

Quantifying direct N₂O emissions in paddy fields during rice growing season in mainland China: Dependence on water regime

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Received 13 May 2006; received in revised form 14 June 2007; accepted 29 June 2007

Abstract

Various water management regimes, such as continuous flooding (F), flooding-midseason drainage-reflooding (F-D-F), and flooding-midseason drainage-reflooding-moist intermittent irrigation, but without water logging (F-D-F-M), are currently practiced in paddy rice production in mainland China. These water regimes have incurred a sensitive change in direct N₂O emission from rice paddy fields. We compiled and statistically analyzed field data on N₂O emission from paddy fields during the rice growing season (71 measurements from 17 field studies) that were published in peer-reviewed Chinese and English journals. Seasonal total N₂O was, on average, equivalent to 0.02% of the nitrogen applied in the continuous flooding rice paddies. Under the water regime of F-D-F or the F-D-F-M, seasonal N₂O emissions increased with N fertilizer applied in rice paddies. An ordinary least square (OLS) linear regression model produced the emission factor (EF) of nitrogen for N₂O averaged 0.42%, but background N₂O emission was not pronounced under the water regime of F-D-F. Under the F-D-F-M water regime, N₂O EF and background emission were estimated to be 0.73% and 0.79 kg N₂O-N ha⁻¹, respectively, during the paddy rice growing season. Based on results of the present study and national rice production data, subsequently, direct N₂O emissions during the rice growing season amounted to 29.0 Gg N₂O-N with the uncertainty of 30.1%, which accounted for 7–11% of the reported estimates of annual total emission from croplands in mainland China. The results of this study suggest that paddy rice relative to upland crop production could have contributed to mitigating N₂O emissions from agriculture in mainland China.

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Keywords: Background emission; Emission factor; Nitrous oxide; Regression model

1. Introduction

Nitrous oxide (N₂O), produced naturally in soils through the microbial processes of nitrification and

denitrification, causes global warming and stratospheric ozone depletion. Although it remains difficult to assess global emission rates of N₂O versus individuals of N₂O at present, fertilized agricultural soils have been believed to be a major source, equivalent to 13% of annual global N₂O emission (Olivier et al., 1998) or 24% (Mosier et al., 1998; Kroeze et al., 1999). The emissions of N₂O that result from anthropogenic N inputs occur through a direct pathway (i.e. directly from soils to

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which the N is added), and through two indirect pathways: volatilization of compounds such as NH_3 and NO_x and subsequent redeposition, and through leaching and runoff. Relative to the indirect pathways, the direct emission contributes most to the agricultural N_2O sources (e.g., Zheng et al., 2004). Thus, a good estimate of direct N_2O emission from agricultural fields will help assess its global source strength.

The United Nations Frame Convention on Climate Change (UNFCCC) obligates all signatory parties to periodically provide national inventories on emissions and/or removals of greenhouse gases that are not controlled by the Montreal protocol, such as N_2O releases from crop production. Accordingly, the Intergovernmental Panel on Climate Change (IPCC) developed “Revised 1996 IPCC guidelines for national and Greenhouse Gases Inventories (IPCC, 1997) and Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories” (IPCC, 2000). The present IPCC guidelines for estimating direct N_2O emission from fields include a default emission factor (EF) of 1.25% (0.25–2.25%) for fertilizer-induced emission plus a background emission (B) rate of $1 \text{ kg N}_2\text{O-N ha}^{-1} \text{ yr}^{-1}$ (IPCC, 1997). While most global extrapolations are based on the IPCC default, nevertheless, cropping-specific and country-specific emission factors should be used where possible, in order to reflect the specific conditions of the country and the agricultural practices involved (IPCC, 2000).

China is the most important rice producing country in the world. Rough rice production in China contributes ~30% to the world total (International Rice Research Institute (IRRI), 2004). Its planting area accounts for about 20% of the world total and 23% of all cultivated land in China (Frolking et al., 2002). Of this, ~93% is irrigated rice paddies; ~5% is distributed in rainfed lowlands and ~2% is in the uplands (IRRI, 2004). Various water management regimes are currently practiced in China’s rice paddies, such as seasonal continuous flooding (F), flooding-midseason drainage-frequent water logging with intermittent irrigation (F-D-F), and flooding-midseason drainage-reflooding-moist intermittent irrigation but without water logging (F-D-F-M) (Gao and Li, 1992; Huang et al., 2004). An episode of midseason drainage for 7–10 days rather than continuous flooding is commonly employed in China to inhibit ineffective tillers, remove toxic substances and improve roots activities.

A water regime often incurs a sensitive change in N_2O emission in rice paddies (Akiyama et al., 2005). It is well documented that midseason drainage in rice paddies triggers substantial N_2O emission in contrast with continuous flooding (e.g., Cai et al., 1997; Zheng et al., 2000; Jiang et al., 2003). In addition, N_2O fluxes during intermittent irrigation periods depend strongly on whether or not water logging is present in paddy fields, which often begets a significant difference in seasonal total of N_2O emissions between the water regimes of F-D-F and F-D-F-M (Zou et al., 2005a).

