Journal of Agricultural Science (2016), **154**, 1378–1391.
doi:10.1017/S0021859615001355

CROPS AND SOILS RESEARCH PAPER

Methane and nitrous oxide emissions as affected by long-term fertilizer management from double-cropping paddy fields in Southern China

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(*Received 8 May 2015; revised 29 September 2015; accepted 15 December 2015; first published online 21 January 2016*)

SUMMARY

There is limited information about the influences of long-term fertilizer management on methane (CH_4) and nitrous oxide (N_2O) emissions from double-cropping paddy fields in Southern China. Therefore, the objective of the present study was to characterize the changes of CH_4 and N_2O related to different fertilizer treatments based on a long-term field experiment. The experiment was initiated in 1986 and consisted of five treatments: unfertilized (CK), mineral fertilizer alone (MF), rice residues plus mineral fertilizer (RF), low manure rate plus mineral fertilizer (M1 + F), and high manure rate plus mineral fertilizer (M2 + F). Investigations were conducted over 2 years, from 2013 to 2014, to examine the CH_4 and N_2O emissions from paddy field of Southern China. The results indicated that M2 + F plots had the largest CH_4 emissions during the early rice and late cropped rice and that MF and RF had larger N_2O emissions than CK in both early and late cropped rice. When compared with the control, total N_2O emissions in both rice-growing seasons increased in both MF and RF in 2013 and 2014. The global warming potentials (GWP) from paddy fields were ranked as M2 + F > M1 + F > RF > MF > CK. Meanwhile, the results demonstrated that CH_4 and N_2O emissions were closely associated with the soil redox potential and soil temperature. In summary, the incorporation of rice residues in addition to the use of mineral fertilizer (RF treatment) may be an effective fertilizer management practice for mitigating total GWP per grain yield and maintaining rice grain yield in southern China.

INTRODUCTION

With the current rise in global temperature, numerous studies have focused on greenhouse gas (GHG) emissions (Levy *et al.* 2007; Saggar *et al.* 2007; Hernandez-Ramirez *et al.* 2009). In addition to carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) play important roles in global warming. The global warming potentials (GWP) of CH_4 and N_2O are 25 and 298 times that of CO_2 in a time horizon of 100 years, respectively (Bhatia *et al.* 2005) and their concentrations in the atmosphere are estimated to be increasing at the rates of 1 and 0·2–0·3% per year (Verge *et al.* 2007), respectively. In addition to industrial emissions, farmland and agricultural production are major sources of GHG emission (Wassmann *et al.* 2004; Lokupitiya & Paustian 2006; Verma *et al.* 2006; Liu *et al.* 2008; Tan *et al.* 2009). Numerous findings have indicated that rice (*Oryza sativa* L.) paddy fields are a significant source of CH_4 and N_2O emissions (Tan *et al.* 2009; Kallenbach *et al.* 2010). Thus, the characteristics of CH_4 and N_2O emissions from paddy fields and the reduction of these emissions has received attention from scientists.

A considerable number of studies have shown that some farm operations can influence CH_4 and N_2O emissions. For example, cropping system, crop type, water and nitrogen (N) management, organic matter application and tillage can help to regulate CH_4 and N_2O emissions (Yagi & Minami 1990; Akiyama & Tsuruta 2002; Al-Kaisi & Yin 2005). Cropping system can affect the quality and quantity of crop residues returned to the soil, and eventually influence CH_4 and N_2O emissions (Mosier *et al.* 2006; Sainju *et al.* 2008). Tillage and crop residue (straw) retention have a tremendous influence on CH_4 and N_2O

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emission through the alteration of soil properties (e.g. porosity, temperature, moisture, etc.) (Al-Kaisi & Yin 2005; Yao *et al.* 2009). In paddy soils, CH_4 is produced by archaea bacteria during the anaerobic degradation of organic matter and oxidized by methanotrophic bacteria (Groot *et al.* 2003). Incorporation of organic material into the soil can enhance numbers of archaea bacteria and their activity (Yue *et al.* 2005), and provide large quantities of active organic substrate for CH_4 production (Sethunathan *et al.* 2000). Soil amendment with organic material, such as crop residue (Ma *et al.* 2008) and manure incorporation (Wang *et al.* 2013), has been estimated to promote CH_4 emission in paddy fields. Biogenic N_2O production originates from nitrification and denitrification (Chu *et al.* 2007), which are processes involving soil microorganisms. Some studies have indicated that N fertilization usually stimulates N_2O emissions (Mosier *et al.* 2006; Dusenbury *et al.* 2008; Robertson & Vitousek 2009).

