

Direct emission factor for N₂O from rice–winter wheat rotation systems in southeast China

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Abstract

A field experiment was conducted in a rice–winter wheat rotation agroecosystem to quantify the direct emission of N₂O for synthetic N fertilizer and crop residue application in the 2002–2003 annual cycle. There was an increase in N₂O emission accompanying synthetic N fertilizer application. Fertilizer-induced emission factor for N₂O (FIE) averaged 1.08% for the rice season, 1.49% for the winter wheat season and 1.26% for the whole annual rotation cycle. The annual background emission of N₂O totaled 4.81 kg N₂O–N ha⁻¹, consisting of 1.24 kg N₂O–N ha⁻¹ for rice, 3.11 kg N₂O–N ha⁻¹ for wheat seasons. When crop residue and synthetic N fertilizer were both applied in the fields, crop residue-induced emission factor for N₂O (RIE) was estimated as well. When crop residue was retained at the rate of 2.25 and 4.50 t ha⁻¹ for each season, the RIE averaged 0.64% and 0.27% for the whole annual rotation cycle, respectively. Based on available multi-year data of N₂O emissions over the whole rice–wheat rotation cycle at 3 sites in southeast China, the FIE averaged 1.02% for the rice season, 1.65% for the wheat season. On the whole annual cycle, the FIE for N₂O ranged from 1.05% to 1.45%, with an average of 1.25%. Annual background emission of N₂O averaged 4.25 kg ha⁻¹, ranging from 3.62 to 4.87 kg ha⁻¹. It is estimated that annual N₂O emission in paddy rice-based agroecosystem amounts to 169 Gg N₂O–N in China, accounting for 26–60% of the reported estimates of total emission from croplands in China.

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1. Introduction

Nitrous oxide (N₂O) is an atmospheric trace gas that contributes to global warming and the depletion of stratospheric ozone (IPCC, 1996). Although the N₂O budget remains poorly understood at present, the major

anthropogenic source of N₂O is attributed to a number of agricultural activities that add nitrogen to soils such as synthetic fertilizer N application and crop residue incorporation. These activities increase the amount of nitrogen (N) available for nitrification and denitrification, and ultimately the amount of N₂O emitted by these processes (IPCC, 2001). The emissions of N₂O that result from anthropogenic N inputs occur through a direct pathway (i.e. directly from soils to which the N is added), and through two indirect pathways: through volatilization as NH₃ and NO_x and subsequent redeposition, and through leaching and runoff. Of these, the

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direct pathway accounts for the majority of atmospheric N₂O. By the IPCC (1997, 2000) default methodology, for example, Zheng et al. (2004) estimated that about 75% of the annual total N₂O released from anthropogenic reactive nitrogen input into croplands of China is presently due to direct emission. Poor estimation of direct N₂O emission is largely responsible for the uncertainty in N₂O emission inventory of crop production and therefore much research has concentrated on obtaining better estimates of direct N₂O emissions from agricultural fields (Bouwman, 1996; Bouwman et al., 2002a, b; Yan et al., 2003a; Zheng et al., 2004).

The relationship between N application rate and N₂O emission established by Eichner (1990) and Bouwman (1996) motivated the concept of fertilizer-induced emission (FIE) factor. Fertilizer-induced emission 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. Fertilizer-induced emission is supposed to represent the anthropogenic emission caused by N application, although the emission from control plots may not be the same as the “natural” emission of the original vegetation in pre-agricultural times. The IPCC guidelines for estimating direct N₂O emissions from the application of synthetic N fertilizers include a default global emission factor of 1.25% (0.25–2.25%) for the FIE (IPCC, 1997). This default emission factor is also assumed to be available for the crop residues incorporated in the fields (IPCC, 2000). While most global extrapolations are based on the IPCC default, country-specific emission factors should be used where possible, in order to reflect the specific conditions of the country and the agricultural practices involved. Such emission factors should be based on measurements that are conducted frequently enough in typical cropping types within a country and over a long enough period time to fully reflect the variability of the underlying biogeochemical processes (IPCC, 2000).

China is the most important rice producing country in the world. Its planting area accounts for about 20% of the world total (FAO, <http://apps.fao.org/>) and occurs on 23% of all cultivated land in China. Wheat cultivation represents some 26% of the total national food crop growing area in China and some 13% of the international wheat cropping acreage (FAO, <http://apps.fao.org/>). Paddy rice–winter wheat rotation accounts for 16% of the total rice production area in China (Frolking et al., 2002). Particularly in southeast China, it is the major type of cropping system that N₂O emissions have been paid much attention (e.g., Cai et al., 1997; Zheng et al., 1999; Jiang et al., 2003; Zou et al., 2003a). Various water management patterns in rice paddies are practiced in China, such as seasonal continuous flooding (F), flooding-midseason drainage-

frequent waterlogging with intermittent irrigation (F–D–F), and flooding-midseason drainage-reflooding-moist but without waterlogged by intermittent irrigation (F–D–F–M). In contrast with the seasonal continuous flooding paddies, the water regime of flooding interspersed with midterm drainage and dry–wet alteration in this area creates a favorable soil environment for N₂O production in the paddy fields (Cai et al., 1997; Zheng et al., 2000; Jiang et al., 2003). In addition, the combination of synthetic N fertilizer and crop residues applications to the soil, which has been widely adopted in this area to maintain soil fertility and enhance crop productivity, may greatly facilitate N₂O emissions (Slemr et al., 1984; Cochran et al., 1997). Finally, the aerobic conditions after draining the paddy fields increases the N₂O production from the following winter wheat season (Byrnes et al., 1993; Bronson et al., 1997; Bouwman et al., 2002b).

