

Methane and nitrous oxide emissions from organic and conventional rice cropping systems in Southeast China

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Received: 10 May 2010 / Revised: 21 July 2010 / Accepted: 26 July 2010 / Published online: 6 August 2010
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Abstract To evaluate the impacts of organic cropping system on global warming potentials (GWPs), field measurements of CH₄ and N₂O were taken in conventional and organic rice (*Oryza sativa* L.) cropping systems in southeast China. Rice paddies were under various water regimes, including continuous flooding (F), flooding–midseason drainage–reflooding (F-D-F), and flooding–midseason drainage–reflooding and moisture but without waterlogging (F-D-F-M). Nitrogen was applied at the rate of 100 kg N ha⁻¹, as urea-N or pelletized, dehydrated manure product in conventional or organic rice paddies, respectively. Seasonal fluxes of CH₄ averaged 4.44, 2.14, and 1.75 mg m⁻² h⁻¹ for the organic paddy plots under the water regimes of F, F-D-F and F-D-F-M, respectively. Relative to conventional rice paddies, organic cropping systems increased seasonal CH₄ emissions by 20%, 23%, and 35% for the plots under the water regimes of F, F-D-F, and F-D-F-M, respectively. Under the water regimes of F-D-F and F-D-F-M, seasonal N₂O-N emissions averaged 10.85 and 13.66 µg m⁻² h⁻¹ in organic rice paddies, respectively, which were significantly lower than those in conventional rice paddies. The net global warming potentials (GWPs) of CH₄ and N₂O emissions from organic rice paddies relative to conventional rice paddies were significantly higher or comparable under various water regimes.

The greenhouse gas intensities were greater, while carbon efficiency ratios were lower in organic relative to conventional rice paddies. The results of this study suggest that organic cropping system might not be an effective option for mitigating the combined climatic impacts from CH₄ and N₂O in paddy rice production.

Keywords CH₄ · Global warming potential (GWP) · Mitigation for greenhouse gases · N₂O · Organic agriculture · Rice paddy

Introduction

Methane (CH₄) and nitrous oxide (N₂O) are significant long-lived greenhouse gases, and they together contribute about 20% of the annual increase in radiative forcing (Smith et al. 2007). Globally, anthropogenic sources of N₂O and CH₄ are dominated by agriculture, and agricultural CH₄ and N₂O emissions have increased by nearly 17% from 1990 to 2005 (Robertson and Grace 2004; Forster et al. 2007). Agricultural N₂O emissions are projected to increase by 35–60% up to 2030 due to increased chemical and manure N inputs (FAO 2003).

Agriculture releases significant amount of CH₄ and N₂O to the atmosphere, but changes in agricultural management regime also offer possibilities for mitigation (Robertson et al. 2000; Mosier et al. 2006; Smith et al. 2008). Various organic techniques have been utilized for about 6,000 years to make agriculture sustainable and improve the environment (Pimentel et al. 2005). Recently, organic agriculture has been promoted as a partial means for mitigating agricultural CH₄ and N₂O emissions (FAO 2002). In the Olesen et al. (2006) modeling analysis, total CH₄ emissions (primarily originated from enteric fermentation and from manure storage) were

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generally higher in European conventional dairy farms than in organic dairy farms. Relative to conventional cropping systems, on the other hand, N_2O emissions are generally lower in organic cropping systems (Flessa et al. 2002; Burger et al. 2005; Petersen et al. 2006; Phillips 2007), while some other studies showed that N_2O emissions were not significantly different or greater from organically farmed soils relative to conventionally farmed soils (Kaiser and Ruser 2000; Robertson et al. 2000; Kramer et al. 2006; Syväsalo et al. 2006). Nevertheless, literature comparing agricultural greenhouse gases emission from organic and conventional cropping systems is limited in upland arable soils. To our knowledge, no such studies have been carried out in rice paddies, although water regime has distinguished CH_4 and N_2O emissions in rice paddies from upland cropping systems.

Rice paddies have been identified as a major source of atmospheric CH_4 . The global CH_4 emission rate from paddy fields was estimated to be $20\text{--}40\text{ Tg year}^{-1}$ (Neue and Sass 1998; Sass et al. 1999; Yan et al. 2009), which accounts for about 11% of the total CH_4 emissions (USEPA 2006). While N_2O emission is mostly produced in upland fields, much research indicates that N_2O is also pronounced as a result of the midseason drainage and dry–wet episodes in paddy fields (Cai et al. 1997; Zheng et al. 2000; Zou et al. 2004; Akiyama et al. 2005).

