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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

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[1] A 3-year field experiment was conducted to simultaneously measure methane (CH_4) and nitrous oxide (N_2O) emissions from rice paddies under various agricultural managements including water regime, crop residue incorporation, and synthetic fertilizer application. In contrast with continuous flooding, midseason drainage incurred a drop in CH_4 fluxes while triggering substantial N_2O emission. Moreover, N_2O emissions after midseason drainage depended strongly on whether or not fields were waterlogged due to intermittent irrigation. Urea application tended to reduce CH_4 emissions but significantly increased N_2O emissions. Under a water regime of flooding-midseason drainage-reflooding-moist intermittent irrigation but without water logging (F-D-F-M), both wheat straw and rapeseed cake incorporation increased CH_4 emissions by 252%, and rapeseed cake increased N_2O by 17% while wheat straw reduced N_2O by 19% compared to controls. Seasonal average fluxes of CH_4 ranged from 25.4 mg m^{-2} d^{-1} when no additional residue was applied under the water regime of flooding-midseason drainage-reflooding to 116.9 mg m^{-2} d^{-1} when wheat straw was applied at 2.25 t ha^{-1} under continuous irrigation flooding. Seasonal average fluxes of N_2O varied between 0.03 mg N_2O-N m^{-2} d^{-1} under continuous flooding and 5.23 mg N_2O-N m^{-2} d^{-1} under the water regime of F-D-F-M. Both crop residue-induced CH_4, ranging from 9 to 15% of the incorporated residue C, and N_2O, ranging from 0.01 to 1.78% of the applied N, were dependent on water regime in rice paddies. Estimations of net global warming potentials (GWPs) indicate that water management by flooding with midseason drainage and frequent water logging without the use of organic amendments is an effective option for mitigating the combined climatic impacts from CH_4 and N_2O in paddy rice production.

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1. Introduction

[2] Methane (CH_4) is one of the most important greenhouse gases. The atmospheric abundance of CH_4 has increased by about a factor of 2.5 since the pre-industrial era [*Etheridge et al.*, 1998]. Over the period 1992 through 1998, the annual increase in atmospheric CH_4 averaged 14 Tg (1 Tg = 10^{12} g) [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001]. Methane has about 23 times higher global warming potential than CO_2 in a time horizon of 100 years [*IPCC*, 2001] and may account for 15–20% of the radiative forcing added to the atmosphere [*Houghton et al.*, 1996]. Rice paddies have been identified as a major source of atmospheric CH_4. The global CH_4 emission rate from paddy fields was recently estimated to be 40 Tg yr^{-1} [*Neue and Sass*, 1998; *Sass et al.*, 1999],

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which accounts for about 6% of the total CH_4 emissions [*IPCC*, 2001]. Predictions based on population growth rates in countries where rice is the main food crop indicate that rice production must increase 65% by 2020 to meet the rice demand for the growing population [*International Rice Research Institute* (*IRRI*), 1989]. This increasing rice production will most likely be accompanied by an increase in methane emissions [*Bouwman*, 1991].

[3] Nitrous oxide (N_2O), 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 N_2O versus individual sources of N_2O at present, fertilized agricultural soils have been believed to be a major source, accounting for about 13% of annual global N_2O emission [*Olivier et al.*, 1998] or 24% [*Kroeze et al.*, 1999; *Mosier et al.*, 1998]. This major anthropogenic source of N_2O is attributed to a number of agricultural activities that add nitrogen to soils, such as increased organic and synthetic fertilizer use. These activities increase the amount of nitrogen (N) available for nitrification and denitrification, and ultimately the amount of N_2O emitted [*IPCC*, 2001]. The emissions of N_2O 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: volatilization of compounds such as NH_3 and NO_X and subsequent redeposition, and through leaching and runoff. Direct and indirect emissions from agricultural systems are now thought to contribute approximately 6.2 Tg N_2O-N yr^{-1} to total global source strength of 17.7 Tg N_2O-N yr^{-1} [*Kroeze et al.*, 1999]. Worldwide, application of synthetic fertilizer to meet the food demand for a growing population has increased rapidly. The consumption of synthetic fertilizer N in Asia, for example, was estimated to increase approximately 50% by 2030 [*Zheng et al.*, 2002]. It is likely that increasing fertilizer application will lead to a proportionate increase in N_2O emissions.

[4] China is the most important rice producing country in the world. Its planting area accounts for about 20% of the world total (Food and Agriculture Organization, http://apps.fao.org/) and occurs on 23% of all cultivated land in China [*Frolking et al.*, 2002]. Much research has focused on CH_4 and N_2O emissions in rice paddies under various agricultural managements, including water regime, synthetic and organic fertilizer application, etc. [e.g., *Cai et al.*, 1997; *Khalil et al.*, 1998; *Zheng et al.*, 1999]. Water regime has been recognized as one of the most important practices that affect CH_4 and N_2O emissions in rice production. 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) [*Gao and Li*, 1992; *Huang et al.*, 2004a; *Su*, 2000]. An episode of midseason drainage for 7–10 days rather than continuous flooding is commonly adopted in China to inhibit ineffective tillers, remove toxic substances, and improve roots activities [*Gao et al.*, 1992].