Some studies have gone into quantifying fertilizer-induced N_2O emission and its background emission from rice paddies at the regional and global scales (Yan et al., 2003; Zheng et al., 2004; Akiyama et al., 2005). Yan et al. (2003) estimated N_2O emission factors and background emissions in irrigated paddy fields during the rice growing season, but they did not differentiate N_2O emissions under different water regimes. In contrast, Akiyama et al. (2005) recently reported that the EFs averaged 0.22% for the continuous flooding paddies and 0.37% for the fertilized paddies with midseason drainage. In the data set employed to estimate N_2O emission factors by Akiyama et al. (2005), however, only five field studies were carried out in China (i.e., Cai et al., 1997; Chen et al., 1997; Hou et al., 2000; Zheng et al., 2000; Xiong et al., 2002). In addition, some N_2O measurements from rice paddies under the F-D-F-M water regime (e.g., Xing and Zhu, 1997; Zheng et al., 2000) were treated as statistical outliers, and thus they were excluded by Akiyama et al. (2005) as well.

Consequently, estimates of EF and background N_2O emission in previous studies may not sufficiently reflect N_2O emissions from rice paddies in China, where various water regimes are practiced. Here, we compiled and statistically analyzed the available field measurements of N_2O from rice paddies in China. The objective of this study was to quantify the cropping-specific direct EF and background emission for N_2O during the rice growing season, and thereafter to estimate seasonal direct N_2O emissions from paddy rice production in mainland China.

2. Material and methods

2.1. Data collection

We compiled measurements of direct N_2O emission from rice field studies that were published to

date in peer-reviewed Chinese and English journals. Data published in Chinese were gathered from the Chinese Journal Net (CJN) full-text database and those in English from the Science Citation Index (SCI) database. Measurements of N₂O flux taken from field studies over an abnormally shorter period (e.g., Xu et al., 1995), from pot experiments (e.g., Xiong et al., 2003a) or from incubation studies (e.g., Yan et al., 2000) were not considered in this study. We did not adopt an obviously abnormal result that N₂O fluxes were not detectable when pig manure was incorporated at the rate of 164 kg N ha⁻¹ under the water regime of F-D-F (Yang et al., 1996). Measurements from aerobic rice fields (e.g., Xu et al., 2004), and from those in which the controlled release fertilizers were applied (e.g., Li et al., 2004a) or the amount of organic amendments was not presented for nitrogen treatments (e.g., Khalil et al., 1998) and were excluded as well.

In the end, we employed 71 field measurements from 17 studies to estimate the EF and background emission of N₂O during the paddy rice growing season under different water regimes (Tables 1a–c). These studies were performed at eight field sites that were located in Beijing, Guangdong, Henan, Jiangsu, Jiangxi and Liaoning provinces, China, over the period of 1992–2002. For each field study, we documented the seasonal N₂O emission, the type and amount of organic amendment and fertilizer nitrogen application, the water management regime, the drainage duration, the field location and cropping season. If seasonal N₂O amounts were not originally presented, they were calculated from

average fluxes of N₂O over the entire rice growing season.

Major types of chemical N fertilizer in agriculture in China, such as urea, compound fertilizer, ammonium sulfate, and ammonium bicarbonate were included in this study (Tables 1a–c). For the fertilized fields, seasonal chemical N fertilizer was, on average, applied at the rate of 247 kg N ha⁻¹, ranging from 100 to 450 kg N ha⁻¹ (Tables 1a–c). Besides chemical nitrogen fertilizer application, organic manure or crop residue amendment was used as basal fertilizer in some studies. Organic amendments comprised farmyard manure and crop residue such as winter wheat, milk vetch, rice straw, mushroom and rapeseed cake. Due to lack of available data, we could not distinguish between organic and inorganic nitrogen fertilizer-induced N₂O emissions. Thus, seasonal total nitrogen input was used to quantify the fertilizer-induced EF of N₂O in this study.

In all employed measurements, N₂O fluxes were measured in situ by the static chamber-gas chromatograph method. They were measured by manual sampling system, except that an automatic system was used to continuously measure N₂O fluxes in one study in Shuzhou (Zheng et al., 2000). In general, gas samples were taken twice weekly (e.g., Cai et al., 1997; Cao et al., 1999; Chen et al., 1999; Zou et al., 2005b) or once a week (e.g., Yang et al., 1996; Cai et al., 1999; Xiong et al., 2002) over the entire rice growing season, except for once a day during the midseason drainage (e.g., Xiong et al., 2003b; Zou et al., 2005a).

Table 1a
Direct N₂O emissions from continuous flooding paddy fields during rice growing season

Location	Year	Chemical fertilizer		Organic amendment		N ₂ O emission (kg N ha ⁻¹)	References
		Type ^a	Amount (kg N ha ⁻¹)	Type ^b	Amount (kg N ha ⁻¹)		
Shenyang, 41°32'N, 122°23'E	1992	No	0	No	0	0	Chen et al. (1995)
	1992	U	374	No	0	0	Chen et al. (1995)
	1996	U	374	FM	42	0.04	Hou et al. (2000)
Nanjing, 32°00'N, 118°48'E	2000	CF + urea	277	No	0	0.06	Zou et al. (2005a)
	2000	CF + urea	277	WR	18	0.03	Zou et al. (2005a)
Guangzhou, 23°26'N, 113°30'E	1995	U	306		0	0.16	Lu et al. (1997)

^aType of chemical fertilizer: CF, compound fertilizer; U, urea.

^bType of organic amendment: FM, farmyard manure; WR, winter wheat residue.