China is the most important rice-producing country in the world, and its planting area accounts for about 20% of the world total and occurs on 23% of all cultivated land in China (Frolking et al. 2002). Since the 1980s, water regime has greatly changed from continuous flooding to midseason drainage and moisture irrigation in rice paddies, which results in a trade-off between CH_4 and N_2O emissions (Cai et al. 1997; Li et al. 2005; Zou et al. 2005a). The total CH_4 emissions from Chinese rice paddies were estimated to be $6\text{--}10\text{ Tg year}^{-1}$ in 1990s (Huang et al. 2004a; Yan et al. 2009). Nitrogen input has increased from 87.5 kg N ha^{-1} in the 1950s to $224.6\text{ kg N ha}^{-1}$ in the 1990 s, accompanied by direct N_2O emissions increased from $9.6\text{ Gg N}_2\text{O-N}$ to $32.3\text{ Gg N}_2\text{O-N}$ in Chinese paddy rice production over the period of 1950s to 1990s (Zou et al. 2009).

Excessive N fertilization has resulted in serious environmental problems, and thus the change in cropping practices is of increasing concern in Chinese rice production (Ju et al. 2009). For example, eutrophication in the Taihu Lake region has recently attracted national attention, which is partially due to excessive fertilization in agriculture. To effectively improve water quality in the Taihu Lake where it is mainly surrounded by rice cropping system, the conversion of conventional rice paddies to organic paddy rice production is currently promoted by the Chinese government in this area. Although CH_4 and N_2O emissions from Chinese rice paddies have been extensively documented,

the impacts of organic management on global warming potential, crop production and CH_4 and N_2O intensity in Chinese rice paddies remain unknown.

An organic rice cropping system initiated in 2000 was used to evaluate the impacts of organic cropping system on global warming potentials (GWPs) in this study. We present field measurements of CH_4 and N_2O emissions from organic and conventional rice paddies in southeast China under various water regimes. We predict that CH_4 emissions would be greater in organic rice paddies than in conventional rice paddies since CH_4 emissions increased with organic material amendment, while N_2O emissions would be lower given that mineral N was slowly released from organic manure in organic rice paddies as compared to synthetic N fertilizer inputs in conventional rice paddies. The main objectives of this study are to compare the net GWPs and greenhouse gas intensities (GHGIs, i.e., GWPs in terms of grain yield) of CH_4 and N_2O emissions from organic vs. conventional rice paddies, and thereby to examine whether or not organic cropping management is a potential for mitigating the global warming potentials of CH_4 and N_2O emissions from rice paddies.

Materials and methods

Experiment site

The conventional and organic rice field studies were performed in Nanjing, Jiangsu province, China ($31^\circ52'\text{ N}$, $118^\circ50'\text{ E}$) in 2007. The field site was located at the experimental farm of the Nanjing Agricultural University where cropping regime was primarily dominated by annual rice paddy-winter wheat rotation. The region has a monsoonal climate with typical mean temperature of 25°C and rainfall of $600\text{--}700\text{ mm}$ during the rice-growing season. At the experimental farm, some part of the arable area was converted from conventional to organic cropping systems. The conversion of conventional rice paddies to organic rice production was initiated in 2000 and certified by the Ministry of Environmental Protection (MEP) of China in 2005. The organic farm area was 10 ha and dominated by organic rice paddies (Lu et al. 2005). Soil of the experimental fields was classified as gleysols or hydromorphic. Soil samples were collected before rice transplanting, and the physicochemical properties of soils and climate were comparable between the two experimental fields (Table 1).

Field experiments

A randomized block experiment with three replicates was established, with two cropping systems (conventional rice

Table 1 Physicochemical properties of soil in conventional and organic rice paddies and climate during rice-growing season

Cropping system	pH	BD (gcm ⁻³)	TOC (gkg ⁻¹)	TN (gkg ⁻¹)	NH ₄ ⁺ -N (mgkg ⁻¹)	NO ₃ ⁻ -N (mgkg ⁻¹)	P (mm)	T (°C)
Organic	6.6	1.23	13.1	1.17	6.44	9.57	693	25.3
Conventional	6.5	1.24	15.3	1.50	6.95	9.86	680	25.1

BD bulk density, TOC soil total organic carbon content, TN soil total nitrogen content, P and T total precipitation and air mean temperature during rice-growing season, respectively

vs. organic rice cropping systems) and three irrigation regimes (continuous flooding, flooding–midseason drainage–reflooding, and flooding–midseason drainage–reflooding–moisture irrigation). The field plots were established in a 15×100-m grid of conventional rice field and a 25×100-m grid of rice field under the long-term organic cropping farm.