Nitrous oxide and CH_4 emissions are indirectly affected by soil temperature and redox potential (Parkin & Kaspar 2003; Dusenbury *et al.* 2008; Liebig *et al.* 2010). The emission of N_2O and CH_4 has been shown to depend on the atmospheric N-input rate, soil temperature, water content, and the chemical and physical characteristics of the soil (Vor *et al.* 2003). Similarly, cropping sequence and crop species can influence soil temperature by affecting shade intensity and evapotranspiration (Curtin *et al.* 2000; Amos *et al.* 2005). Nitrogen fertilization can reduce soil temperature compared with no N fertilization by increasing shade intensity through increased biomass production (Sainju *et al.* 2008).

The middle and lower Yangtze River Plain is one of the most vital rice production bases in China. Since the 1980s, traditional fertilizer management practices have been altered considerably (Du *et al.* 2009; Tang *et al.* 2014). With the continuous increase of mineral fertilizer application rates, manure inputs have been declining dramatically. Meanwhile, returning crop residue to the field is being accepted gradually. There is a growing concern that the increase of mineral fertilizer application rates may be unsustainable due to their promoting soil CH_4, N_2O emission and decreasing crop yield. The effect of mineral fertilizer alone on CH_4 and N_2O emissions under a barley–double-cropping rice system is still undocumented. In addition, applications of crop residue and manure are viable options for maintaining crop yield, but it is important to monitor CH_4 and N_2O emissions and related microbial activities.

Therefore, the objectives of the current research were to quantify CH_4 and N_2O emissions from a paddy field and rice grain yield with long-term application of crop residue, manure and mineral fertilizer in barley–double-cropping rice systems in Southern China.

MATERIALS AND METHODS

Sites and cropping system

The experiment was established in 1986. It was conducted in Ning Xiang County (28°07′N, 112°18′E; 36 m asl) of Hunan Province, China. Under a continental monsoon climate, the annual mean precipitation is 1553 mm and potential evapotranspiration of 1354 mm. The monthly mean temperature is 17·2 °C. Soil texture in the plough layer (0–20 cm) was silt clay loam with 13·71% sand and 57·73% silt. At the beginning of the study, the surface soil characteristics (0–20 cm) were as follows: soil organic carbon (SOC) 29·4 g/kg, total N 2·0 g/kg, available N 144·1 mg/kg, total phosphorous (P) 0·59 g/kg, available P 12·87 mg/kg, total potassium (K) 20·6 g/kg, and available K 33·0 mg/kg. There were three crops in a year, barley (*Hordeum vulgare* L.), early rice and late rice. Barley was sown in the middle of November and harvested in early May of the following year. Early rice was then transplanted and harvested in the middle of July. The growing season of late transplanted rice lasted from late July to the end of October.

Experimental design

The experiment had five treatments: control (without fertilizer input, CK), mineral fertilizer only (MF), rice residue plus mineral fertilizer (RF), low manure rate plus mineral fertilizer (M1 + F), and high manure rate plus mineral fertilizer (M2 + F). The design ensured all fertilized treatments received the same N rate (the amount of N in mineral fertilizer plus that from rice residue or manure) of 142·5 kg/ha during the early rice growing season and 157·5 kg/ha during the late rice growing season. All the fertilized treatments received the same amount of phosphorus pentoxide (P_2O_5), including the amount of P_2O_5 in mineral fertilizer plus that from rice residue or manure: 54·0 kg/ha during the early rice growing season and 43·2 kg/ha during the late rice growing season. Likewise, all the fertilized treatments received the same amount of potassium oxide (K_2O), constituting the amount of K_2O in mineral fertilizer plus that from rice residue or manure:

63·0 kg/ha during the early rice growing season and 81·0 kg/ha during the late rice growing season. The mineral fertilizers included urea, ordinary superphosphate and potassium chloride. Details about the fertilizer management are listed in Table 1. Before transplanting rice seedlings, air-dried rice residue was manually spread onto the soil surface and incorporated into the soil at a cultivation depth of *c.* 20 cm. For early and late cropped rice, 40 and 30%, respectively, of mineral N fertilizer was applied at seeding and the remaining N fertilizer was applied by top dressing (7–10 days after transplanting) during crop growth. All the P and K fertilizers were applied at seeding. There were three replications and each plot size was 66·7 m^2 (10 × 6·67 m^2). Data for the individual cropping periods investigated in the present study are referred to as 2013 and 2014, respectively.