Table 1b
Direct N₂O emissions from paddy fields under the water regime of flooding-midseason-reflooding (F-D-F) during rice growing season

Location	Year	Chemical fertilizer		Organic amendment		N ₂ O emission (Kg N ha ⁻¹)	References
		Type ^a	Amount (kg N ha ⁻¹)	Type ^b	Amount (kg N ha ⁻¹)		
Nanjing, 32°00'N, 118°48'E	1994	No	0	No	0	0.14	Cai et al. (1997)
	1994	U	100	No	0	0.17	Cai et al. (1997)
	1994	AS	100	No	0	0.17	Cai et al. (1997)
	1994	U	300	No	0	0.62	Cai et al. (1997)
	1994	AS	300	No	0	0.98	Cai et al. (1997)
	2000	U	277	No	0	1.55	Zou et al. (2005a)
	2000	U	277	No	18	1.43	Zou et al. (2005a)
Jurong, 31°58'N, 119°10'E	1995	No	0	No	0	0.62	Cao et al. (1999)
	1995	U	100	No	0	0.86	Cao et al. (1999)
	1995	U	200	No	0	0.82	Cao et al. (1999)
	1995	U	200	No	0	0.74	Cao et al. (1999)
	1995	U	300	No	0	0.93	Cao et al. (1999)
Yingtian, 28°15'N, 116°55'E	2000	No	0	MV	124	0.26	Xiong et al. (2002, 2003b)
	2000	No	0	MV	124	0.30	Xiong et al. (2002, 2003b)
	2000	No	0	No	0	0.18	Xiong et al. (2002, 2003b)
	2000	No	0	No	0	0.23	Xiong et al. (2002, 2003b)
	2000	U	276	No	0	0.35	Xiong et al. (2002, 2003b)
	2000	U	276	No	0	0.28	Xiong et al. (2002, 2003b)
	2000	U	276	MV	0	0.34	Xiong et al. (2002, 2003b)
	2000	U	276	MV	124	2.81	Xiong et al. (2002, 2003b)
Guangzhou, 23°26'N, 113°30'E	1994	U	162	PM	64	0.49	Yang et al. (1997)
	1994	U	287	No	0	3.14	Yang et al. (1997)
	1995	U	140	MR	10	0.24	Yang et al. (1996)
	1995	U	140	PM	82	0.40	Yang et al. (1996)
	1995	U	280	No	0	3.14	Yang et al. (1996)
	1995	U	306	No	0	0.28	Lu et al. (1997)
	1995	U	306	No	0	1.32	Lu et al. (1997)

^aType of chemical fertilizer: AS, ammonium sulfate; U, urea.

^bType of organic amendment: MR, mushroom residue; MV, milk vetch residue; PM, pig manure.

2.2. Statistical analysis

The relationship between N application and N₂O emission established by Eichner (1990) and Bouwman (1996) motivated the concept of fertilizer-induced EF. The EF is defined as N₂O emission from nitrogen fertilizer plots minus the emission from unfertilized control plots (all other conditions being equal to those of the fertilized plots) expressed as a percentage of N applied. This IPCC methodology suggests that linear regression models could be used to quantify N₂O emissions. In the present study, thus, we used a linear regression model ($N_2O-N = EF \cdot N + B + \varepsilon$) with the personality of ordinary least squares (OLS) to fit N₂O emissions (N₂O-N) by nitrogen inputs (N). In this model, ε denotes the error term; EF and B are the simulated parameters that represent N₂O EF and background emission, respectively. A *t*-test was used

to examine statistic significance of the parameter estimates. An analysis of variance (ANOVA) *F*-test partitioned the total variation of N₂O-N into the linear relationship with N and the part not explained by the relationship. The model fitness to the data was examined by both residual distribution pattern and power analysis. We also used a one-way ANOVA to test whether seasonal N₂O amount depended on the water regime. The statistical analyses were conducted using JMP IN 5.1 (SAS INC., 2003).

3. Results and discussion

3.1. Interannual and spatial variations of N₂O emissions

It is apparent that N₂O emissions varied inter-annually and spatially (Tables 1b, c). Under an

Table 1c

Direct N₂O emissions from paddy fields under the water regime of flooding-midseason-reflooding-moist intermittent irrigation but without water logging (F-D-F-M) during rice growing season