In the conventional rice paddies, rice seeds (*O. sativa* L., cv. Wuyunjing 7) were sown in a nursery bed on May 15; seedlings were transplanted in the paddies on June 10 and harvested on October 10, 2007. We plowed, mixed the surface soil and leveled the ground before rice transplanting. Urea was applied at the rate of 100 kg N ha⁻¹ on the fields, representing the low fertilization level in rice production. In agreement with the local conventional fertilizer application methods, urea was broadcasted on the field plots, with a split of 40% of the total as basal fertilizer, 40% at turning-green, and 20% at tillering stage for rice. For each plot, calcium superphosphate used as phosphorus fertilizer was identically applied as the basal fertilizer at the rate of 50 kg ha⁻¹. Potassium chloride used as potassium fertilizer was applied at the rate of 100 kg ha⁻¹ before rice transplanting.

In the organic rice paddies, rice seeds (cv. Wuyunjing 7) were sown in a nursery bed on May 20; seedlings were transplanted in the paddies on June 19 and harvested on October 17. A pelletized, dehydrated manure product (Jiangning Farms, Jiangsu) that was made of crop residue and farmyard manure was applied at the rate of 100 kg N ha⁻¹ on the fields. In agreement with the local organic manure application methods, a split of 60% of the total manure as basal fertilizer was amended and homogenized into the top 5 cm of soil before rice transplanting, and the other 40% was broadcasted on the field at turning-green stage for rice. Total nitrogen, phosphorus and potassium inputs were comparable in the conventional and organic rice paddy fields. The organic-certified, dehydrated, partially composted, pelletized manure applied to organic rice paddies had the following chemical characteristics: 179.24 g C kg⁻¹; 20.66 g N kg⁻¹; 10.52 g P kg⁻¹; 24.49 g Ca kg⁻¹; 6.95 g Mg kg⁻¹; 0.10 g Zn kg⁻¹; 0.03 g Cu kg⁻¹; 0.07 g Mn kg⁻¹; and 0.15 g Fe kg⁻¹. No crop residue was incorporated, but about 5–10 cm crop stubble from the preceding wheat season was retained in conventional and organic rice paddies. Chemical or

biological insecticides were applied in accordance with local conventional or organic rice production management, respectively. Over the whole rice-growing season, a commercial formulation of carbofuran (3% active ingredient, 2,3-dihydro-2,2-dimethyl-7-benzofuranyl N-methylcarbamate, HC Agrochemicals Co., Ltd., Shanghai) was broadcast twice at the rate of 5 kg active ingredient ha⁻¹ in conventional rice paddies, and a commercial Bt-insecticide product (*Bacillus thuringiensis*, 8,000 IU/mg, Liaoning Biochemical CO, LTD, Liaoning) was broadcast twice at the rate of 4 kg ha⁻¹ in organic rice paddies.

To investigate the effects of water regime on CH₄ and N₂O emissions, similar water regime treatments were adopted in the conventional and organic rice paddy fields. For each cropping system, the experiment field was divided into three irrigation blocks consisting of 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). Three replicated field plots were established under each irrigation regime block, and each field plot is 4 m×4 m. For continuously flooded plots, the field was kept waterlogged until 1 week before rice harvesting. For the plots under the F-D-F and F-D-F-M water regimes, flooding was initiated 1 week before rice transplanting and lasted until 45 days after transplanting, and followed by drainage for 10 days. Thereafter, the F-D-F plots were frequently flooded by intermittent irrigation from 55 days after transplanting through a week before crop harvesting, while the F-D-F-M plots were re-flooded from 55 days through 90 days after transplanting and followed by maintaining a moist soil but without water logging (a dry–wet alteration with intermittent irrigation) until a week before rice harvesting. Blocks of different water regimes were completely isolated by levees with plastic covering.

Gas sampling

The CH₄ and N₂O fluxes were determined by the static chamber-GC method (Wang and Wang 2003; Zou et al. 2005a). During the rice-growing season, boardwalks to randomly selected 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 N_2O emission measurements in the whole rice-wheat rotation season. The top edge of the collar had a groove (5 cm in depth) for filling with water to seal the rim of the chamber with leveled surface. 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 $0.25\text{ (}0.5\text{ m}\times0.5\text{ m)}\text{ m}^2$ and three chambers were placed in each plot. While gas sampling, the chamber was placed over six hills of rice vegetation with the rim of the chamber fitted into the groove of the collar. The planting density inside the chamber (hill spacing was $0.25\text{ m}\times0.15\text{ m}$, with three seedlings per hill) was the same as that outside the chamber. Gas samples were taken once or twice weekly. During the midseason drainage period, gas samples were taken once a day. Air samples from the chamber headspace were collected using 60 ml plastic syringes fitted with three-way stopcocks via a Teflon tube (with an outer diameter of 1/8 in.) connected to the chamber. Gas samples were taken from local time 0800 through 1000 LST since the soil temperature during the sampling period was close to the daily average soil temperature (Zou et al. 2005a). Air temperature inside the chamber was recorded for each set of emission measurements. Gas samples in the syringes were stored for analysis by GC in the lab within a few hours.