[5] Organic residue amendments have been ordinarily accepted to improve soil fertility for rice production in China. Incorporation of crop residues provides a source of readily available C and N, which is believed to induce a higher CH_4 release from rice paddies [*Denier van der Gon and Neue*, 1995; *Wang*, 1999] and to influence N_2O emissions [*Aulakh et al.*, 1991; *Cochran et al.*, 1997; *Flessa and Beese*, 1995; *Lemke et al.*, 1999]. Decomposition of incorporated organic material is the predominant source of methanogenic substrates in early stage of rice growing [*Watanabe and Roger*, 1985], and CH_4 emission via ebullition during this period contributes significantly to the total emissions of this gas [*Shangguan and Wang*, 1993]. Residue type was also thought to be an important factor affecting N_2O emission [*Aulakh et al.*, 1991; *Mckenney et al.*, 1993; *Shelp et al.*, 2000]. Although the amount of residue N that recycles through agricultural fields may globally add 25–100 Tg N yr^{-1} into agricultural soils (mainly from crop residues), the amount converted to N_2O is unknown [*Mosier and Kroeze*, 1998]. Because the quality of different residues used by farmers is largely undocumented, N_2O emissions have been analyzed implicitly by comparing studies where different residues have been used [e.g., *Mckenney et al.*, 1993].

[6] Although most N_2O emission is produced in upland fields, recent research indicates that N_2O is also pronounced as a result of the midseason drainage and dry-wet episodes in paddy fields [e.g., *Cai et al.*, 1997; *Jiang et al.*, 2003; *Zheng et al.*, 2000; *Zou et al.*, 2004]. Some studies have attempted to quantify fertilizer-induced N_2O emissions and background N_2O emissions from rice paddies; however, they exhibit wide variations [*Yan et al.*, 2003; *Zheng et al.*, 2004], so further investigation is recommended. Some studies suggested that fertilizer application increased CH_4 emissions [e.g., *Aerts and Ludwig*, 1997; *Aerts and Toet*, 1997; *Lindau et al.*, 1991], while others reported that CH_4 emissions decreased with fertilizer application [*Cai et al.*, 1997; *Wang et al.*, 1992], or that no obvious relationship existed [*Bronson et al.*, 1997; *Wang et al.*, 1993].

[7] We present a 3-year field measurement of CH_4 and N_2O emissions from rice paddies in southeast China under various water regime, crop residue amendments, and synthetic N fertilizer applications. In the present study, CH_4 and N_2O emissions were simultaneously measured by the static chamber and gas chromatograph (GC) method. The objectives of this study are to quantify CH_4 and N_2O emissions as affected by various agricultural managements, to assess the combined climatic impact of CH_4 and N_2O, and thereby to optimize the agricultural managements for mitigating climatic impacts in paddy rice production.

2. Material and Methods

2.1. Experiment Sites

[8] Three field studies were performed in Nanjing, Jiangsu province, China (31°52′N, 118°50′E). In the 2000 and 2001 seasons, the field sites were located at a Jiangning farm. Soil of the experimental fields was classified as hydromorphic, consisting of 4% sand, 45% silt, and 51% clay with an initial pH (H_2O) of 6.7. Total N and organic C

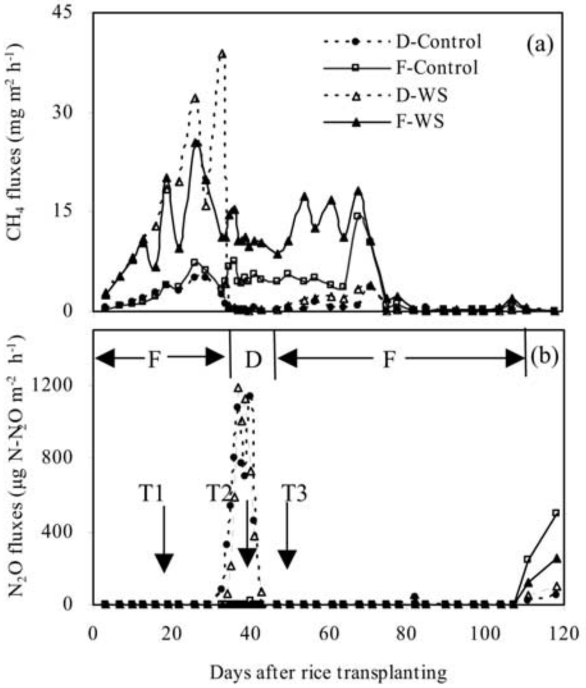

Figure 1. Seasonal dynamics of (a) CH_4 and (b) N_2O emissions from rice paddies in 2000. Abbreviations in Figures 1, 2, and 3 show the following agricultural practices: F, D, M, and experimental treatments represent the same as Table 1; T1, T2, and T3 represent top-dress application of supplemental synthetic fertilizer.

were 0.19% and 1.75%, respectively. In 2002, field plots were established at the experimental farm of the Jiangsu Academy of Agricultural Sciences. Soil pH (H_2O) was 6.1. Total N and organic C were 0.11% and 1.31%, respectively. The mean annual precipitation and air temperature in Nanjing are about 1000 mm and 16.0°C, respectively. Rainfall in the rice season totaled 564 mm in 2000, 365 mm in 2001, and 554 mm in 2002. The mean seasonal air temperature (25.0°C) was almost the same in three rice experiments. The mean seasonal soil temperature at 10 cm depth was 24.5°C in 2000, 25.1°C in 2001, and 24.3°C in 2002.