Collection and measurement of methane and nitrous oxide

Methane and N_2O emitted from paddy fields were collected using the static chamber technique at 09 : 00–11 : 00 h during the early rice and late rice growing seasons. The chamber (80 × 80 × 120 cm^3) was made of 5-mm polyvinyl chloride (PVC) board and a PVC base with a collar. The base had a groove in the collar, into which the sides of the chamber were settled, and inserted into the soil *c.* 5 cm deep with nine rice plants growing inside the base. The groove was 1 cm below the level of the flooded water, and the sides of the chamber were settled into the groove of the collar with water to prevent leakage and gaseous exchange. The chamber contained a small fan for circulating the air, a thermometer sensor and a triple-vent hole. From the second day after transplanting of early or late rice, gases were sampled weekly. Before sampling, the fan in the chamber was switched on to allow even air mixture before extracting the air with a 50-ml syringe at 0, 10, 20 and 30 min after closing the box. The air samples were transferred into 0·5-litre sealed sample bags by rotating the trinal vent hole.

The quantities of CH_4 and N_2O emission were measured with a gas chromatograph (Agilent 7890A, Agilent Technologies Co., Ltd., CA, USA) equipped with flame ionization detector (FID) and electron capture detector (ECD). Methane was separated using a 2-m stainless-steel column with an inner diameter of 2 mm, 13XMS column (60/80 mesh), with FID at 200 °C. Nitrous oxide was separated using a 1-m

Table 1. *Nutrient supply* from rice straw, chicken manure and mineral fertilizer under different fertilizer treatments*

Treatment†	Early rice			Late rice			Total		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
CK	0 + 0	0 + 0	0 + 0	0 + 0	0 + 0	0 + 0	0	0	0
MF	142·5 + 0	54·0 + 0	63·0 + 0	157·5 + 0	43·2 + 0	81·0 + 0	300·0	97·2	144·0
RF‡	124·4 + 18·1	50·4 + 3·6	38·3 + 24·7	133·0 + 24·5	37·8 + 5·4	48·2 + 32·8	300·0	97·2	144·0
M1 + F§	96·0 + 46·5	33·0 + 21·0	33·6 + 29·4	110·2 + 47·3	21·8 + 21·4	51·1 + 29·9	300·0	97·2	144·0
M2 + F#	49·6 + 92·9	12·0 + 42·0	4·2 + 58·8	63·0 + 94·5	0·5 + 42·7	21·2 + 59·8	300·0	97·2	144·0

N, nitrogen; P_2O_5, phosphorus pentoxide; K_2O, potassium oxide; CK, without fertilizer; MF, mineral fertilizer alone; RF, crop residue plus mineral fertilizer; M1 + F, low manure rate plus mineral fertilizer; M2 + F, high manure rate plus mineral fertilizer.

* Input from mineral fertilizer + input from organic fertilizer. The numbers are in kg/ha.

† The N, P and K content of air-dry early rice straw was 6·5, 1·3 and 8·9 g/kg, N, P and K content of air-dry late rice straw was 6·8, 1·5 and 9·1 g/kg, respectively, and N, P and K content of decomposed chicken manure was 17·7, 8·0 and 11·2 g/kg, respectively.

‡ For the RF treatment,the rice straw return rate (air dry) was 2780 and 3600 kg for early and late rice.

§ For the M1 + F treatment, the manure application rate (decomposed) was 2625·0 and 2670·0 kg for early and late rice.

For the M2 + F treatment, the manure application rate (decomposed) was 5250·0 and 5340·0 kg for early and late rice.