Location	Year	Chemical fertilizer		Organic amendment		N ₂ O emission (kg N ha ⁻¹)	References
		Type ^a	Amount (kg N ha ⁻¹)	Type ^b	Amount (kg N ha ⁻¹)		
Beijing, 40°30'N, 116°24'E	1992	AB	125	No	0	1.32	Khalil et al. (1998)
	1993	AB	125	No	0	1.21	Khalil et al. (1998)
Fengqiu, 35°04'N, 113°10'E	1994	AB+U	364.5	PM	67	4.42	Cai et al. (1999)
	1994	AB+U	364.5	PM	67	2.01	Cai et al. (1999)
	1994	AB+U	364.5	PM	67	1.71	Cai et al. (1999)
Nanjing, 32°00'N, 118°48'E	2001	CF+AB	333	CM	29	3.26	Zou et al. (2004)
	2001	CF+AB	333	PM	50	3.38	Zou et al. (2004)
	2001	CF+AB	333	No	0	4.11	Zou et al. (2005a)
	2001	CF+AB	333	RC	146	4.83	Zou et al. (2005a)
	2001	CF+AB	333	WR	18	3.33	Zou et al. (2005a)
	2002	No	0	No	0	1.38	Zou et al. (2005b)
	2002	U	150	No	0	2.67	Zou et al. (2005b)
	2002	U	150	WR	36	2.97	Zou et al. (2005b)
	2002	U	225	WR	18	3.79	Zou et al. (2005b)
	2002	U	300	No	0	4.44	Zou et al. (2005b)
Wuxi, 31°37'N, 120°28'E	2002	U	450	No	0	6.17	Zou et al. (2005b)
	2001	U	150	No	0	1.50	Zheng et al. (2004)
	2001	U	250	No	0	2.31	Zheng et al. (2004)
	2001	U	250	No	0	1.21	Zheng et al. (2004)
	2002	U	0	No	0	0.90	Zheng et al. (2004)
	2002	U	150	No	0	1.71	Zheng et al. (2004)
	2002	U	250	No	0	1.99	Zheng et al. (2004)
	2002	U	250	No	0	2.99	Zheng et al. (2004)
Shuzhou, 31°16'N, 120°38'E	1993	No	0	No	0	0.86	Xing and Zhu (1997)
	1993	U	210	No	0	2.57	Xing and Zhu (1997)
	1993	AS	220	No	0	3.27	Xing and Zhu (1997)
	1993	U	210	PM	68	3.01	Xing and Zhu (1997)
	1993	U	310	No	0	2.82	Xing and Zhu (1997)
	1994	No	0	No	0	0.46	Zheng et al. (2000)
	1994	AB	191	No	0	1.24	Zheng et al. (2000)
	1994	AB	191	No	0	1.72	Zheng et al. (2000)
	1994	AB	191	No	0	1.52	Zheng et al. (2000)
	1996	No	0	No	0	0.50	Zheng et al. (2000)
	1996	U	161	RS	30	1.01	Zheng et al. (2000)
	1996	AB	191	No	0	3.45	Zheng et al. (2000)
Guangzhou, 23°26'N, 113°30'E	2002	No	0	No	0	0.93	Li et al. (2004a)
	2002	U	180	No	0	2.45	Li et al. (2004a)

^aType of chemical fertilizer: AB, ammonium bicarbonate; AS, ammonium sulfate; CF, compound fertilizer; U, urea.

^bType of organic amendment: CM, cow manure; PM, pig manure; RC, rapeseed cake; RS, rice straw; WR, winter wheat residue.

identical water regime of F-D-F, for example, seasonal total N₂O in 1994 averaged 1.49 kg N₂O-N ha⁻¹ when ammonium bicarbonate was applied at the rate of 191 kg N ha⁻¹, which was 57% lower than that in 1996 in Shuzhou (Table 1b). In Wuxi, seasonal N₂O emission from plots with urea applied

at the rate of 250 kg N ha⁻¹, on average, amounted to 2.49 kg N₂O-N ha⁻¹ in the 2002 season, which was increased by 41% in comparison with that in the 2001 season. In 2002, on the other hand, seasonal total of N₂O emissions from plots with urea applied at the rate of 150 kg N ha⁻¹ was 2.67 kg

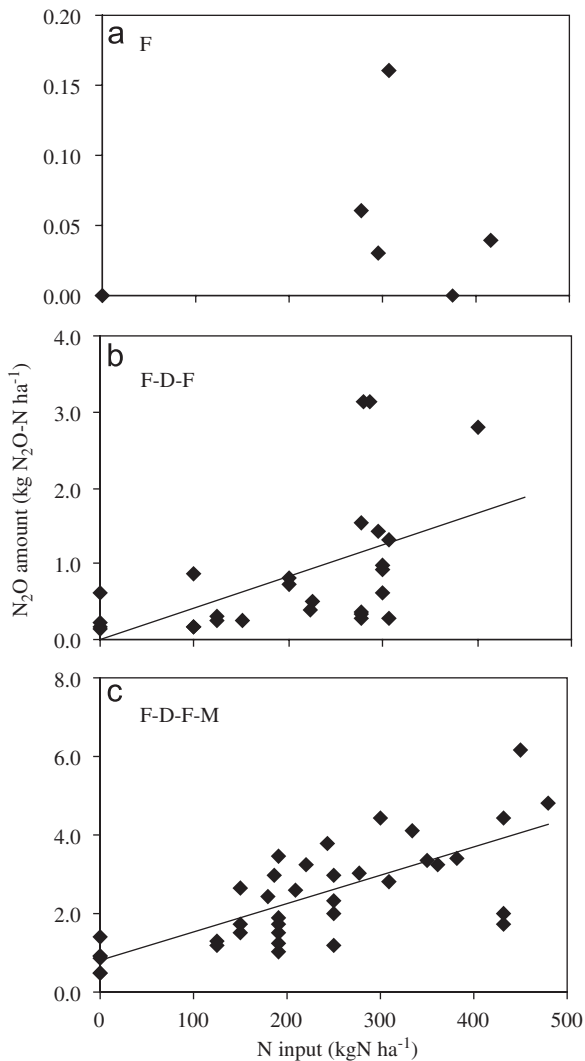


Fig. 1. Dependence of seasonal N_2O amount on nitrogen input in rice paddies under different water regimes: (a) continuous flooding (F); (b) flooding-midseason drainage-reflooding (F-D-F); and (c) flooding-midseason drainage-reflooding-moisture intermittent irrigation but without water logging (F-D-F-M).

$\text{N}_2\text{O-N ha}^{-1}$ in Nanjing, while that from plots with the identical fertilizer application and water regime was only $1.71 \text{ kg N}_2\text{O-N ha}^{-1}$ in Wuxi (Table 1c). Although it varied interannually and spatially, seasonal N_2O emissions generally increased with nitrogen input under the water regime of F-D-F or the F-D-F-M (Fig. 1b, c).