Much research has centered on the fertilizer-induced emission factor for N₂O in agricultural fields, however, studies focusing on FIE for N₂O in an annual rice paddy–wheat rotation agroecosystem are rare. Accordingly, these conventional agricultural practices may provide an insight into the cropping-specific emission factor of N₂O. In this study, we measured annual N₂O emissions in a rice–winter wheat rotation according to the “Good Practice in Derivation of Country—specific Emission Factors” in the IPCC guidelines and gathered all available site-scale data over the whole annual rotation cycle to estimate the cropping-specific direct emission factor of N₂O for synthetic N fertilizer and N₂O background emission in southeast China.

2. Materials and methods

2.1. Field experiment

In the 2002–2003 annual cycle, a field experiment in a rice–wheat rotation cropping system was performed at the experimental farm of the Jiangsu Academy of Agricultural Sciences, in Nanjing, Jiangsu province, China (31°52′N, 118°50′E). Soil of the experimental field was classified as hydromorphic, consisting of 4% sand, 45% silt and 51% clay with an initial pH of 6.7. Total organic C and N were 13.1 and 1.1 g kg⁻¹, respectively. Annual precipitation was about 1100 mm, consisting of 600 mm during the rice season and 500 mm during the wheat season. The mean seasonal air temperature was 24.0 and 15.9 °C during rice and winter wheat seasons, respectively.

A *japonica* cultivar of rice named Wuyunjing 7 was planted in a seedling bed on 20 May, transplanted on 20 June and harvested on 15 October 2002. The local predominant water regime of flooding-midseason–drainage–reflooding–moist but without waterlogged by

intermittent irrigation (F–D–F–M) was adopted in this study. Flooding was initiated 3 days before transplanting and the field remained flooded until July 25, and followed by a drainage period of 1 week. Thereafter, rice paddy was reflooded from 1 August to 9 September 2002 and followed by a dry–wet alteration but non-waterlogged period until 10 days before harvest. After rice was harvested, a short fallow period was followed from 16 October to 9 November 2002. A winter wheat cultivar of Yangmai 158 was planted on 10 November 2002 and harvested on 5 June 2003.

The practical fertilization regime in local rice production was adopted in this study. Fertilizer application treatments are presented in Table 1. Crop stalks were left at about 10 cm height in the fields for each treatment after harvest. The plots without synthetic fertilizer N applied and without additional crop residue retained were designed as the controls (N0). Urea was used as the synthetic N fertilizer at the rate of 150, 300 or 450 kg N ha⁻¹ for the rice-growing season and 100, 200 or 300 kg N ha⁻¹ for the wheat-growing season (N1, N2 and N3), respectively. To investigate the emission factor of N₂O for crop residue, in addition, wheat and rice residue was retained at the rate of 4.50 t ha⁻¹ for plots with 150 kg N ha⁻¹ urea application (NS1) and 2.25 t ha⁻¹ for plots with 225 kg N ha⁻¹ urea application (NS2), respectively. The amounts of crop residue were almost equivalent to half and total of the above ground crop biomass harvested in the fields, respectively. Crop residue was chopped to the length of 10–15 cm and evenly distributed in the field just before rice transplanting or wheat sowing. The organic C and N contents were 579.0 and 10.4 g kg⁻¹ for rice residue and 504.0 and 8.0 g kg⁻¹ for wheat residue, respectively.

In agreement with the local conventional fertilizer application methods, urea was broadcasted on the fields, with a split of 40% of the total as basal fertilizer, 40% at turning-green and 20% at tillering stage in the rice season, and 30% of the total as basal fertilizer, 45% at booting and 25% at heading stage in the wheat season. For each plot, calcium superphosphate used as phos-

phorus fertilizer was identically applied as the basal fertilizer at the local rate of 375 kg ha⁻¹ during rice and wheat seasons, respectively. Potassium chloride used as potassium fertilizer was applied at the rate of 150 kg ha⁻¹ for rice and 225 kg ha⁻¹ for wheat seasons, respectively.

2.2. Gas sampling and analysis

During rice growing season, boardwalks to randomly selected N₂O measurement sites were installed from border levees to reduce soil disturbance during flux measurements. Aluminum flux collars permanently installed near the boardwalks ensured reproducible placement of gas collecting chambers during successive N₂O emission measurements in the whole rice–wheat rotation season. The top edge of the collar had a groove for filling with water to seal the rim of the chamber. The chamber was equipped with a circulating fan to ensure complete gas mixing and wrapped with a layer of sponge and aluminum foil to minimize air temperature changes inside the chamber during the period of sampling. The cross-sectional area of the chamber was 0.25 (0.5 × 0.5 m)². While gas sampling, the chamber was placed over the vegetation with the rim of the chamber fitted into the groove of the collar. Gas samples were taken twice weekly. During the drainage period between 25 July and 31 July 2002, gas samples were taken once a day. In wheat-growing season, gas samples were taken once a week except that daily gas sampling was lasted for 1 week after precipitation events and for 2 weeks after fertilization. Gas samples were taken from local time 08:00 through 10:00 LST for rice and 13:00–15:00 LST for wheat seasons since the soil temperature (T_s) during the sampling period was close to the daily average soil temperature (T_d , $T_d = 1.008T_s$, $P < 0.0001$ for rice and $T_d = 1.013T_s$, $P < 0.0001$ for wheat seasons).

The mixing ratio of N₂O was analyzed with a modified gas chromatograph (Agilent 4890D) equipped with the ECD (Zou et al., 2002; Wang and Wang, 2003).