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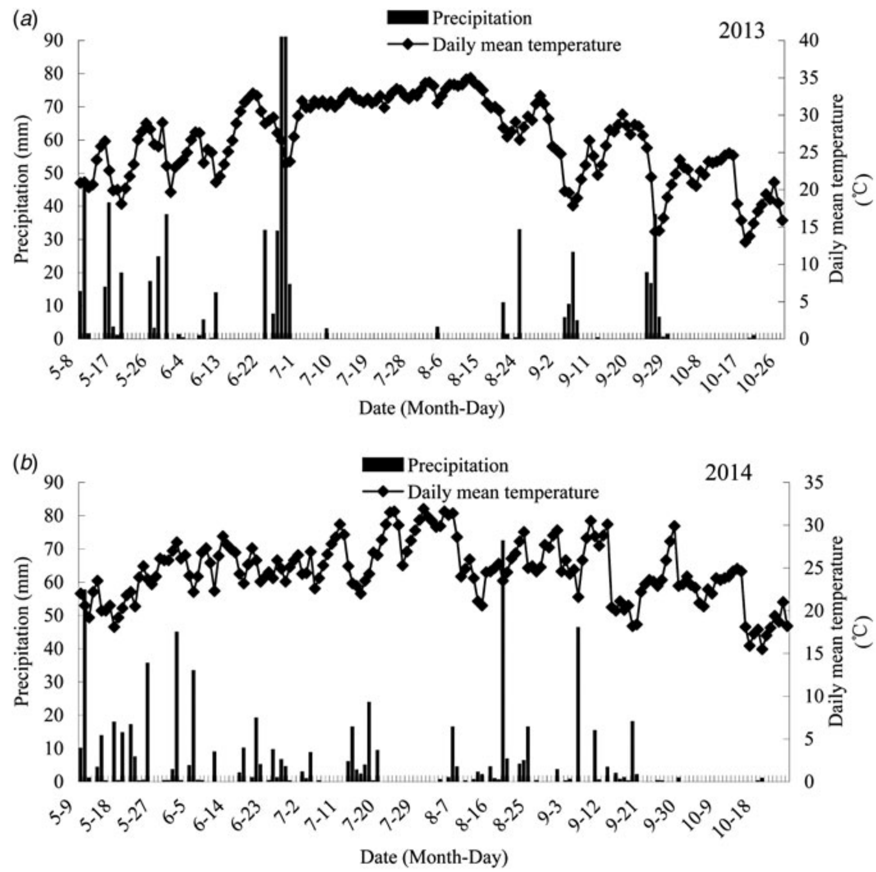

Fig. 1. Daily precipitation and mean temperature during the experimental period at the experimental site.

stainless-steel column with an inner diameter 2 mm, Porapak Q (80/100 mesh) and ECD at 330 °C.

Methane and N_2O fluxes were calculated with the following equation (Liebig *et al.* 2010):

$$F = \rho h[273/(273 + T)]\mathrm{d}C/\mathrm{d}t$$

where F was the CH_4 flux (mg/m^2/h) or N_2O flux (μg/m^2/h); T was the air temperature (°C) inside the chamber; ρ was the CH_4 or N_2O density at standard state (0·714 kg/m^3 for CH_4 and 1·964 kg/m^3 for N_2O); h was the headspace height of the chamber (m); and dC/dt was the slope of the curve of gas concentration variation with time.

The total CH_4 and N_2O emissions were sequentially computed from the emissions between every two adjacent intervals of measurements, based on a non-linear, least-squares method of analysis (Parashar *et al.* 1993; Singh *et al.* 1996).

Global warming potential was defined as the cumulative radiation forcing both direct and indirect effects integrated over a period of time from the emission of a unit mass of gas relative to some reference gas. Carbon dioxide was chosen as the reference gas. The GWP conversion parameters of CH_4 and N_2O (over 100 years) were adopted with 25 and 298 kg CO_2-equivalent/ha (IPCC 2013).

Investigation of soil properties

Soil redox potential (Eh value) and soil temperature were periodically recorded along with gas collection throughout the early rice and late rice cultivation period. The Eh electrode was installed permanently at 10 cm soil depth and measured in each plot using an Eh meter (PRN-40, Fuji-wara Scientific, Japan). Soil temperature was recorded with a thermometer (PC-9125, AS ONE Co., Tokyo, Japan) installed at 10 cm soil depth. Air temperature and rainfall data were obtained from Ning Xiang Meteorological Observatory of Changsha Meteorological Station, China (2·5 km east of the experimental site). The daily precipitation and mean temperature during the experimental period are shown in Fig. 1. The temporal variations of the soil temperature and soil Eh at 10 cm