3.2. Modeling emission factor and background emission for N_2O

A one-way ANOVA indicated that seasonal total N_2O in rice paddies significantly varied with the

water regime ($F_{2,70} = 21.7$, $P < 0.0001$), which suggests that the effect of water regime on seasonal pattern of N_2O fluxes has incurred a pronounced difference in seasonal N_2O amount. To accurately quantify seasonal N_2O emissions and minimize its uncertainties, thus, the data set of N_2O was classified into three categories based on water regime (F, F-D-F and F-D-F-M, Tables 1a–c) and seasonal N_2O emissions were separately modeled under different water regimes in this study.

Probably due to limited available data and low N_2O emissions, no pronounced relationship between N_2O emission and nitrogen input was found in the continuous flooding rice paddy fields (Fig. 1a, $F_{1,5} = 0.25$, $P = 0.65$). Mean and standard error of seasonal N_2O amounts were estimated to be 0.048 and $0.024 \text{ kg N}_2\text{O-N ha}^{-1}$, and those of N inputs to be 278 and 60 kg N ha^{-1} for the six field measurements, respectively (Table 1a). Seasonal total of N_2O was, on average, equivalent to 0.02% of the N fertilizer applied under continuous flooding.

In contrast, a significant linear relationship between seasonal N_2O amount and N input in rice paddies was found under the water regime of F-D-F (Table 2, Fig. 1b). Based on simulated parameters of the model F-D-F-1 (Table 3), the fertilizer-induced EF for N_2O during the rice growing season averaged 0.42% , with a standard error of 0.13% . Seasonal background N_2O emission was estimated to be $0.009 \text{ kg N}_2\text{O-N ha}^{-1}$, with a high standard error ($0.30 \text{ kg N}_2\text{O-N ha}^{-1}$) suggesting its large uncertainty. A *t*-test showed that this estimated value did not significantly differ with the assumed value of zero (term “B” for the model F-D-F-1, Table 3). Subsequently, we used a reduced model $\text{N}_2\text{O-N} = \text{EF} \cdot \text{N} + \varepsilon$, in which the background emission (B) was omitted (model F-D-F-2, Table 2). The reduced model F-D-F-2 suggested that N_2O EF averaged 0.42% , with a standard error of 0.06% (Table 3). Compared with the model F-D-F-1, the model F-D-F-2 minimized substantially the uncertainty in estimates of direct N_2O emission.

Similarly, direct N_2O emissions depended greatly on nitrogen inputs in rice paddies under the water regime of F-D-F-M (model F-D-F-M, Table 2; Fig. 1c). The F-D-F-M model showed that N_2O EF and background emission averaged 0.73% and $0.79 \text{ kg N}_2\text{O-N ha}^{-1}$, respectively (Table 3). Standard errors of EF and background emission were estimated to be 0.11% and 0.28% , respectively. Results of *t*-tests suggested that both nitrogen application and background emission contributed

Table 2
ANOVA *F*-tests for the simulated OLS models in rice paddies with midseason drainage

Model	Term	DF	SS	<i>F</i>	<i>P</i>	Power	<i>r</i> ²
F-D-F-1	Regression	1	5.9	10.4	0.004	0.87	0.293
	Error	25	14.4				
F-D-F-2	Regression	1	25.2	45.6	<0.0001	1.00	0.293
	Error	26	14.4				
F-D-F-M	Regression	1	36.2	45.3	<0.0001	1.00	0.557
	Error	36	28.8				
MSD-Akiyama ^a	Regression	1	13.1	18.8	<0.0001	0.99	0.28
	Error	44	30.5				

^aThe MSD-Akiyama model simulated using the data that were shown in Table 1b in Akiyama et al.'s (2005) study.

Table 3
t-Tests for parameter estimates in the simulated models in rice paddies with midseason drainage

Model	EF				<i>B</i>			
	Estimate	Stand error	<i>t</i> -ratio	<i>P</i>	Estimate	Stand error	<i>t</i> -ratio	<i>P</i>
F-D-F-1	0.0042	0.0013	3.22	0.004	0.0087	0.3	0.03	0.98
F-D-F-2	0.0042	0.0006	6.75	<0.0001				
F-D-F-M	0.0073	0.0011	6.73	<0.0001	0.79	0.28	2.82	0.008
MSD-Akiyama ^a	0.0043	0.001	4.34	<0.0001	0.20	0.19	1.06	0.30

^aThe MSD-Akiyama model simulated using the data that were shown in Table 1b in Akiyama et al.'s (2005) study.

significantly to seasonal N₂O total in rice paddies under the F-D-F-M water regime (Table 3).

3.3. Fitness of OLS model

The assumptions of the OLS linear regression model strictly concern the error term (ϵ) that can be represented by the pattern of residuals. The residuals from the fitted model are important for checking whether the assumptions of linear regression analysis are met (Quinn and Keough, 2004). The residuals of the OLS models tended to be symmetrically distributed and centered on zero, suggesting that these models were well fit for the data in rice paddies under the F-D-F and the F-D-F-M (Fig. 2a–c). Power analyses for the model F-D-F-2 and the model F-D-F-M also showed that these linear relationships were strong enough to model the N₂O data (Table 2). On the other hand, a stronger power for the model F-D-F-2 relative to the model F-D-F-1 suggested that it was better fit for the data, although both models had a similar determination coefficient (*r*²) (Table 2). However, great care should be taken in using the *r*² values for comparing the fitness of different models, such as

the model F-D-F-1 and the reduced model F-D-F-2 in this study, since it is inappropriate for comparing models with different numbers of parameters (Scott and Wild, 1991).