2.2. Field Experiments

2.2.1. 2000 Season

[9] Rice (*Oryza sativa* L., cv. 9516) seeds were sown in a nursery bed on 30 May; seedlings were transplanted in the paddies on 28 June and harvested on 24 October 2000. Urea used as nitrogen fertilizer was broadcasted on the fields, with a seasonal amount of 277 kg N ha^{-1} for each field treatment. Urea was split by 44% of the total as basal fertilizer, 25% on 14 July, 19% on 3 August, and 12% on 10 August 2000 (Figure 1).

[10] A split-plot experiment comprised of water treatments and crop residue incorporations in rice paddies was carried out (Table 1). The main emphasis was on various water regimes consisting of continuous flooding (F), and flooding-midseason drainage-frequent water logging with intermittent irrigation (F-D-F). For continuously flooded plots (F-Control and F-WS, Table 1), the field was kept waterlogged until 1 week before crop harvesting. For plots under the F-D-F water regime, flooding was initiated 3 days before rice transplanting and lasted until 29 July, and was followed by drainage for 10 days. Thereafter these rice paddies were frequently flooded by intermittent irrigation from 8 August through a week before crop harvesting (D-Control and D-WS, Figure 1). Blocks of different water regimes were completely isolated by levees with plastic covering. For each water treatment, winter wheat straw from the preceding season was retained in some fields at the rate of 2.25 t ha^{-1} (F-WS and D-WS, Table 1). The plots without crop residue application were set up as the control for each water treatment (F-Control and D-Control). Crop straw was incorporated at the depth of 10–15 cm just before rice transplanting. The organic C and N contents of the wheat straw were 39.4% and 0.5%, respectively. CH_4 and N_2O were simultaneously measured from two replicates for each treatment.

2.2.2. 2001 Season

[11] Rice (cv. 9516) seeds were sown in a nursery bed on 19 May, and seedlings were transplanted on 21 June and harvested on 15 October 2001. Flooding was initiated 3 days before transplanting and maintained until 24 July,

Table 1. Seasonal Amounts of Nitrous Oxide and Methane Emissions From Rice Paddies as Affected by Water Regime, Crop Residue Incorporation, and Fertilizer N Application

Year	Treatment[a]	Water Regime[b]	N Fertilizer, kg N ha^{-1}	Crop Residue, t ha^{-1}	CH_4,[c] g m^{-2}	N_2O-N, mg m^{-2}	Percent of the N Applied
2000	F-Control	F	277		8.5(±0.7)	6(±3)	0.02
	D-Control	F-D-F	277		3.0(±0.4)	155(±89)	0.56
	F-WS	F	277	wheat straw 2.25	22.0(±1.6)	3(±1)	0.01
	D-WS	F-D-F	277	wheat straw 2.25	14.1(±1.9)	143(101)	0.52
2001	Control	F-D-F-M	333		3.9(±0.4)	411(±15)	1.23
	RC	F-D-F-M	333	rapeseed cake 2.25	13.8(±0.4)	483(±25)	1.45
	WS	F-D-F-M	333	wheat straw 2.25	13.6(±0.4)	333(±9)	1.00
2002	FN150	F-D-F-M	150		17.3(±0.9)	267(±7)	1.78
	FN300	F-D-F-M	300		7.3(±0.1)	444(±16)	1.48
	FN450	F-D-F-M	450		4.2(±0.1)	617(±42)	1.37

[a] FN, synthetic N fertilizer; RC, rapeseed cake; WS, wheat straw.

[b] F, flooding; D, midseason drainage; M, moist but non-waterlogged by intermittent irrigation.

[c] Values in parentheses represent ±1 standard error of the mean.

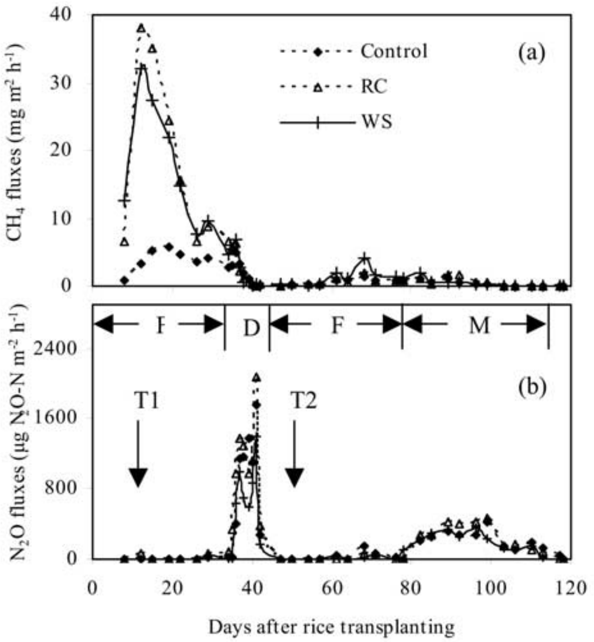

Figure 2. Seasonal dynamics of (a) CH_4 and (b) N_2O emissions from rice paddies in 2001.