Table 1

Synthetic N fertilizer (kg N ha⁻¹) and crop residue (t ha⁻¹) application rates and N₂O emission amounts (Mean ± SE, $n = 3$; kg N₂O–N ha⁻¹) in a rice–winter wheat rotation ecosystem

Treatment	Rice season			Winter-wheat season			Annual cycle
	Urea	Wheat residue	N ₂ O–N	Urea	Rice residue	N ₂ O–N	N ₂ O–N
N0	0		1.38 ± 0.01	0		2.84 ± 0.03	4.68 ± 0.04
N1	150		2.67 ± 0.07	100		4.83 ± 0.06	8.01 ± 0.06
N2	300		4.44 ± 0.16	200		6.44 ± 0.08	11.33 ± 0.17
N3	450		6.17 ± 0.42	300		7.27 ± 0.43	14.03 ± 0.77
NS1	150	4.50	2.97 ± 0.01	150	4.50	5.41 ± 0.22	8.90 ± 0.27
NS2	225	2.25	3.79 ± 0.03	225	2.25	6.60 ± 0.11	10.83 ± 0.14

N_2O was separated by 2 stainless steel columns (column-1 with 1 m length and 2.2 mm i.d., column-2 with 3 m length and 2.2 mm i.d.) that were packed with 80–100 mesh porapak Q, and detected by the ECD. The oven was operated at 55 °C, and the ECD was operated at 330 °C. The flux was determined from the slope of the mixing ratio change in the five samples, taken at 0, 5, 10, 15 and 20 min after chamber closure. Average flux and standard deviation of N_2O emissions were determined by three individual plot experiments. Seasonal amounts of N_2O emissions were sequentially accumulated from the emissions between every two adjacent intervals of the measurements. Statistical correlations and regressions were analyzed by SYSTAT 10.0 (SPSS Inc. 2000).

3. Results

3.1. N_2O emission in a rice–wheat rotation

Earlier studies reported that N_2O emissions from paddy fields were negligible (Denmead et al., 1979; Freney et al., 1981). Later, however, much field observation indicated that N_2O emission depends greatly on water management in rice paddy (Cai et al., 1997; Zheng et al., 1999; Zou et al., 2003b). Based on water status in the paddies, rice-growing season in this study was simply divided into three courses, namely waterlogged, drainage and dry-wet alteration periods. The seasonal average flux of N_2O was 125.0 $\mu\text{g } N_2O-N \text{ m}^{-2} \text{ h}^{-1}$, ranging from 48.2 $\mu\text{g } N_2O-N \text{ m}^{-2} \text{ h}^{-1}$ for N0 to 215.9 $\mu\text{g } N_2O-N \text{ m}^{-2} \text{ h}^{-1}$ for N3 treatment (Fig. 1a). Intensive flux of N_2O happened during the non-waterlogged period of the rice-growing season. In the course of drainage, the mean fluxes of N_2O

emissions were from 56.3 $\mu\text{g } N_2O-N \text{ m}^{-2} \text{ h}^{-1}$ for N0 to 373.5 $\mu\text{g } N_2O-N \text{ m}^{-2} \text{ h}^{-1}$ for N3 treatment, with an average of 246.5 $\mu\text{g } N_2O-N \text{ m}^{-2} \text{ h}^{-1}$ (Fig. 1a). On average, N_2O emissions from 1-week drainage amounted to 12.2% of the seasonal total emissions for fertilized plots (Fig. 1b). During dry-wet alterations, on the other hand, the fluxes of N_2O averaged 130.5 $\mu\text{g } N_2O-N \text{ m}^{-2} \text{ h}^{-1}$, ranging from 38.09 $\mu\text{g } N_2O-N \text{ m}^{-2} \text{ h}^{-1}$ for N0 to 213.9 $\mu\text{g } N_2O-N \text{ m}^{-2} \text{ h}^{-1}$ for N3 treatment and its amount, on average, accounted for 37.1% of the seasonal total emissions for fertilized plots. The other 50.7% of the seasonal total happened during the waterlogged periods (Fig. 1a and b).

To outline the seasonal trend of N_2O emission influenced by wheat development and soil temperature and moisture, we divided winter wheat development into three stages (Huang et al., 2001): early stage (sowing to winter-through, about 0–50 days after sowing), middle-stage (winter-through to turning-green, 51–110 days) and late-stage (turning-green to harvest, 111–220 days). The seasonal fluxes of N_2O averaged 53.8 $\mu\text{g } N_2O-N \text{ m}^{-2} \text{ h}^{-1}$ for N0, while those from fertilized plots averaged 115.74 $\mu\text{g } N_2O-N \text{ m}^{-2} \text{ h}^{-1}$, ranging from 91.5 $\mu\text{g } N_2O-N \text{ m}^{-2} \text{ h}^{-1}$ for N1 to 137.8 $\mu\text{g } N_2O-N \text{ m}^{-2} \text{ h}^{-1}$ for N3 treatment (Fig. 2a). Most emissions happened during the late-stage, which amounted to 64.3%, while the early stage and middle-stage amounts accounted for 23.2% and 12.5% of the seasonal total, respectively (Fig. 2b).

During the fallow period between wheat harvesting and rice transplanting, no obvious N_2O emissions occurred since no fertilizer was applied in the waterlogged fields. However, N_2O emissions were observed during the fallow period between rice harvesting and wheat planting. No significant difference in N_2O emissions was found among the field plots. The fluxes