3.4. Emission factor of nitrogen for N₂O

The fertilizer-induced EF of N₂O in the present study was, on average, 0.42% for the water regime of F-D-F and 0.77% for the F-D-F-M. Obviously, these estimated emission factors of N₂O in rice paddies are significantly lower than the IPCC (1997) default factor of 1.25% or estimates in upland croplands in this area (e.g., Zheng et al., 2004). Yan et al. (2003) estimated that N₂O emission factors and background emissions averaged 0.25% and 0.26 kg N₂O-N ha⁻¹, respectively, in the rice growing season. However, they did not distinguish N₂O emissions under different water regimes in rice paddies. In contrast, Akiyama et al. (2005) recently reported that the EFs averaged 0.22% for the continuous flooding rice paddies and 0.37% for the fertilized paddies with midseason drainage. These estimates represent the mean of 16 and 23 emission factors directly measured from field studies in which

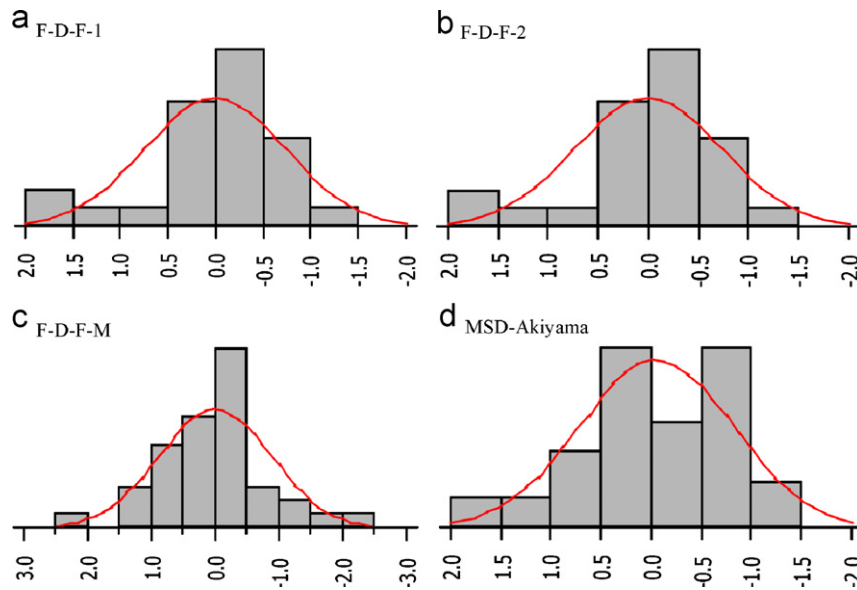


Fig. 2. Distribution pattern of residuals for the simulated ordinary least square (OLS) linear regression models. (a) Model F-D-F-1; (b) model F-D-F-2; (c) model F-D-F-M; and (d) model MSD-Akiyama. The MSD-Akiyama model simulated using the data that were shown in Table 1b in Akiyama et al.'s (2005) study. The fit line represents the normal distribution pattern.

both nitrogen and no-nitrogen treatments were designed, respectively. As the authors pointed out, seasonal total N_2O emissions were not significantly related to nitrogen input during the rice growing season over all water regimes or for continuous flooding (Akiyama et al., 2005). Based on the data that were exhibited in Table 1b by Akiyama et al. (2005), however, a pronounced relationship between N_2O emission and N input during the rice growing season was found in the rice paddies with midseason drainage. Using Akiyama et al.'s (2005) identical data (excluding measurements from nitrification inhibitors and controlled released fertilizers), the simulated OLS linear model MSD-Akiyama predicted that N_2O EF averaged 0.43%, with a background emission of $0.20 \text{ kg } N_2O\text{-N ha}^{-1}$ (Table 3). This EF simulated by the OLS model is slightly higher than that obtained by Akiyama et al. (2005), which was based on the maximum likelihood (ML) estimate.

Indeed, the EF of N_2O estimated by Akiyama et al. (2005) refers to the value of EF that maximizes the likelihood of observing N_2O emission measurements. Point and interval estimation using the ML model relies heavily on distributional assumptions, that a sample of observations (response variables) has a normal distribution (Quinn and Keough, 2004). However, the direct EF data in Akiyama et al.'s (2005) study had a log-normal distribution

pattern. In contrast, the EF estimated by the OLS model in this study represents the value with the least uncertainty. The OLS point estimates require no distributional assumptions for variables, but instead concentrate on residual distribution (Quinn and Keough, 2004). As shown in Fig. 2(d), the residuals of the model MSD-Akiyama were close to being normally distributed. A power analysis also showed that it was strong enough to model the data (Table 2). In order to minimize the uncertainty in estimates of EF for N_2O , presumably, the OLS model could be more appropriate for N_2O data than the ML model used by Akiyama et al. (2005).