The mixing ratios of CH_4 and N_2O were simultaneously analyzed with a modified gas chromatograph (Agilent 7890) equipped with a flame ionization detector (FID) and an electron capture detector (ECD; Wang and Wang 2003). A purified gas of nitrogen was used as the carrier gas for CH_4 , and a gas mixture of argon and methane (Ar-CH_4) was used as the carrier gas for N_2O . To remove CO_2 and water vapor in the air samples entering the ECD detector, a filter column filled with ascarite was connected to the beginning of the separation column for N_2O (Zheng et al. 2008). 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 porapak Q, and detected by the ECD. Methane was detected by the FID. The oven was operated at 55°C , the ECD at 330°C and the FID at 200°C . 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 deviations of N_2O were calculated from triplicate plots. Seasonal amounts of CH_4 and N_2O emissions were sequentially accumulated from the

emissions between every two adjacent intervals of the measurements (Zou et al. 2005a, b).

Climatic impact of CH_4 and N_2O

The concept of 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). 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 the agriculture impacts on radiative forcing (Frolking et al. 2004; Mosier et al. 2006; Robertson and Grace 2004). In the present study, we used the IPCC factors to calculate the combined GWPs for 100 years ($\text{GWP}=25\times\text{CH}_4+298\times\text{N}_2\text{O}$, $\text{kg CO}_2\text{-equivalents ha}^{-1}$) from CH_4 and N_2O under various agricultural practices (Forster et al. 2007).

Recently, some studies proposed other concepts for relating agricultural practices to GWP, such as GHGI and carbon efficiency ratio (CER; Bhatia et al. 2005; Mosier et al. 2006). The GHGI is calculated by dividing GWP by crop yield (grain yield for rice). The CER is estimated by dividing grain yield of rice (in terms of C) by GWP in terms of carbon equivalent (27.3% of GWP). Little is known about the impacts of organic cropping practice on GHGI and CER. We thereby calculated GHGI and CER of rice to assess the radiative forcing of CH_4 and N_2O emissions in the perspective of crop production (Table 2).

Other data measurements

Ambient air temperature and precipitation data were recorded by weather station, which was established on the experimental farm. Grain yields were measured at physiological maturity by hand harvesting two rows 2 m long per plot. Above-ground biomass and grain yields of the rice were determined at harvest by oven drying to a constant weight at approximately 70%.

Statistical analyses

Differences in grain yields, seasonal CH_4 and N_2O emissions and the climatic impacts as affected by cropping system, water irrigation type, and their interaction were examined by using a two-way analysis of variance. Differences among treatments were further examined by the Tukey’s multiple range test. Statistical analyses were carried out using JMP, ver. 5.1 (SAS Institute, Cary, NC, USA, 2003).

Table 2 Rice yield and seasonal amounts (Mean $\pm$ SD, $n=3$) of CH₄ and N₂O emissions and their calculated GWP, GHGI and CER in organic and conventional rice paddies under various irrigation regimes

Cropping system	Irrigation regime ^a	Yield (t ha ⁻¹)	CH ₄ (kg ha ⁻¹)	N ₂ O-N (kg N ha ⁻¹)	GWP ^b	GHGI ^c	CER ^d
Organic rice paddy	F	4.40 $\pm$ 0.65 ^d	126.7 $\pm$ 24.7 ^a	0.18 $\pm$ 0.03 ^{c,d}	3252 $\pm$ 614 ^a	0.74 $\pm$ 0.03 ^a	2.28 $\pm$ 0.32 ^c
	F-D-F	4.67 $\pm$ 0.34 ^{cd}	61.0 $\pm$ 3.9 ^c	0.31 $\pm$ 0.05 ^c	1670 $\pm$ 77 ^c	0.36 $\pm$ 0.04 ^c	4.82 $\pm$ 0.49 ^b
	F-D-F-M	4.75 $\pm$ 0.62 ^{cd}	49.9 $\pm$ 7.3 ^d	0.39 $\pm$ 0.08 ^c	1430 $\pm$ 205 ^c	0.30 $\pm$ 0.01 ^d	4.99 $\pm$ 0.46 ^b
Conventional rice paddy	F	5.48 $\pm$ 0.55 ^{bc}	105.3 $\pm$ 1.4 ^b	0.05 $\pm$ 0.03 ^d	2656 $\pm$ 11 ^b	0.48 $\pm$ 0.05 ^b	3.10 $\pm$ 0.22 ^c
	F-D-F	6.20 $\pm$ 0.38 ^{ab}	49.4 $\pm$ 4.9 ^d	0.90 $\pm$ 0.16 ^b	1656 $\pm$ 29 ^c	0.27 $\pm$ 0.01 ^{de}	6.18 $\pm$ 0.38 ^a
	F-D-F-M	6.51 $\pm$ 0.72 ^a	36.9 $\pm$ 3.2 ^d	1.30 $\pm$ 0.11 ^a	1531 $\pm$ 108 ^c	0.24 $\pm$ 0.02 ^e	6.70 $\pm$ 0.50 ^a