until a midseason drainage for 1 week. Thereafter the rice paddies were re-flooded from 1 August to 9 September 2001 and followed by maintaining a moist soil but without water logging (a dry-wet alteration with intermittent irrigation) until a week before rice harvesting (F-D-F-M, Figure 2). The seasonal synthetic N fertilizer totaled 333 kg ha^{-1} for each field treatment. Mineral compound fertilizer (N: P_2O_5: K_2O = 8%: 8%: 9%) and NH_4HCO_3 were applied at the same rate of 750 kg ha^{-1} as basal fertilizers at transplanting. Topdressing was applied as urea at turning-green time and at tillering with the same rate of 70 kg N ha^{-1}, respectively (Figure 2).

[12] Crop residue treatment consisted of incorporations of rapeseed cake (RC) and wheat straw (WS), as well as a control with no additional organic amendment (Control). Crop residue was incorporated at the same rate of 2.25 t ha^{-1} for each treatment with two replicates. The placement of crop residue was identical to the 2000 season. The organic C and N contents were 51.8% and 6.5% for the rapeseed cake and 50.4% and 0.8% for the wheat straw, respectively. There was no difference in synthetic N fertilizer application for three field treatments.

2.2.3. 2002 Season

[13] A new cultivar of rice (*Oryza sativa* L., cv. Wuyunjing 7) was planted in the 2002 season. The schedule of rice cultivation, rice developmental stage, and water regime were almost the same as those in 2001 (Figures 2 and 3). Different local fertilization rate was designed in the field treatment of the 2002 season. The plots with urea were applied at the rate of 150 (FN150), 300 (FN300), and 450 kg N ha^{-1} (FN450) representing the low, normal (recommendation: 250–300 kg N ha^{-1}), and high fertilization levels in rice production, respectively (Table 1). Urea was broadcasted on the fields, with a split of 40% of the total as basal fertilizer, 40% at turning-green, and 20% at the tillering stage (Figure 3). For each plot, calcium superphosphate used as phosphorus fertilizer was identically applied at the local rate of 375 kg ha^{-1} and potassium chloride at the rate of 150 kg ha^{-1} as the basal fertilizer.

2.3. CH_4 and N_2O Measurements

[14] Before fields were initially flooded, boardwalks to randomly selected greenhouse gases 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 CH_4 and N_2O emission measurements over the whole rice growing 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 was 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 m^2 (0.5 m × 0.5 m). 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 in 2000 and 2001, and once a week in the 2002 season. During the midseason drainage periods in three seasons, gas samples were taken once a day. Gas samples were taken from 0800 through 1000 LST since the soil temperature (T_s) during this period was close to the mean daily soil temperature (T_d, e.g., $T_d = 1.008\ T_s$, $p < 0.0001$ in 2002).

[15] The mixing ratios of CH_4 and N_2O were simultaneously analyzed with a modified gas chromatograph (Agilent 4890D) equipped with a flame ionization detector (FID) and an electron capture detector (ECD) [*Wang and Wang*,

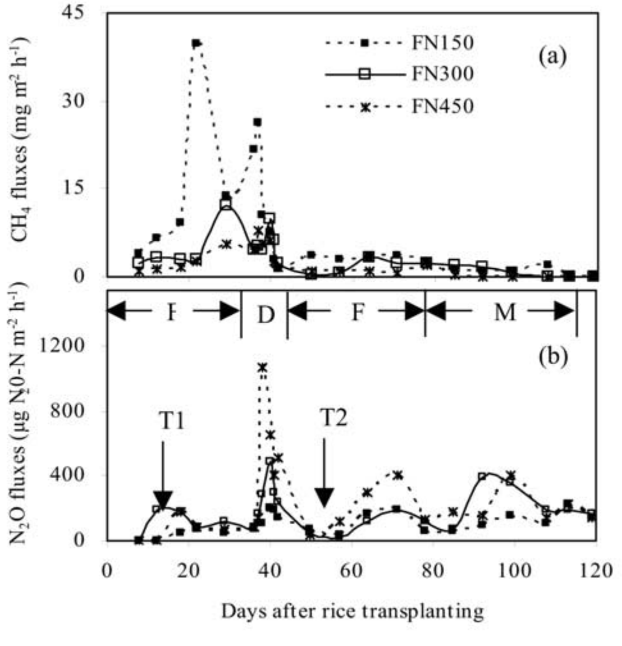

Figure 3. Seasonal dynamics of (a) CH_4 and (b) N_2O emissions from rice paddies in 2002.