3.5. Background N_2O emission

In the present study, background emission of N_2O in rice paddies was pronounced only under the water regime of F-D-F-M (Table 3). Background N_2O emissions during the rice growing season were negligible for the continuous flooding paddy fields. Under the water regime of F-D-F, background N_2O emission was estimated to be $0.009 \text{ kg } N_2O\text{-N ha}^{-1}$, which was not significantly different from "0" (Table 3). This negligible background emission is partially due to water management when water logging dominated over the rice season except for a short-term episode of midseason drainage. An intensive N_2O emission occurred only in the course

of midseason drainage under the F-D-F. In contrast, background N_2O emission was, on average, as high as $0.79 \text{ kg N}_2\text{O-N ha}^{-1}$ under the F-D-F-M water regime. Based on seven measurements in the continuous flooding and intermittent irrigation rice paddies, Yan et al. (2003) estimated background N_2O emission, on average, to be $0.26 \text{ kg N}_2\text{O-N ha}^{-1}$ in the paddy rice season. As the authors acknowledged, however, there was much uncertainty with respect to the background emission estimate in paddy fields. Indeed, the background emission has become one of the most sensitive factors for developing an inventory of agricultural N_2O emissions (e.g., Bouwman et al., 2002; Yan et al., 2003; Akiyama et al., 2005).

3.6. Effect of water regime on N_2O emissions

Different water regimes caused a sensitive change in N_2O emission in rice paddies. Under continuous flooding, N_2O emissions were generally pronounced only when fields were drained before rice harvesting (e.g., Chen et al., 1995; Lu et al., 1997). In contrast with continuous flooding, midseason drainage triggered substantial N_2O emission from rice paddies under the F-D-F water regime (e.g., Xiong et al., 2002; Jiang et al., 2003; Zou et al., 2005a). Based on the results of this study, we predict that seasonal N_2O emissions will amount to $0.03 \text{ kg N}_2\text{O-N ha}^{-1}$, when nitrogen is applied at the rate of 150 kg N ha^{-1} in the continuous flooding rice paddies, which is similar to the results of earlier studies at other regions (e.g., Smith et al., 1982; Granli and Bøckman, 1994). However, seasonal total N_2O will be, on average, up to $1.87 \text{ kg N}_2\text{O-N ha}^{-1}$ under the water regime of F-D-F-M, which is threefold as much as that under the water regime of F-D-F.

Primarily, N_2O is produced in soils via the biogeochemical processes of nitrification and denitrification that are greatly influenced by soil water status. In contrast to paddies with the water regime of F-D-F, or the seasonal continuous flooding paddies, the dry–wet alteration after midterm drainage created a favorable soil environment for both nitrification and denitrification processes, which contributed greatly to higher N_2O emissions under the water regime of F-D-F-M. Under continuous flooding, in contrast, a large proportion of N_2O produced from denitrification would be further reduced to N_2 before leaving the soil (Firestone and Davidson, 1989). On the other hand,

water regime might influence the availability of nitrogen, labile C compounds, and O_2 in paddy soils that are key factors to N_2O production in general denitrification models (Firestone and Davidson, 1989). The midseason drainage and dry–wet alteration are able to improve root activities and accelerate soil organic C decomposition, which might produce more available C and N for soil microbes, and thereby favor N_2O emissions.

Water management pattern in rice production has been greatly changed in mainland China since the 1950s. Before the early 1980s, irrigated rice paddies were dominated by continuous flooding. Since the 1980s, however, midseason drainage has been commonly adopted to increase rice productivity. Due to water resources scarcity and cultivation technique development, the water regime of F-D-F-M as a water-saving irrigation technology has been increasingly practiced in China's rice production. For example, water is especially scarce in the North China Plain that contains 26% of the China's cultivated land, 30% of its irrigated land, and 24% of its total grain production (Geng et al., 2001). The water regime of F-D-F-M and aerobic rice paddies instead of anaerobic paddies have been suggested as potential options for rice production in this area. However, a process-based model estimated that shifting water management from continuous flooding to midseason drainage increased N_2O emissions from Chinese rice paddies by $0.13\text{--}0.20 \text{ Tg N}_2\text{O-N yr}^{-1}$ (Li et al., 2004b) or $0.15 \text{ Tg N}_2\text{O-N yr}^{-1}$ (Li et al., 2005). In addition, N_2O emissions have been shown to be extremely higher from aerobic rice paddies compared with anaerobic paddies (Xu et al., 2004). Therefore, these options would increase N_2O emissions from rice production in China. Indeed, how to reconcile increasing N_2O emissions and scarcity of water resources with the development of rice production has become a real challenge in mainland China.

3.7. Uncertainty in quantifying direct N_2O emission

In the present study, we did not find a pronounced relationship between N_2O emission and nitrogen input in the continuous flooding rice paddy fields. Besides the scanty measurements, low N_2O emission may be another important cause. In contrast with continuous flooding, N_2O emissions were significantly higher in paddy fields with midseason drainage, and thereby relationship between N_2O emission and nitrogen input became pronounced.

Under the water regime of F-D-F, fertilizer input and background emission in the simulated regression model can only explain 29% of the variability in the 27 observed seasonal average N₂O fluxes. Under the water regime of F-D-F-M, however, up to 56% of the variability in the 38 observed N₂O measurements can be explained by fertilizer together with background emission in the simulated regression model (Table 2).

Obviously, some factors other than water regime may also be important to N₂O EF in rice paddy fields. Besides the fertilizer amount, for example, fertilizer type has been recognized as another factor influencing N₂O emissions in agricultural fields (e.g., Bouwman et al., 2002). Although seasonal N₂O emissions generally increased with fertilizer input, it varied with the type of fertilizer as well in rice paddy fields. Compared with urea, application of ammonium sulfate or ammonium bicarbonate induced higher N₂O emission under an identical water regime of F-D-F or F-D-F-M (e.g., Cai et al., 1997; Zheng et al., 2000). In contrast with pure chemical fertilizer application, on the other hand, organic manure and crop residue amendments increased seasonal N₂O emissions in some studies (e.g., Zheng et al., 2000; Zou et al., 2004, 2005b), while they decreased N₂O emissions in other studies (e.g., Xiong et al., 2003b).