^a Irrigation regime, *F* continuous flooding, *F-D-F* flooding–midseason drainage–reflooding, *F-D-F-M* flooding–midseason drainage–reflooding–moist irrigation but without flooding

^b The IPCC GWP factors (mass basis, kg CO₂-equivalent ha⁻¹) for CH₄ and N₂O are 25 and 298 in the time horizon of 100 years, respectively (Forster et al. 2007)

^c GHGI (kg CO₂-equivalent kg⁻¹ grain yield) is calculated by dividing GWPs of CH₄ and N₂O emissions by rice yield

^d CER (kg C-grain yield kg⁻¹ C-equivalent) is determined by dividing rice yield in terms of C by GWP carbon equivalent of CH₄ and N₂O emissions

Results

CH₄ emissions

Seasonal pattern of CH₄ emissions did not differ between organic and conventional rice paddies, while it varied with irrigation regime (Figs. 1 and 2). When the field was waterlogged, CH₄ emissions increased steadily until the peak fluxes were attained approximately 20–30 days after rice transplanting. In comparison with continuous flooding (*F*), thereafter, CH₄ emission was dramatically decreased by midseason drainage and then remained at a lower release rate. Seasonal amounts of CH₄ emissions from organic rice paddies were significantly greater than those from conventional rice paddies ($F_{1,17}=9.1$, $P=0.01$, Table 2). In contrast with conventional rice paddies, seasonal CH₄ emissions from organic rice paddies were increased by 20%, 23%, and 35% for the plots under the water regimes of *F*, *F-D-F* and *F-D-F-M*, respectively (Table 2). Under continuous waterlogging, seasonal fluxes of CH₄ averaged 4.44 mg m⁻² h⁻¹ for the organic paddy plots and 3.63 mg m⁻² h⁻¹ for the conventional paddy plots. For the water regime of *F-D-F*, seasonal fluxes of CH₄ averaged 2.14 and 1.70 mg m⁻² h⁻¹ for the organic and conventional rice paddy plots, respectively. Seasonal fluxes of CH₄ averaged 1.75 and 1.27 mg m⁻² h⁻¹ for the organic and conventional rice paddy plots under the water regime of *F-D-F-M*, respectively. Compared with continuous flooding, midseason drainage and dry–wet alteration decreased CH₄ emissions by 55–60% for the organic and conventional rice paddy plots (Table 2).

N₂O emissions

Midseason drainage resulted in a trade-off between CH₄ and N₂O emissions (Figs. 1 and 2). Drainage resulted in a

peak flux of N₂O emission in organic and continuous rice paddies. During moist conditions but without waterlogging, a smaller N₂O emission occurred for conventional rice paddy plots, but N₂O emission was not pronounced for organic rice paddy plots (Figs. 1 and 2). Seasonal total N₂O emissions depended significantly on cropping system ($F_{1,17}=108.1$, $P<0.001$), water regime ($F_{2,17}=90.6$, $P<0.001$) and their interaction ($F_{2,17}=46.3$, $P<0.001$). Under continuous waterlogging, seasonal N₂O-N emissions were low, with average of 6.25 and 1.72 μ g m⁻² h⁻¹ for organic

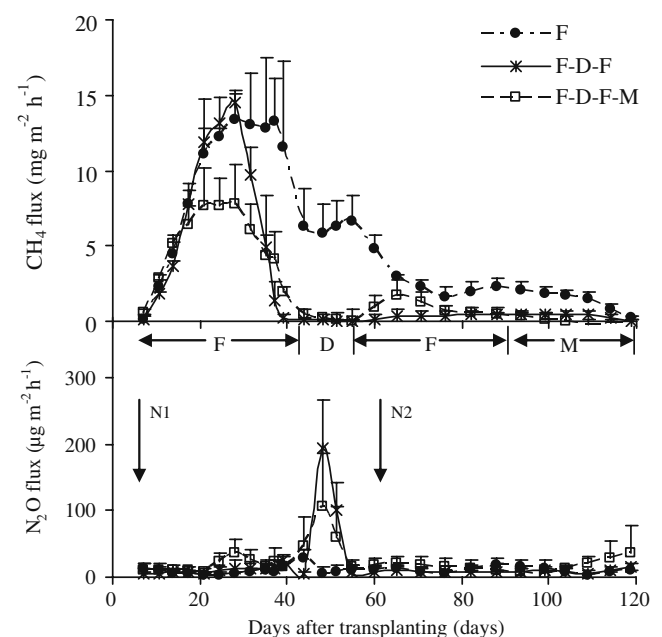


Fig. 1 Seasonal dynamics of CH₄ (a) and N₂O (b) emissions from organic rice paddies. Error bars represent 1 stand deviation. F, D, and M represent the plots under the water regime of *F-D-F-M*: *F* flooding, *D* midseason drainage, *M* moist but non-waterlogged by intermittent irrigation. *N1* and *N2*, organic manure application