2003; *Zou et al.*, 2002]. N_2 was used as the carrier gas. Nitrous oxide was separated by two 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 porapack Q, and detected by the ECD. CH_4 was detected by the FID. The oven was operated at 55°C, the ECD at 330°C, and the FID at 200°C, respectively. Fluxes were determined from the slope of the mixing ratio change in five samples, taken at 0, 5, 10, 15, and 20 min after chamber closure. Sample sets were rejected unless they yielded a linear regression value of r^2 greater than 0.90. Average fluxes and standard errors of greenhouse gases were calculated from two individual plots in the 2000 and 2001 seasons and from triplicate plots in 2002. Seasonal amounts of CH_4 and N_2O emissions were sequentially accumulated from the emissions between every two adjacent intervals of the measurements. Statistical analysis was conducted by SYSTAT 10.0 (SPSS Inc., 2000).

2.4. Other Data Measurements

[16] Ambient air temperature and precipitation data were provided by the climate data acquisition station in Nanjing. Air temperature inside the chamber was recorded for each set of emission measurements. Soil temperature at approximately 10 cm depth was automatically recorded by an Optic Stowaway Temperature Logger (Onset Computer Corporation) through the entire rice season. Field flooded water depth was monitored as well. Aboveground biomass and grain yields of the rice were determined at harvest by oven at approximately 70°C drying to a constant weight.

3. Results

3.1. 2000 Season

[17] Seasonal pattern of CH_4 emissions varied with water regime (Figure 1a). When the field was waterlogged, CH_4 emissions ascended steadily until the peak fluxes were attained approximately 25 days after rice transplanting. In comparison with continuous flooding (F), thereafter, CH_4 emission was dramatically decreased by midseason drainage and then remained at a lower release rate. Without crop residue amendments, seasonal fluxes of CH_4 averaged 72.0 mg m^{-2} d^{-1} for the continuous flooding (F-Control) and 25.4 mg m^{-2} d^{-1} for the water management of F-D-F (D-Control). In contrast to continuous flooding, seasonal amounts of CH_4 emissions from the plots with and without wheat straw incorporated, on average, were decreased by 65% and 36% as a result of midseason drainage, respectively. On the other hand, contribution of the incorporated crop residue to CH_4 emissions was also affected by water management. When wheat straw was incorporated at the rate of 2.5 t ha^{-1}, seasonal fluxes of CH_4 averaged 186.4 mg m^{-2} d^{-1} for the F-WS plots and 119.5 mg m^{-2} d^{-1} for the D-WS plots. Compared with the control without organic amendment, therefore, CH_4 was increased by 160% under the continuous flooding and 370% under the water management of F-D-F (Table 1).

[18] Under continuous flooding, no recognizable N_2O emissions were observed both with and without crop residue incorporation, except a slight N_2O emission within 1 week before rice harvesting (Figure 1b). This emission constituted the entire seasonal N_2O fluxes with an average of 0.06 mg N_2O-N m^{-2} d^{-1} for the F-Control and 0.03 mg N_2O-N m^{-2} d^{-1} for the F-WS treatment. Under the F-D-F water management, however, much N_2O emission was triggered by the midseason drainage episode (Figure 1b). During the course of midseason drainage, mean N_2O fluxes were 15.7 mg N_2O-N m^{-2} d^{-1} for the D-Control, and 14.1 mg N_2O-N m^{-2} d^{-1} for the D-WS treatment, contributing 86–89% to their seasonal amounts, respectively. Seasonal N_2O emissions totaled 0.14 and 0.16 g N_2O-N m^{-2}, accounting for 0.52–0.56% of the synthetic fertilizer N applied with or without crop residue incorporation, respectively. For the continuous flooding plots, however, seasonal N_2O emissions only amounted to 0.01–0.02% of the applied fertilizer N (Table 1).

3.2. 2001 Season

[19] In 2001, CH_4 and N_2O emissions were simultaneously measured in the paddies under the F-D-F-M water regime (Figure 2). Without crop residue amendments (Control), seasonal CH_4 emissions averaged 33.1 mg m^{-2} d^{-1} and totaled 3.9 g m^{-2}. In comparison with the control, crop residue incorporation resulted in an increase of 252% in CH_4 (Table 1), with an average of 116.9 mg m^{-2} d^{-1}. There was no significant difference in CH_4 emissions between rapeseed cake (RC) and wheat straw (WS) application treatments. This may be attributed to their comparable carbon contents.

[20] On the basis of water status in the paddies, the rice season was simply divided into three conditions: water logging (F), midseason drainage (D), and moist (M) periods (Figure 2). N_2O emission was pronounced during the non-waterlogged period of rice-growing season, i.e., the drainage and moist periods (Figure 2b). Drainage resulted in a peak flux of N_2O emission. A smaller N_2O emission was observed during conditions that were moist but not waterlogged, while flooding led to unperceivable N_2O emission flux throughout the rice-growing season. N_2O emissions from a 1-week drainage, on average, accounted for 37–41% of the seasonal totals. Seasonal fluxes of N_2O averaged 3.48 mg N_2O-N m^{-2} d^{-1} for the control, 4.09 mg N_2O-N m^{-2} d^{-1} for the RC, and 2.82 mg N_2O-N m^{-2} d^{-1} for the WS treatment, respectively. Relative to the control, rapeseed cake incorporation resulted in an increase of 18%, while wheat straw application induced a decrease of 19% in seasonal N_2O emissions. The seasonal amount of N_2O emissions accounted for 1.00–1.45% of the total fertilizer N applied (Table 1), or 0.95–1.01% of the total N inputs, including fertilizer and crop residue N, for the RC and WS treatments, respectively.