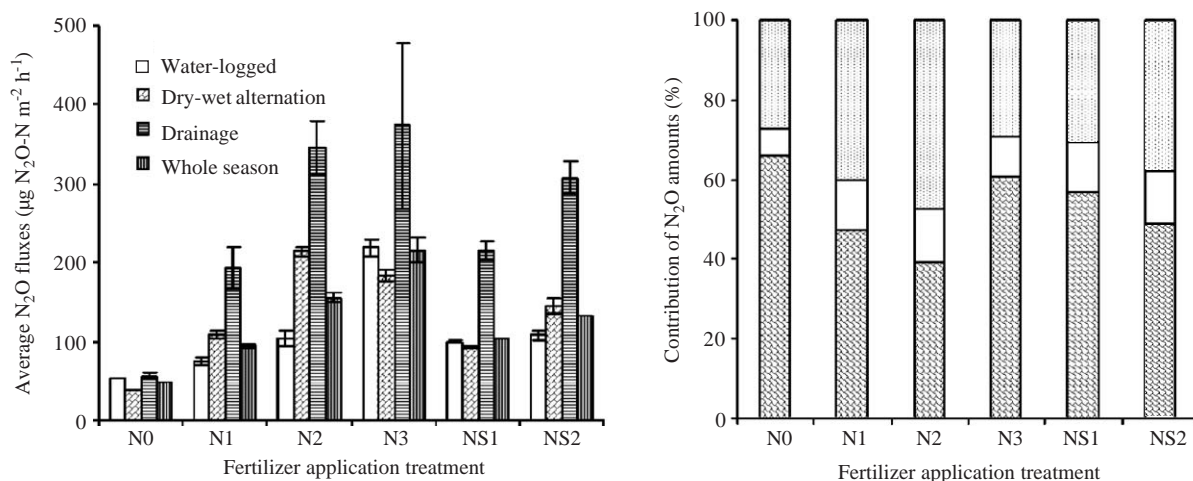


Fig. 1. N_2O emissions (Mean \pm SE, $n = 3$) during rice developmental stages and their contributions to seasonal amounts.

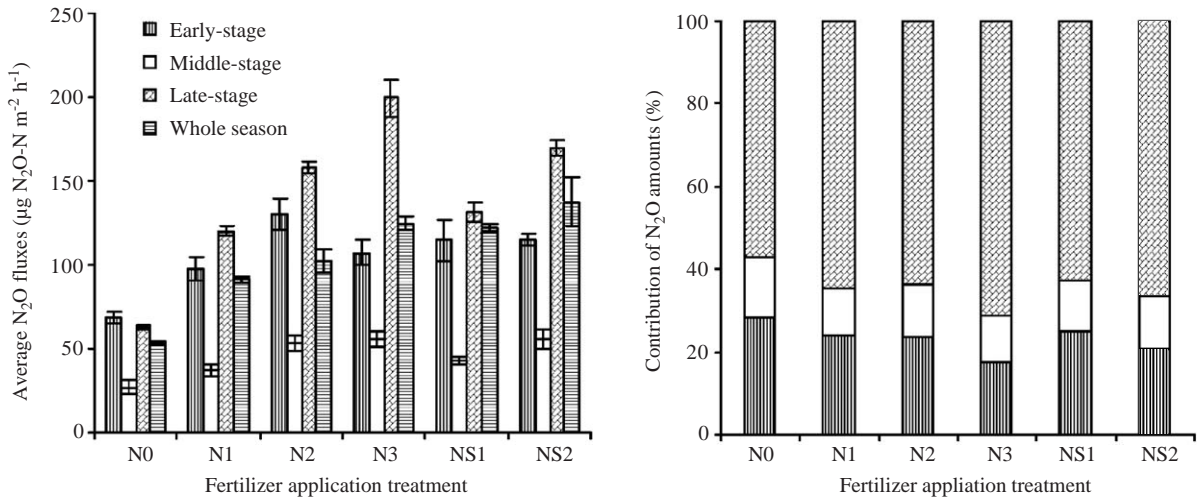


Fig. 2. N_2O emissions (Mean \pm SE, $n = 3$) during winter-wheat developmental stages and their contributions to seasonal amounts.

of N_2O emissions averaged $103.3 \mu\text{g N}_2\text{O-N m}^{-2} \text{h}^{-1}$, with a variation of from $92.3 \mu\text{g N}_2\text{O-N m}^{-2} \text{h}^{-1}$ for NS1 to $123.9 \mu\text{g N}_2\text{O-N m}^{-2} \text{h}^{-1}$ for N3 treatment. N_2O emissions during this fallow period accounted for 9.8% of the annual total for the control plots and, on average, 4.9% for fertilized plots (data not shown).

3.2. Interannual and spatial variations of N_2O emission in rice–wheat rotations

Much field research has been conducted to quantify N_2O emissions in paddy rice and wheat croplands (e.g., Cai et al., 1997; Dong et al., 2001; Xiong et al., 2002), however, few studies covered the whole annual rice–wheat rotation cycle. We collected all the available data from field measurements over at least 1 year on N_2O emissions from paddy rice–winter wheat rotation systems in China (Xu et al., 1997; Xing and Zhu, 1997; Xing, 1998; Zheng et al., 2000, 2004; Jiang et al., 2003; Zou et al., 2003b). Based on measurements over the whole annual rotation cycle, the multi-year data of N_2O emissions from rotation cropping systems were compiled from 3 sites (Wuxi, Nanjing and Suzhou) located in Jiangsu province of China (Table 2). Of these, some were collected by our group and the others were gathered from the literature. The typical local agricultural practices adopted in these fields were similar to those in this study (e.g., Zheng et al., 2000), however, it is apparent that N_2O emissions varied interannually and spatially (Table 2). For example, annual N_2O emissions from plots with synthetic fertilizer applied at 300 kg N ha^{-1} in the 2002–2003 season decreased by 20% in contrast with that in the 2001–2002 season at Wuxi site. Over the 2002–2003 rotation cycle, on the other hand, annual N_2O emission from plots with synthetic fertilizer

applied at 250 kg N ha^{-1} was $8.01 \text{ kg N}_2\text{O-N ha}^{-1}$ in Nanjing, while that from plots with synthetic fertilizer applied at 300 kg N ha^{-1} in Wuxi was only $5.16 \text{ kg N}_2\text{O-N ha}^{-1}$. Nevertheless, N_2O emission generally increased with N fertilization rate (Table 2).