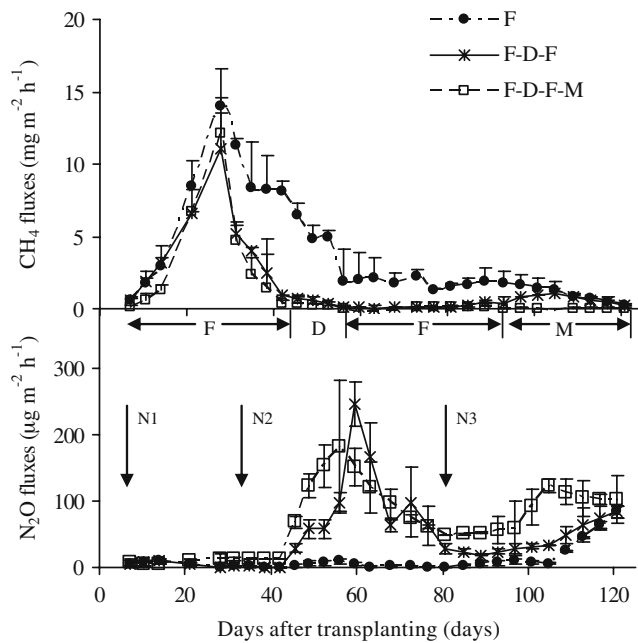


Fig. 2 Seasonal dynamics of CH₄ (a) and N₂O (b) emissions from conventional rice paddies. Error bars represent 1 stand deviation. F, D, and M represent the plots under the water regime of F-D-F-M: F flooding, D midseason drainage, M moist but non-waterlogged by intermittent irrigation. N1, N2, and N3, synthetic nitrogen fertilizer application

and conventional rice paddy plots, respectively. Under the water regimes of F-D-F and F-D-F-M, however, seasonal N₂O emissions were significantly lower in organic rice paddies than in conventional rice paddies (Table 2). Seasonal fluxes of N₂O-N averaged 10.85 and 13.66 $\mu\text{g m}^{-2} \text{h}^{-1}$ for organic rice paddies, accounting for 0.31% and 0.39% of the manure N applied under the water regimes of F-D-F and F-D-F-M, respectively. In conventional rice paddies, seasonal fluxes of N₂O-N averaged 30.99 and 44.76 $\mu\text{g m}^{-2} \text{h}^{-1}$, amounted to 0.90% and 1.30% of the synthetic fertilizer N applied under the water regimes of F-D-F and F-D-F-M, respectively.

Net GWP, GHGI, and CER

Compared with continuous flooding, midseason drainage and moist irrigation significantly decreased the net GWPs in organic and conventional rice paddies ($F_{2,17}=52.9$, $P<0.001$, Table 2). In addition, differences in the net GWPs of CH₄ and N₂O emissions between organic and conventional rice paddies depended on irrigation regime (interaction term: $F_{2,17}=2.9$, $P=0.05$). Under continuous flooding, CH₄ and N₂O emissions from organic rice paddies were significantly greater, and thereby estimated GWP was greater in organic rice paddies than in conventional rice paddies. For rice paddies with midseason drainage, CH₄ emissions were significantly higher, while N₂O emissions were significantly

lower for organic rice paddies relative to conventional rice paddies, which resulted in no pronounced differences in estimated GWPs between the two cropping systems (Table 2).