3.3. 2002 Season

[21] A similar pattern of CH_4 emission was exhibited under the water treatment of F-D-F-M for the 2001 and 2002 seasons (Figures 2 and 3). In the 2002 fields, CH_4 fluxes tended to decrease with increasing urea application (Table 1). Seasonal flux of CH_4 was, on average, 146.6 mg m^{-2} d^{-1} for the plots with urea applied at 150 kg N ha^{-1} (FN150), 61.9 mg m^{-2} d^{-1} for the FN300,

and 35.6 mg m^{-2} d^{-1} for the FN450 treatment. Compared with the FN150 treatments, CH_4 emissions decreased by 58% for the FN300 and 76% for the FN450 (Table 1).

[22] Contrary to CH_4, N_2O emissions increased with urea application (Table 1). Seasonal fluxes of N_2O averaged 2.26 mg N_2O-N m^{-2} d^{-1} for the FN150, 3.76 mg N_2O-N m^{-2} d^{-1} for the FN300, and 5.23 mg N_2O-N m^{-2} d^{-1} for the FN450 treatments. Most of N_2O was emitted during the non-waterlogged period of the rice-growing season. In the course of midseason drainage, for example, mean fluxes of N_2O emissions were 4.63 mg N_2O-N m^{-2} d^{-1} for the FN150, 8.28 mg N_2O-N m^{-2} d^{-1} for the FN300, and 8.96 mg N_2O-N m^{-2} d^{-1} for the FN450. On average, N_2O emissions during the 1-week drainage period contributed 12% to the seasonal total emissions. During the moist period, fluxes of N_2O averaged 4.05 mg N_2O-N m^{-2} d^{-1}, and their amounts, on average, accounted for 39% of the seasonal totals for fertilized plots. Seasonal N_2O emissions totaled 0.27 g m^{-2} for the FN150, 0.44 g m^{-2} for the FN300, and 0.62 g m^{-2} for the FN450, accounting for 1.37%, 1.48%, and 1.78% of the applied fertilizer N, respectively.

4. Discussion

4.1. Effect of Water Regime on CH_4 and N_2O Emissions

[23] There are three water management patterns in the present study, namely, F and F-D-F (2000 season), as well as F-D-F-M (2001 and 2002 seasons). A steadily increasing CH_4 flux during the continuous flooding period and a rapid decrease in CH_4 flux resulting from midseason drainage were in agreement with the results in previous studies [e.g., *Corton et al.*, 2000; *Sass et al.*, 1992; *Wassmann et al.*, 2000; *Yagi et al.*, 1996; *Zheng et al.*, 2000]. Under continuous flooding, some recognizable CH_4 flushes was observed over the whole season, particularly when crop residues were incorporated (Figure 1a). No obvious CH_4 flush, however, was observed after a midseason drainage (Figures 1a, 2a, and 3a), which is also consistent with the previous studies [*Nishimura et al.*, 2004; *Yagi et al.*, 1996; *Zou et al.*, 2003a].

[24] Midseason drainage of irrigated rice paddies often gives rise to a drop in seasonal CH_4 flux. In the present study, midseason drainage resulted in a decrease of CH_4 flux by 65% and 36% for the plots without and with wheat straw applied, respectively. Field observations indicated that CH_4 emissions were reduced in the intermittent irrigation system compared with the continuous flooding paddies [*Yang and Chang*, 2001]. A pot experiment with different courses of periodic drainage indicated the reduction factor was about 45% to 72% [*Mishra et al.*, 1997]. *Cai* [1997] suggested that midseason aeration could mitigate CH_4 emissions by as much as 50%. On the other hand, water management would exert an influence on the decomposition of crop residue applied, and therefore their contributions to CH_4 emissions.

[25] It is clear that water regime has distinguished N_2O emissions in rice paddies from upland crops. Earlier studies showed that N_2O emissions from paddy fields were negligible [*Denmead et al.*, 1979; *Freney et al.*, 1981; *Smith et al.*, 1982]. Later, however, field research indicated that N_2O emission depends greatly on water management in rice paddies [e.g., *Cai et al.*, 1999; *Lindau et al.*, 1990a, 1990b; *Zheng et al.*, 1999]. Although midseason drainage has been proposed as a mitigation strategy for CH_4 emissions, a trade-off relationship between CH_4 and N_2O emissions resulting from midseason drainage has been well documented in paddy studies [e.g., *Cai et al.*, 1997; *Zheng et al.*, 1999; *Zou et al.*, 2003a]. Consistent with the earlier studies [e.g., *Granli and Bøckman*, 1994; *Smith et al.*, 1982], little N_2O emission was observed when fields were continuously flooded in this study. Midseason drainage, however, caused intense emissions of N_2O, which contributed greatly to the seasonal amount. After the midseason drainage, on the other hand, no recognizable N_2O was observed when the field was frequently waterlogged by the intermittent irrigation in 2000 (Figure 1b). In contrast, a great deal of N_2O was observed when the field was moist but not waterlogged by the intermittent irrigation (i.e., dry-wet alternation) in the 2001 and 2002 seasons (Figures 2b and 3b). Thus N_2O emissions during intermittent irrigation periods depended strongly on whether or not water logging was present in the fields. Different water regimes cause a sensitive change in N_2O emissions from rice paddies.