3.3. Fertilizer-induced emission factor for N_2O

An FIE is defined as the percentage of the N input released as $\text{N}_2\text{O-N}$ within the current seasonal or annual period (IPCC, 1997, 2000). The site-scale FIE of a given cropland (E) is quantified by observing the net $\text{N}_2\text{O-N}$ emissions in the equation: $\text{FIE} = (E_f - E_n)/N - 100$, where E_f and E_n are the seasonally or annually released $\text{N}_2\text{O-N}$ from a unit area of nitrogen-fertilized and non-nitrogen control fields, respectively. The seasonal amount of N_2O emissions significantly increased with N application rate (Table 1). Plotting N_2O emissions against synthetic N application rate produced pronounced linear relationships (Fig. 3). The relationships suggested that the direct emission factor of N_2O for synthetic N fertilizer application averaged 1.08% in rice season ($y = 0.0108x + 1.245$, $r^2 = 0.996$, $P < 0.0001$) and 1.49% ($y = 0.0149x + 3.109$, $r^2 = 0.970$, $P < 0.0001$) in winter wheat season, respectively (Fig. 3a). Over the whole seasonal data sets (Fig. 3b), likewise, the significant relationship between synthetic N application rates and N_2O emission amounts ($y = 0.0126x + 4.807$, $r^2 = 0.998$, $P < 0.0001$) produced FIE for N_2O , with an average of 1.26% for the annual rotation cycle. The data sets for the treatment of synthetic N fertilization combined with crop residue application (designated as “ \times ” in Fig. 3) were almost in agreement with these correlations for rice, wheat or whole rotation seasons.

Table 2
Available site-scale N₂O emission data in annual rice–wheat rotation ecosystems in southeast China

Site	Season	Fertilizer application rate (kg N ₂ O–N ha ⁻¹)			N ₂ O–N emission (kg N ₂ O–N ha ⁻¹)			Reference	
		Rice	Wheat	Annual	Rice	Wheat	Annual		
Nanjing 32°00'N, 118°48'E	2000–2001	275	156	431	2.44	11.70	14.14	Zou et al. (2003b), Jiang et al. (2003)	
	2002–2003	0	0	0	1.38	2.84	4.68	This study	
		150	100	250	2.67	4.83	8.01		
		300	200	500	4.44	6.44	11.33		
		450	300	750	6.17	7.27	14.03		
Wuxi 31°37'N, 120°28'E	2001–2002	150	150	300	1.50	4.97	6.47	Zheng et al. (2004)	
		250	250	500	2.31	6.45	8.76		
		250	250	500	1.21	11.78	12.99		
	2002–2003	0	0	0	0.90	1.32	2.22	Zheng et al. (2004)	
		150	150	300	1.71	3.45	5.16		
Suzhou 31°16'N, 120°38'E	1993–1994	0	0	0	0.86	1.67	2.53	Xing and Zhu (1997), Xu et al. (1997), Xing (1998)	
		210	180	390	2.57	2.83	5.40		
		220	180	400	3.27	3.68	6.95		
		278	180	458	3.01	3.20	6.21		
	1994–1995	0	0	0	0.70	3.20	3.90	Zheng et al. (2000)	
		191	191	382	2.00	9.80	11.80		
	1996–1997	0	0	0	0.80	8.10	8.90	Zheng et al. (2000)	
		191	191	382	1.60	11.00	12.60		
			191	191	382	3.20	12.10	15.10	

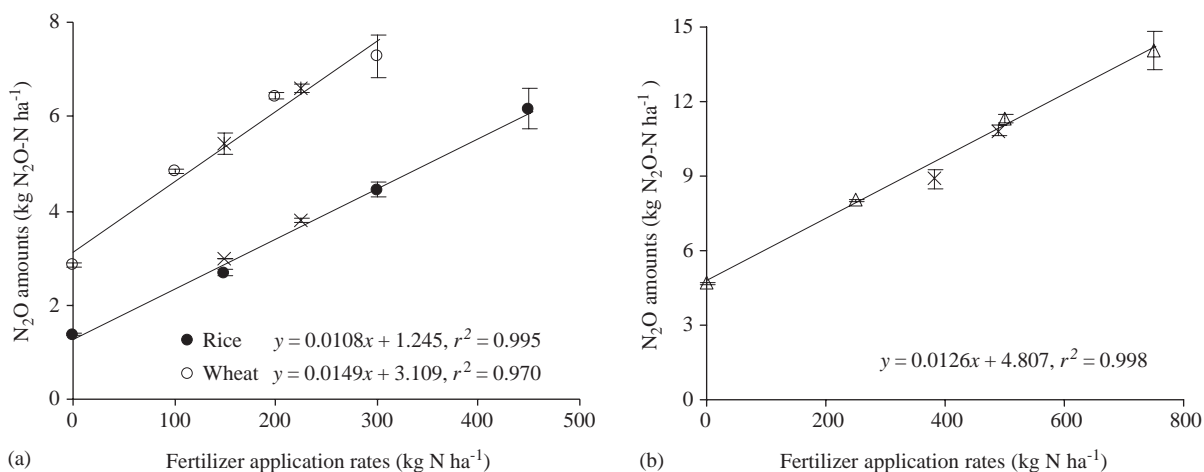


Fig. 3. Relationship between N₂O emissions (Mean ± SE, *n* = 3) and synthetic fertilizer application rates in a rice–winter wheat rotation ecosystem. (a) Rice and winter wheat seasons; (b) the whole annual rotation cycle.