The difference in frequency of N₂O measurements may also contribute to its estimate uncertainty. Ideally, N₂O emissions should be measured frequently enough to capture its peak fluxes. Sharp peaks of N₂O fluxes in paddy fields were observed in a study using an automated monitor system (Zheng et al., 2000). Relative to measurements once a week, measurements twice weekly showed more peak fluxes of N₂O, particularly after nitrogen fertilizer was applied in rice paddies (Zou et al., 2005a). However, most studies in the data set measured N₂O flux only once a week. As a consequence, some flux peaks might have been missed and seasonal N₂O emissions could have been underestimated in these studies.

3.8. Quantifying seasonal direct N₂O emissions in paddy fields in China

In the past decades, paddy rice production has been greatly developed in China. For example, rice cultivated land area in mainland China totals about 31.4 million hectare in 1997, which is 19% greater than in 1950 (IRRI, 2004). In 1997, chemical

fertilizer application rate was estimated to be 145.0 kg N ha⁻¹ in rice paddy fields in mainland China (Food and Agricultural Organization (FAO), 2002). Various water regimes and organic amendments in rice paddies in China are not well documented. Our survey on national greenhouse gases inventories of agriculture (unpublished data) suggests that 12% of rice paddy is continuous flooding, 75% under the water regime of F-D-F and 13% under the F-D-F-M. Xing (1998) estimated that continuous flooding rice paddies accounted for 10% of the total in 1995. Li et al. (2002) reported that rice paddies with midseason drainage contributed ~80% to the total in China in 2000. Yan et al. (2003) estimated that two-thirds of rice paddy is under intermittent irrigation or middle season drainage in China. Based on survey data and national statistics, we estimated that half of the rice fields receive organic input at the rate of 24% of crop biomass and 9.86 t ha⁻¹ of organic manure. We assume that harvested biomass of crop residue is 4.5 t ha⁻¹ and that the nitrogen content of crop residue and organic manure is 0.45% and 0.71%, respectively. The emission factors and background emissions simulated under different water regimes in the present study are assumed to be applicable for N₂O emissions from rice paddies in mainland China. Thus, N₂O emissions during the rice growing season amounted to 29.0 Gg N₂O-N in China. According to the methodology recommended by the IPCC for quantifying uncertainties (2000), the uncertainty in N₂O estimate is combined by uncertainties in emission factors and activity data, and eventually their combined uncertainty of this study was estimated to be 30.1%.

Using a precipitation-rectified EF model and the IPCC uncertainty estimate methodology, we estimated the EF of N₂O in China's uplands to be 1.14% in 1997 with an uncertainty of 29% (Lu et al., 2006). Xing (1998) reported that direct N₂O emissions from paddy fields totalled 88 Gg N₂O-N, consisting of 35 Gg N₂O-N emitted during the rice growing season and 53 Gg N₂O-N during the upland crop seasons. Direct N₂O emission from croplands in China was estimated to be 275 Gg N₂O-N yr⁻¹ in the 1990s by Zheng et al. (2004), or 398 Gg N₂O-N in 1995 by Xing (1998). These estimates suggest that rice production occurring on 23% of the cultivated land accounts for 7–11% of the total N₂O emission from croplands in China. Due to the increase in rice planting area in the past decades and lower emission factor, therefore, paddy

rice relative to upland crop production could have greatly contributed to mitigating N₂O emissions from agriculture in China.

Note that this study estimated only direct N₂O emissions during the rice growing season, but did not count those during the following non-rice seasons in paddy fields. Although a water regime has distinguished N₂O emissions in rice paddies from upland crops, some agricultural practices such as water management and organic incorporation during the rice growing season may have a substantial effect on the following seasonal N₂O emissions (Zou et al., 2005b). The results of our previous study in a paddy rice-winter wheat rotation system indicated that, compared with the water regime of F-D-F, continuous flooding in the rice season significantly increased N₂O emissions from the winter wheat growing season. Also, wheat residue incorporation before rice transplanting had a far-lasting effect on N₂O emissions during the winter wheat growing season (Zou et al., 2003). Therefore, annual total N₂O emissions in rice paddies would be underestimated by extrapolating N₂O data during the rice growing season.

4. Conclusions

During the rice growing season, N₂O emissions depended significantly on the water regime in paddy fields. Seasonal total N₂O was, on average, equivalent to 0.02% of the nitrogen input in the continuous flooding rice paddies. The EF of fertilizer for N₂O averaged 0.42% and 0.73% under the F-D-F and the F-D-F-M water regimes, respectively. N₂O background emission during the rice growing season was not pronounced under the water regime of F-D-F, but it amounted to 0.79 kg N₂O-N ha⁻¹ under the F-D-F-M water regime. Seasonal N₂O emissions amounted to 29.0 Gg N₂O-N, accounting for 7–11% of the reported estimates of annual total emission from croplands in mainland China. Relative to upland crop production, paddy rice development in the past decades could have greatly contributed to mitigating N₂O emissions from agriculture in China.

Acknowledgment

This study was supported by the Nanjing Agricultural University and the National Natural Science Foundation of China (40431001, 2040175030).

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