The GHGI relating GWP to crop production was significantly affected by cropping system ($F_{1,17}=90.7$, $P<0.001$), water regime ($F_{2,17}=251.9$, $P<0.001$), and their interaction ($F_{2,17}=17.7$, $P<0.01$). Compared with conventional rice paddies, GHGI were increased by 54%, 33%, and 30% in organic rice paddies under the water regime of F, F-D-F and F-D-F-M, respectively. Midseason drainage benefited crop growth in organic and conventional rice paddies. Compared with continuous flooding, midseason drainage increased rice yield by 6–8% and 13–19% in organic and conventional rice paddies, respectively (Table 2). Correspondingly, midseason drainage decreased the GHGI by 51–60% and 44–50% in organic and conventional rice paddies, respectively. Similarly, the CER, i.e., C fixed in grain by rice per unit of C-equivalent emitted as CH₄ and N₂O, depended significantly on cropping system ($F_{1,17}=46.2$, $P<0.001$) and water regime ($F_{2,17}=108.9$, $P<0.001$). Compared with conventional rice paddies, the CER was decreased by 22–26% in organic rice paddies under various water regimes (Table 2). The CER was almost doubled due to midseason drainage and moist irrigation in organic and conventional rice paddies. Overall, higher GHGI and lower CER in organic rice paddies suggest that organic instead of conventional cropping system would intensify the radiative forcing, particularly when rice paddies were under continuous waterlogging.

Discussion

The grain yield was significantly lower in organic rice paddies than in conventional rice paddies ($F_{1,17}=30.0$, $P<0.001$, Table 2). Besides mineral N slowly released from organic manure failed to fairly meet the demand of crop growth in organic rice paddies, chemical insecticides better controlled insects in conventional rice paddies than biological insecticides in organic rice paddies. Insects (e.g., rice stem borer) were totally controlled by carbofuran broadcast, while about 75% control efficiency was achieved by the Bt-insecticide applied at the panicle initiation stage. In addition, 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, which would benefit crop growth and production (Huang et al. 2004a; Zou et al. 2009). In contrast with continuous flooding, midseason drainage tended to increase rice grain yield although this increase was not statistically significant in this study (Table 2).

Agricultural CH₄ and N₂O emissions are generally related to soil properties, cropping practice, and climate. In this study, field measurements of CH₄ and N₂O emissions were taken in the conventional and organic rice paddies. Nevertheless, the physicochemical properties of soils and climate were comparable between the two experimental fields during the experimental season (Table 1). Differences in seasonal total of CH₄ and N₂O emissions are presumably due to differential cropping practice adopted in conventional and organic rice paddies, rather than soil properties and climate.

The seasonal patterns and intensities of CH₄ and N₂O emissions from conventional rice paddies in this study were generally comparable to earlier measurements in this area (Zheng et al. 2000; Zou et al. 2005a, 2007). In comparison with conventional rice paddies, CH₄ emissions were significantly increased due to pelletized, dehydrated manure application in organic rice paddies (Table 2). Several explanations may be given for the higher CH₄ emissions. First, decomposition of organic matter in rice paddies offered the predominant source of methanogenic substrates, and thus promoted CH₄ production over the rice-growing season. Second, manure application may change soil microbial communities and their activities, which would benefit CH₄ production (Zheng et al. 2007). The DGGE analysis showed that microbial communities, including methanogenic archaea, can change depending on the rice growth and decomposition of organic materials and this explained the difference in CH₄ emissions (Watanabe et al. 2010). Third, carbofuran applied in conventional rice paddies might have decreased CH₄ emissions in this study. It is documented that some chemical insecticides (e.g., carbofuran and endosulfan) significantly inhibited CH₄ production (Kumaraswamy et al. 1998; Bharati et al. 1999), while no significant effects of *B. thuringiensis* (Bt) on soil methanogenic activities and microbial community composition were found in flooded rice soils (Liu et al. 2008). In addition, organic manure contained heavy metals. Some heavy metals (e.g., Mn, Cu) are concerned with methanogenesis, and may serve as a constituent of enzymes used for CH₄ production in rice paddies (Banik et al. 1996; Jiao et al. 2005; Ali et al. 2008).

Nitrous oxide is produced primarily during soil nitrification and denitrification processes, which is highly dependent on water regime in rice paddies (Table 2). Seasonal N₂O emission dependent on water regime in the present study is consistent with previous studies (Cai et al. 1997; Smith et al. 1982; Zheng et al. 2000; Zou et al. 2005a). A significant interaction between cropping system and water regime on N₂O emissions was found in this study ($F_{2,17}=53.7$, $P<0.01$). The fluxes of N₂O were low in continuous flooding rice paddies, which led to no pronounced difference in N₂O emissions between the two cropping systems under

waterlogging (Table 2). In contrast with continuous flooding, midseason drainage in rice paddies triggered substantial N₂O emission. In addition, the dry–wet alteration episodes also incurred substantial N₂O emission, which begets a significant difference in seasonal total of N₂O emissions between the two cropping systems under the water regimes of F-D-F and F-D-F-M.