N₂O emission in annual rice–winter wheat rotation ecosystems in southeast China was significantly related with N fertilization rate during the paddy rice, wheat

seasons, and over the whole annual rotation cycle (Fig. 4). Integrating all available site-scale field data sets of N₂O emissions in annual paddy rice–wheat

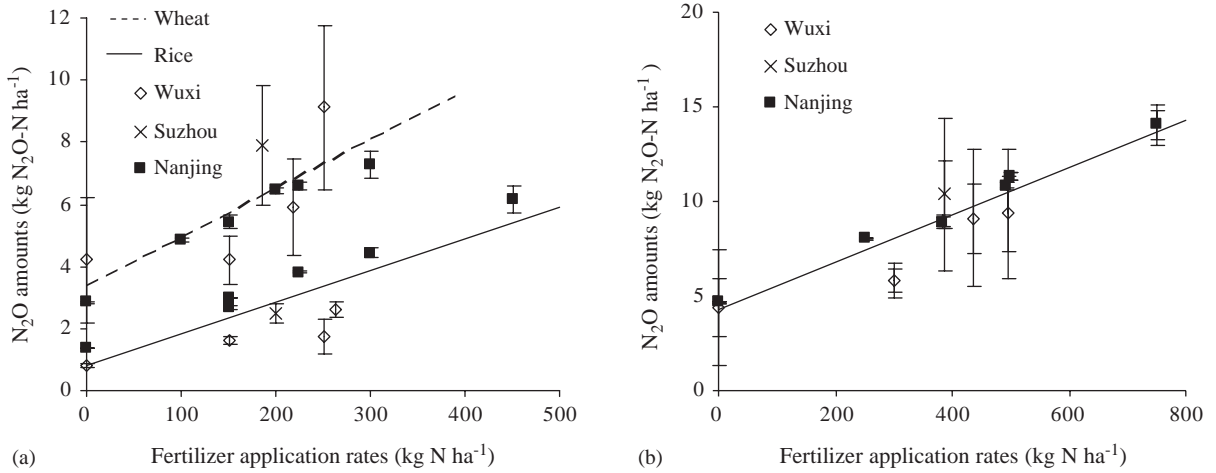


Fig. 4. Dependence of site-scale N₂O emissions on synthetic N fertilizer rates from paddy rice–winter wheat rotations in southeast China. (a) Rice and winter wheat seasons; (b) the whole annual rotation cycle. References for data points of Wuxi, Suzhou, and Nanjing sites shown in Table 2.

Table 3
Correlation of N₂O emissions (*y*, kg N₂O–N ha⁻¹) and synthetic N fertilizer applied (*x*, kg N ha⁻¹)

Growth season	Correlation equation	<i>r</i> ²	<i>P</i>
Rice season	$y = (0.0102 \pm 0.002)x + (0.792 \pm 0.475)$	0.702	0.0008
Wheat season	$y = (0.0165 \pm 0.004)x + (3.438 \pm 0.695)$	0.637	0.002
Annual cycle	$y = (0.0125 \pm 0.002)x + (4.247 \pm 0.623)$	0.876	0.00001

rotation systems, we found that the emission factor of N₂O for synthetic fertilizer averaged 1.02%, ranging from 0.82% to 1.22% for rice season and 1.65% with a variation of from 1.25% to 2.05% for winter wheat season. For the annual rotation, the lowest, mean and highest emission factors of N₂O for fertilizer were 1.05%, 1.25% and 1.45%, respectively (Table 3).

3.4. Crop residue-induced emission factor for N₂O

We assume that synthetic N fertilizer induced N₂O emissions for plots applied with both synthetic N fertilizer and crop residue can be determined by FIE (Fig. 3). Based on this assumption, therefore, we quantified crop residue-induced emission factor for N₂O (RIE) by the equation: $RIE = (E_{fc} - E_f)/N_c \times 100$, where E_{fc} is the seasonal or annual N₂O–N released from a unit area of nitrogen-fertilized in combination with crop residue retained. E_f represents that from the equal nitrogen-fertilized but no additional crop residue retained control plots. E_f is determined by the relationship between synthetic fertilizer and N₂O emission (i.e. determined by FIE). N_c refers to the N input due to crop residue retained. When crop residue was retained at 4.50 t h m⁻²,

therefore, RIE was 0.31% in rice season and 0.15% in wheat season, while it went up to 0.69% in rice season and 0.59% in wheat season for crop residue retained at 2.25 t ha⁻¹. As for the whole annual rotation cycle, emission factors of N₂O were 0.64% and 0.27% for crop residue retained at the rate of 2.25 and 4.50 t ha⁻¹, respectively. Crop residue-induced emission factor for N₂O tended to be decreased with increase in crop residue retained in the fields.

3.5. N₂O background emission

According to the FIE definition, N₂O emission from no-nitrogen control fields refers to its background emission. The relationship between synthetic N fertilizer and N₂O emission shown in Fig. 3 yielded a background emission of 1.24 kg N ha⁻¹ in the rice season, 3.11 kg N ha⁻¹ in the wheat season and 4.81 kg N ha⁻¹ over the whole annual rotation cycle. Based on the relationship between synthetic fertilizer application rates and site-scale N₂O emissions in the rice–wheat rotations in southeast China, the background emission of N₂O was, on average, 0.79 kg N₂O–N ha⁻¹ for the rice season and 3.44 kg N₂O–N ha⁻¹ for the wheat season. The lowest,

mean and highest background emissions of N_2O were 3.62, 4.25 and 4.87 kg $\text{N}_2\text{O}\text{-N ha}^{-1}$ over the whole annual cycle, respectively (Table 3).

4. Discussion

Fertilizer-induced emission factor for N_2O in the present study was, on average, 1.08% for rice, 1.49% for wheat and 1.26% for the whole annual rotation cycle. Based on the available site-scale data sets of N_2O emissions in annual paddy rice–wheat rotation systems, on the other hand, FIE averaged 1.02% for the rice season, 1.65% for the wheat season and 1.25% for the annual season. Over the whole annual rice–winter wheat rotation cycle, the emission factor of N_2O for synthetic fertilizer in southeast China is, on average, very close to the IPCC (1997, 2000) default of 1.25%, but higher than the recent result obtained by Bouwman et al. (2002a). Bouwman et al. (2002a) reported that the FIE of N_2O for synthetic N fertilizer averaged 1.0%, and differed with fertilizer type. The FIE was 1.1% for urea and 0.7% for calcium ammonium nitrate. Based on some recent studies that have included unfertilized treatments in combination with Bouwman's data base, Yan et al. (2003a) estimated that the FIE of N_2O , for experiments that lasted at least 1 year, averaged 1.31%. Recently, Zheng et al. (2004) re-quantified 54 direct N_2O emission factors obtained from 12 sites of Chinese croplands and estimated that site-scale direct emission factor of N_2O averaged 1.35%, ranging from 0.57% to 2.13%. It is logical that FIE in the certain cropping system of this study is more accurate than the global default, or the results obtained by Yan et al. (2003a) and Zheng et al. (2004), which were based on measurements in multi-site and multi-type croplands (Bouwman, 1996).