4.2. Effect of Crop Residue Incorporation on CH_4 and N_2O Emissions

[26] In general, the highest CH_4 emissions are observed in fields receiving organic amendments. Decomposition of organic materials offers the predominant source of methanogenic substrates, particularly in the early stage of rice development. *Adhya et al.* [2000] found that application of *Sesbania* and *Azolla* increased CH_4 by 214% and 55% compared with the application of pure urea. In the present study, CH_4 was increased by a factor of 1.6 and 3.7 due to wheat straw incorporation, dependent on the water regime in 2000. In the 2001 season, crop residue amendments increased CH_4 by 252%. We calculated the percentage difference in CH_4 emissions between the plots with and without wheat straw application, assumed as crop residue-induced CH_4, and found that it accounted for 15% of crop residue C under the continuous flooding treatment, 13% under the F-D-F in 2000, and 9% under the F-D-F-M in 2001. Drainage generally reduced crop residue-induced CH_4 emissions.

[27] N_2O is produced in soils mainly through the microbial processes of nitrification and denitrification. The availability of organic C is often considered to be a major factor influencing denitrification under anaerobic conditions. An earlier study conducted by *Patten et al.* [1980] demonstrated that denitrification was dependent on the quantity of organic C readily utilized by denitrifying microorganisms, while the organic C in various other pools was not completely available to microorganisms. Incorporation of crop residues provides a source of readily available C and N in the soil, and subsequently influences N_2O emissions [*Cochran et al.*, 1997; *Flessa and Beese*, 1995; *Huang et al.*, 2004b; *Lemke et al.*, 1999]. Wheat straw incorporation decreased seasonal N_2O emissions by 8% under the F-D-F in 2000 and by 19% under the F-D-F-M in 2001. A slight decrease in N_2O emission due

to wheat straw incorporation was also found in some previous paddy studies [e.g., *Aulakh et al.*, 2001; *Bronson et al.*, 1997]. Several explanations may be given for lower N_2O emissions when wheat straw is incorporated. In the rice paddies, decomposition of wheat straw accelerates O_2 consumption in the aerobic soil layer and in the rhizosphere, favoring N_2O transformed into N_2 through denitrification. Enhanced immobilization of fertilizer N accompanying the decomposition of straw with high C/N ratio may result in less N available to nitrification and denitrification, in which N_2O is produced [*Bronson et al.*, 1997].

[28] In contrast with the control in 2001, however, rapeseed cake incorporation increased N_2O by 17%, which might benefit from the higher N content and lower C/N ratio of the rapeseed cake. The influence of crop residue type and related quality (C, N, or C/N ratio) on residue decomposition has been well documented [e.g., *Silver and Miya*, 2001]. Generally, N_2O emissions are negatively correlated with C/N ratio of the incorporated residues [*Aulakh et al.*, 1991; *Eichner*, 1990; *Huang et al.*, 2004b; *Németh et al.*, 1996]. Rapeseed cake with a lower C/N ratio (C/N = 8) is decomposed more readily than wheat straw (C/N = 63) [*Huang et al.*, 2004b], This observation is supported by data showing that wheat straw applied in a season had a lasting effect on N_2O emissions from the following winter wheat season in a rice-wheat rotation, while this effect was not found for rapeseed cake application [*Zou et al.*, 2003b, 2004]. In the present study, crop residue incorporated at the depth of 10–15 cm would be in close contact with the rhizosphere. Other placements, such as surface cover and evenly mixed, may impact N_2O emissions differently. Many studies have suggested that N_2O emissions as affected by crop residue amendment were associated with crop residue particle size, quality, and placement [*Ambus et al.*, 2001; *Aulakh et al.*, 1991; *Shelp et al.*, 2000].

4.3. Effect of Nitrogen Fertilizer on CH_4 and N_2O Emissions

[29] Nitrogen fertilizers are commonly used in rice production to increase grain yields. Urea and ammonium sulfate account for 80–90% of the total nitrogen fertilizer demanded in rice cultivation (Food and Agriculture Organization, http://apps.fao.org/). Field studies indicate that the influence of synthetic fertilizer on methane emission from rice fields is inconsistent and not well understood. Although the control without urea application was not included in the 2002 season, CH_4 emissions appeared to decrease with increased urea fertilization, which is consistent with the results in some rice paddies [*Cai et al.*, 1997; *Krüger and Frenzel*, 2003; *Wang et al.*, 1992]. *Lindau et al.* [1991], however, found that methane emission increased with urea application. *Wang et al.* [1993] reported no change in emission with urea application and a decrease in methane production with ammonium nitrate.