Under the water regimes of F-D-F and F-D-F-M, seasonal N₂O emissions totaled 0.90–1.30 kg N ha⁻¹, which fairly fall within the range of recent estimates in conventional rice paddies under similar water regimes in this area (Zou et al. 2007, 2009). Relative to conventional rice paddies, seasonal cumulative N₂O emissions from organic rice paddies were 0.31–0.39 kg N ha⁻¹ under the water regimes of F-D-F and F-D-F-M. Several explanations may be given for lower N₂O emissions from organic rice paddies. First, N₂O emissions depended on soil mineral N availability in rice paddies (Liu et al. 2010; Yao et al. 2010). Soil mineral N was expected to be lower in organic rice paddies since mineral N was slowly released from organic manure in organic rice paddies, as compared to direct mineral N inputs in conventional rice paddies. Second, the flux peak of N₂O emissions due to midseason drainage was lower in organic rice paddies than in conventional rice paddies (Figs. 1 and 2). Finally, organic C substrates can enhance soil denitrifier activity and efficiency, which would benefit nitrate finally transformed into N₂ rather than the mid-product of N₂O during the soil denitrification process (Burger et al. 2005; Ndour et al. 2008). In the Kramer et al. (2006) lab and field studies, higher potential denitrification rates and greater denitrification efficiency were observed in organically farmed soils than in conventionally farmed soils.

Relatively, limited literature has compared N₂O emissions from organic and conventional cropping systems. Lower N₂O emissions from organic rice paddies relative to conventional rice paddies with midseason drainage were found in this study, which is consistent with some literature reports (Burger et al. 2005; Petersen et al. 2006; Phillips 2007; Chirinda et al. 2010). In general, lower N₂O emissions from organic cropping systems are attributed to differential soil microbial responses to irrigation management or lower applied N in organic cropping systems than in conventional systems. In contrast, some other studies found comparable or greater N₂O emissions from organic relative to conventional cropping systems (Kaiser and Ruser 2000; Robertson et al. 2000; Syväsalö et al. 2006). Nevertheless, conflicting comparison results of N₂O emissions may due to soil physicochemical properties, soil microorganism communities and cropping practices. For example, it is well documented that N₂O emissions as affected by organic manure amendment were associated with manure particle size, quality and placement (Huang et al. 2004b; Ma et al.

2009). Further research should integrate these factors and eventually study the effect of microbial diversity and presence of nitrifying and denitrifying microorganisms on N_2O evolution.

Typically, GWP estimates should include the net exchange of CO_2 , CH_4 , and N_2O between agroecosystems and atmosphere. Here, we only calculated GWPs (CO_2 -equivalent kg ha^{-1}) using IPCC factors (Forster et al. 2007) to assess the combined climatic impacts from CH_4 and N_2O emissions in organic and conventional rice paddies, while the net exchange of CO_2 between agroecosystems and atmosphere was not taken into account in the present study. However, long-term organic cropping practice did not increase soil organic C contents in rice paddies (13.1 vs. 15.3 g kg^{-1} , Table 1). Compared with conventional rice paddies, organic system is not more beneficial to soil C sequestration in rice paddies, which may be due to several reasons. First, crop biomass was significantly greater, and thereafter crop residue retained in the field would be greater in conventional rice paddies than in organic rice paddies, although there is much organic manure input in organic rice paddies. Second, organic manure with lower C:N ratio (typical 10–20) relative to rice crop residue retained in the soil with higher C:N ratio (typical >30) is more readily decomposed in the soil. Finally, flooding would lower soil CO_2 emissions, and thus benefit soil C accumulation in organic and conventional rice paddies, which may slack the difference in soil C contents between the two cropping systems. Indeed, it is well documented that soil organic C content in Chinese rice paddies has increased in the past several decades, whether or not in conventional, low-tillage or organic rice cropping systems (Huang and Sun 2006; Xie et al. 2007).

Compared with conventional rice paddies, the net GWPs over a 100-year horizon were significantly increased due to greater CH_4 and N_2O emissions in continuously flooded organic rice paddies (Table 2). Under the water regimes of F-D-F-M, the net GWPs did not significantly differ between the two cropping systems due to greater CH_4 emissions but lower N_2O emissions in organic rice paddies than in conventional rice paddies (Table 2). The GHGI relating GWP to grain yield was significantly higher for organic rice paddies relative to conventional rice paddies. Also, comparing the CER between the two cropping system suggests that organic cropping practice would not benefit paddy rice production at the cost of GWP carbon equivalent of CH_4 and N_2O emissions. Overall, organic cropping system might not be an effective option for mitigating the combined climatic impacts from CH_4 and N_2O in paddy rice production. Nevertheless, global extrapolations are limited since the net GWPs from CH_4 and N_2O increased by organic cropping system were found only in the present study. Further studies deserve to be conducted in the future.

Acknowledgments This work was supported by the Special Fund for Basic Scientific Research of Central Colleges, NAU (Y201018), the NSFC (40971140), the FANEDD (200969), and the NCET (08-0798).

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