As for the seasonal N_2O emission, FIE was 1.02% for the rice season, which is much higher than the FIE of 0.25% estimated by Yan et al. (2003a). Note, however, that Yan et al.'s result was mainly obtained from the measurements in continuous flooding or intermittent irrigation paddies without a drainage course. On the other hand, site-scale FIE for N_2O in wheat season averaged 1.65%, which is much larger than the IPCC default (IPCC, 1997, 2000) and Bouwman et al.'s recent results (Bouwman et al., 2002a). N_2O fluxes from rice paddies are generally lower than those from uplands. This is partially due to the anaerobic conditions prevailing in a rice paddy. However, aerobic conditions after draining the fields favor the N_2O production in the following crop growth season. Therefore, it is reasonable that FIE for N_2O in the wheat season was much higher than in the rice season in this study.

The IPCC default is assumed to be available for calculating N_2O emissions from N input due to crop residue amendments (IPCC, 2000). However, measure-

ments in some studies with crop residue application suggested that the separate treatment of N input from crop residue in the IPCC guidelines may lead to an overestimation of anthropogenic N_2O emissions (Bouwman et al., 2002b). Crop residue-induced emission factor for N_2O in the present study was distinctly lower than synthetic fertilizer-induced emission factor. Moreover, it is noteworthy that there was a general decrease in crop residue-induced emission factor for N_2O accompanying crop residue retained in the fields. Therefore, results in this study suggest that the IPCC default factor of N_2O for crop residue would not only overestimate N_2O emission from crop residue but also enlarge its uncertainty. In addition, our earlier study showed that when crop residue was amended, crop residue-induced N_2O emission depended greatly on the C:N ratio of crop residue that is one of the main factors important to its decomposition in the soil (Huang et al., 2004).

Although some studies quantifying FIE by either considering or ignoring the background emission have been widely adopted (Xing, 1998; Brown et al., 2001; Dobbie and Smith, 2003; Yan et al., 2003a; Zheng et al., 2004), it is certain that ignoring the background emission would beget large estimate biases. Some studies have demonstrated that background emission has become one of the most sensitive factors for developing an inventory of N_2O emissions in some areas (e.g., Yan et al., 2003a). The measurement in an unfertilized winter wheat field conducted by Röver et al. (1998) showed that N_2O background emission was 1.84 kg $\text{N}_2\text{O}\text{-N ha}^{-1}$, consisting of 0.41 kg $\text{N}_2\text{O}\text{-N ha}^{-1}$ in the growing season and 1.43 kg $\text{N}_2\text{O}\text{-N ha}^{-1}$ in the following fallow season. Background emission of N_2O in China croplands was estimated to be 1.22 kg $\text{N ha}^{-1}\text{yr}^{-1}$ (Yan et al., 2003a) or modeled to be 1.66 kg $\text{N ha}^{-1}\text{yr}^{-1}$ (Li et al., 2001). Yan et al. (2003a) estimated that background emission of N_2O accounted for approximately 43% of the total N_2O emission from croplands in east, southeast and south Asia. Furthermore, N_2O background emission is likely to be particularly important at the global scale (Yan et al., 2003a).

Unfortunately, relatively few field measurements initially include a no-nitrogen control treatment, which leads to a high uncertainty in the background emission estimate. As the author acknowledged, for example, Bouwman's estimate for the background N_2O emission that was based on five grassland measurements was highly uncertain (Bouwman, 1996). Yan et al. (2003a) compiled seven measurements in the rice paddies from New Delhi, India (Kumar et al., 2000); Indonesia (Suratno et al., 1998); Nanjing, China (Cai et al., 1997) and Louisiana, USA (Smith et al., 1982), and then estimated that the background emission of N_2O was, on average, 0.26 kg $\text{N}_2\text{O}\text{-N ha}^{-1}$ in the paddy rice season. The authors further assumed that N_2O flux in the fallow season was equal to that in rice season, and then the

annual background emission was estimated to be $0.81 \text{ kg N}_2\text{O-N ha}^{-1}$. As the authors acknowledged, however, there was much uncertainty with respect to the background emission estimate, particularly in paddy fields, because background emissions in the fallow season have not been well documented. In general, N_2O flux from paddy fields is much higher in the fallow season than in the cropping season.

Annual background emission of N_2O in this study was greatly higher than reported estimates although its uncertainty was relatively lower (Table 2). There are some causes attributed to the higher background emission for N_2O in this study. First, drainage and dry–wet alteration in the rice paddy facilitated N_2O emissions in contrast to the continuous flooding paddy fields (Jiang et al., 2003). The result obtained from the continuous flooding or intermittent irrigation paddy (Yan et al., 2003a), therefore, fails to fully reflect N_2O background emission from rice fields in southeast China. Otherwise, its extrapolation would lead to the underestimation of background N_2O emission. Second, it is well documented that the flux of N_2O emission from the following wheat season is enhanced due to soil aerobic conditions after draining the paddy field (Byrnes et al., 1993; Bronson et al., 1997). Finally, crop residue retained in the fields as a conventional agricultural management practice favored N_2O emissions on an annual rotation cycle. Crop residue amendments in agricultural fields are important sources of C and N for nitrification and denitrification, the two microbial processes in which N_2O is mainly produced. Higher denitrification (Flessa and Beese, 1995; Shelton et al., 2000) and N_2O emission (Cochran et al., 1997; Slemr et al., 1984) were both observed after retaining or incorporating residues in the fields instead of removing them. Soils with high organic C content are often prone to high N_2O emission (Bouwman et al., 2002b). Overall, background emission of N_2O in paddy rice–wheat rotation ecosystem in this study was greatly higher than the reported estimates and thus its accurate estimation would minimize the uncertainty in agricultural N_2O inventory in this area. Certainly, more field measurements are needed in order to improve the accuracy of background N_2O emission estimates.