[30] The contribution of applied nitrogen to N_2O emissions is often described as fertilizer-induced N_2O. Our results suggested that the fertilizer-induced N_2O was strongly dependent on water regime. Under the continuous flooding in 2000, N_2O emissions only happened within one week before rice harvesting, which amounted to 0.01–0.02% of the applied urea-N. This is similar to the results of 0.01–0.05% in the continuous flooding rice wetlands [*Smith et al.*, 1982]. Under the F-D-F water regime, however, seasonal N_2O emissions accounted for about 0.56% of the applied fertilizer N in 2000, which is comparable to other results under similar water and fertilizer managements [e.g., *Cai et al.*, 1997, 1999]. In the 2001 and 2002 seasons, N_2O emission accounted for 1.00–1.78% of the fertilizer N applied under the F-D-F-M water regime.

[31] Under identical water regimes, fertilizer-induced N_2O emission was generally lower in 2001 than in the 2002 paddies (Table 1). Besides the conceivable difference in soil moisture important to N_2O emission patterns during non-waterlogged stage between two seasons, it is possible that mineral compound fertilizer and NH_4HCO_3 used as basal fertilizer in 2001 contributed less to N_2O in contrast to urea used in the 2002 fields. In addition, compared with the 2001 season, the vigorous rice cultivar (cv. Wuyunjing 7) in 2002 might produce more root exudates that are available C and N for soil microbes, and thereby favor N_2O emissions. Similar to N_2O, CH_4 emission was slightly greater in 2002 than in 2001 under the similar water regime. Compared with the 2000 and 2001 seasons, the vigorous cultivar of rice in 2002 (data not shown) may be capable of producing more root exudates, which is the predominant substrate of CH_4 produced. CH_4 emission has been well documented to be associated with rice cultivar [*Huang et al.*, 1997].

4.4. Combined Climatic Impact of CH_4 and N_2O Emissions

[32] The concept of global warming potential (GWP), one type of simplified index based upon radiative properties, was introduced in order to estimate the potential future impacts of emissions of different gases upon the climate system in a relative sense [*Lashof and Ahuja*, 1990; *Shine et al.*, 1990]. In GWP estimation, CO_2 is typically taken as the reference gas, and an increase or reduction in emission of CH_4 and N_2O is converted into "CO_2-equivalents" by means of their GWPs. Recently, the net GWP has been estimated to complete understanding of agriculture's impact on radiative forcing [*Frolking et al.*, 2004; *Robertson et al.*, 2000; *Six et al.*, 2004; *Yu et al.*, 2004]. In the present study, we calculated GWPs using IPCC factors [*IPCC*, 2001] to assess the combined climatic impacts from CH_4 and N_2O under various agricultural practices. The total GWPs (CO_2-equivalent g m^{-2}) of CH_4 and N_2O under different agricultural treatments are shown in Table 2. Compared with continuous flooding, midseason drainage and intermittent irrigation decreased significantly the net GWPs whether over a 20-year horizon or a 500-year horizon. On the contrary, organic amendments greatly increased net GWPs. The synthetic fertilizer application generally depressed the net GWPs, but this impact was not pronounced when fertilizer was applied over 300 kg N ha^{-1} (Table 2). Overall, the lowest net GWPs in the treatment of D-Control, whether over a 20-year horizon or a 500-year horizon, suggests that water management of flooding-midseason drainage-reflooding-moist but non-waterlogged without organic amendments is an effective option for mitigating the total climatic impacts of CH_4 and N_2O. Otherwise, continuous

Table 2. Net GWPs From CH_4 and N_2O Emissions in Rice Paddies Under Different Agricultural Treatments[a]

	CH_4		N_2O		CH_4+N_2O	
Treatment[b]	20 Years	500 Years	20 Years	500 Years	20 Years	500 Years
F-Control	527	60	3	1	530	61
D-Control	186	21	67	38	253	59
F-WS	1364	154	1	1	1365	155
D-WS	874	99	62	35	936	134
Control	242	27	178	101	419	128
RC	856	97	209	118	1064	215
WS	843	95	144	82	987	177
FN150	1073	121	115	65	1188	187
FN300	453	51	192	109	644	160
FN450	260	29	267	151	527	181

[a] The IPCC GWPs factors (mass basis) for CH_4 and N_2O are 62 and 275 in the time horizon of 20 years, and 7 and 156 in the time horizon of 500 years, respectively [*IPCC*, 2001].

[b] Treatments are the same as Table 1.

flooding in rice paddies with organic application would extremely intensify the radiative forcing.

5. Conclusion

[33] Clearly, there are some trade-offs between CH_4 and N_2O emissions as affected by agricultural managements in this study. First, in contrast with continuous flooding, midseason drainage incurred a drop in CH_4 fluxes while largely triggering N_2O emissions. Moreover, N_2O emissions after midseason drainage depended strongly on whether or not waterlogging with intermittent irrigation was applied to the fields. Second, wheat straw incorporation increased CH_4 emissions remarkably but slightly decreased N_2O emissions. Finally, urea application led to an increase in N_2O emissions, whereas it tended to decrease CH_4 emissions. Both crop residue-induced CH_4 and fertilizer-induced N_2O emissions were dependent on the water regime in rice paddies. The results of the net GWPs from CH_4 and N_2O indicate that water management of flooding-midseason drainage-reflooding-moist but non-waterlogged without organic amendments is an effective option for mitigating the combined climatic impacts of paddy rice production. Continuous flooding in rice paddies with organic application, however, would extremely intensify the radiative forcing.

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