factors based on field measurements and estimating the direct N_2O emission from Chinese croplands. Glob Biogeochem Cycle 18:GB2018

Zou JW, Huang Y, Jiang JY, Zheng XH, Sass RL (2005a) 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):1–9

Zou JW, Huang Y, Lu YY, Zheng XH, Wang YS (2005b) Direct emission factor for N_2O from rice-winter wheat rotation systems in southeast China. Atmos Environ 39(26):4755–4765

Zou JW, Huang Y, Zheng XH, Wang YS (2007) Quantifying direct N_2O emissions in paddy fields during rice growing season in mainland China: dependence on water regime. Atmos Environ 41(37):8030–8042