Direct emission of N_2O produced naturally in soils through the microbial processes of nitrification and denitrification, has been shown to be influenced by agricultural management, such as water regime, organic amendments and cropping type. For example, fertilizer-induced N_2O emission in the intermittent irrigation paddies depend strongly on whether or not water logging is present in fields (Jiang et al., 2003). Compared 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 to both nitrification and denitrification

processes, which contributed greatly to higher N_2O emissions in this study under the water regime of F–D–F–M (Fig. 1). Besides direct emissions of N_2O from crop residue applied, the decomposition of crop residue with a high C:N ratio may immobilize soil nitrogen, which would potentially increase the nitrogen available for N_2O production in the following season. Our previous study found that wheat straw applied in rice season had a lasting effect on N_2O emissions from the following winter wheat season in an annual rotation (Zou et al., 2003b). On the other hand, plant growth may also have an effect on agroecosystem N_2O emission. In the present study, N_2O emission during the late-stage period of wheat growth contributed greatly to its seasonal total (Fig. 2). During this period, it is predicted that fertilizer application benefited rapid growing plants, thereby increasing soil processes, such as soil nitrification and denitrification where N_2O is produced.

Currently, there are two general approaches to estimating direct N_2O emissions from agroecosystems, i.e., a strict empirical model (e.g., the IPCC methodology) and a process-oriented model such as the DNDC model (Li et al., 2001). Although field studies have shown that besides additional nitrogen input, many other agricultural practices are also important to N_2O emissions, the IPCC methodology does not consider these factors effects on N_2O emissions. On the other hand, plots with no nitrogen fertilization are established to estimate N_2O background emission in the IPCC methodology. However, the experiment plots with no nitrogen fertilization may be inappropriate to mirror N_2O background emission. In the present study, the background emission of N_2O was greatly higher in the wheat season than in the rice season, suggesting that previous land use and agricultural practices may have a substantial effect on the following seasonal N_2O background emission. To establish the national or regional inventory of agricultural N_2O emissions, therefore, we suggest that combining the process-oriented model and the IPCC methodology may be an effective approach to minimizing the uncertainty in N_2O emission estimate. For example, some functions of key factors to N_2O emission in the process-oriented model could be introduced to rectify the FIE in the IPCC methodology.

Factors related to measurements, including length of experiment and frequency of measurements, have a significant influence on N_2O emission (Bouwman et al., 2002b). In general, N_2O emission increases with the length of experiment but decreases with frequency of measurements (Yan et al., 2003a; Zheng et al., 2004). The “Good Practice in Derivation of Country-specific Emission Factors” in the IPCC guidelines underlined that N_2O emission estimates in agricultural fields should be based on measurements covering periods of at least 1 year, with a measurement frequency of at least once per day in periods with high flux rates (e.g. periods following

fertilizer application or rainfall events) and lower frequencies in periods with low flux rates. In this study, measurements covered a whole annual rotation cycle. As mentioned above, annual N₂O emission would be decreased by 9.8% if N₂O emissions from fallow period between two crop-growing seasons were not included. N₂O emission during winter-through period contributed 12.5% to the total N₂O emissions in winter wheat season. These two periods were, nevertheless, sometimes ignored for seasonal and annual N₂O estimates in some studies (e.g., Chen et al., 1995; Dong et al., 2001; Xiong et al., 2002). In this study, on the other hand, N₂O flux was measured daily during drainage in rice paddy. N₂O emission from 1-week drainage amounted to 12.2% of the seasonal total. In contrast with weekly measurements, daily measurements for a week after rainfall on 13 February, on average, resulted in the reduction of 17.3% for N₂O emission. Therefore, lengths of experiment and measurement frequency are factors important to N₂O emission estimates.

According to the new map of the distribution of rice agriculture in China developed by combining remote sensing and ground census data, rice cultivated land area totals about 0.30 million km². One quarter is planted as single rice, 15% is under a double-crop rotation with two rice plantings a year (rice–rice), 19% is under a double-crop rotation with a single rice planting (rice–other), and 41% is under a triple-crop rotation with two rice plantings per year (rice–rice–other). It is estimated that half of the rice fields receives organic input and two-thirds is under intermittent irrigation or middle season drainage in China (Yan et al., 2003b). In these, FIE and background emissions in the present study are assumed to be applicable, while FIE and background emissions obtained by Yan et al. (2003a) are used for the rice fields under continuous flooding and no organic inputs. The synthetic N fertilizer is assumed to be applied at the rate of 400 kg N ha⁻¹ yr⁻¹. Thus, N₂O emission in paddy rice-based agroecosystems amounts to 169 Gg N₂O–N yr⁻¹ in China. Xing (1998) estimated N₂O emission from croplands in China in 1995 to be 398 Gg N₂O–N, about 15% lower than the result obtained by Yan et al. (2003a). Zheng et al. (2004) estimated that the direct N₂O emission from croplands in China was 275 Gg N₂O–N yr⁻¹ in 1990s. Based on these estimates, N₂O emissions from rice-based agroecosystems account for 26–60% of the total emissions from croplands in China. This suggests that rice-based agroecosystems have greatly contributed to the N₂O emission from croplands in China.

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