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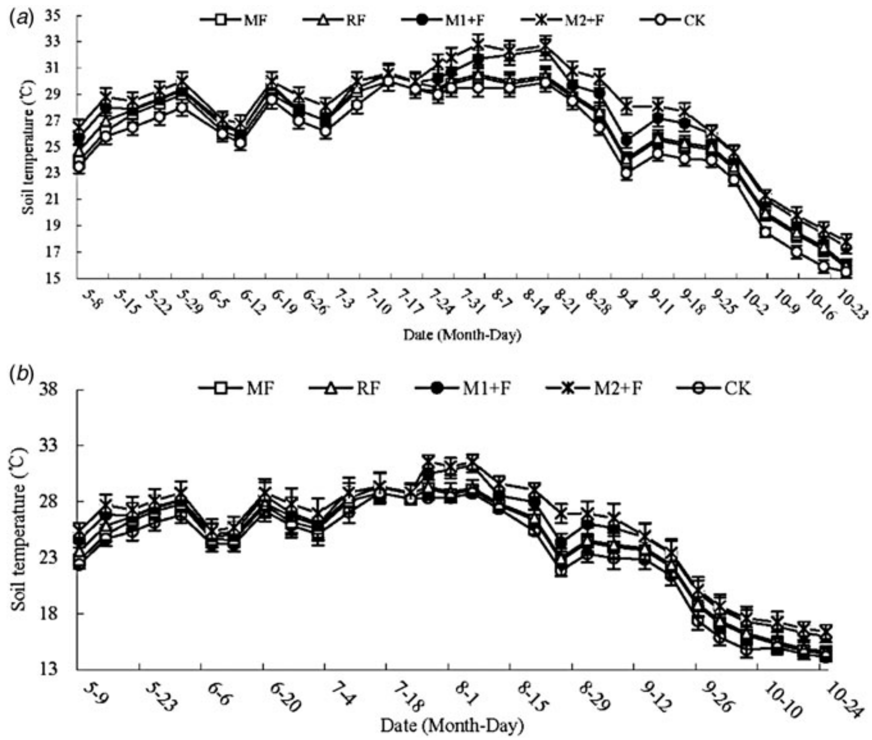

Fig. 2. Soil temperature at 10 cm depth in paddy field during early and late cropped rice in (*a*) 2013 and (*b*) 2014. MF, mineral fertilizer alone; RF, crop residue + mineral fertilizer; M1 + F, low manure rate + mineral fertilizer; M2 + F, high manure rate + mineral fertilizer; CK, without fertilizer. Bars show s.d.

deep during the experimental period are shown in Figs 2 and 3.

Other measurements

Grain yield was determined from a 1 m^2 sampling area at harvest and was expressed as rough (unhulled) rice at 14% moisture content. Above-ground straw yield was determined after drying plant material at 80 °C for 2 days.

Statistical analysis

All data were expressed as mean ± s.e.. The data were analysed as a randomized complete block, using the PROC ANOVA procedure of SAS (SAS Institute 2003). Mean values were compared using the least significant difference test, significant at $P < 0{\cdot}05$.

RESULTS

Methane emission

For the early rice crop the curve of CH_4 flux was low following transplanting but increased quickly until the peak appeared at 24 and 23 days after transplanting in 2013 and 2014, respectively. In both the seasons, there then followed a dramatic decline to a low level (Fig. 4). In the early rice season, the CH_4 flux values were significantly different among treatments of the order of M2 + F > M1 + F > RF > MF > CK ($P < 0{\cdot}05$) (Fig. 4).

Methane emission in the late rice crop was focused mainly at the tillering stage (growth stage (GS) 21–29; Zadoks *et al.* 1974), and the peak value of CH_4 flux was observed at 25 and 24 days after transplanting in all treatments in both years. The emission rate then decreased dramatically to a low and stable level, especially from field drainage to harvest. The order of treatments in CH_4 emission was the same as for the early rice crop. (Fig. 4).

Nitrous oxide emissions

The peak flux of N_2O was emitted when the field was drained. Meanwhile, some N_2O was also emitted during the alternating wetting–drying irrigation period. The first peak value of N_2O flux appeared at 7 days after transplanting in all treatments in both 2013 and 2014, before decreasing. The order among treatments was MF > M2 + F > M1 + F > RF >

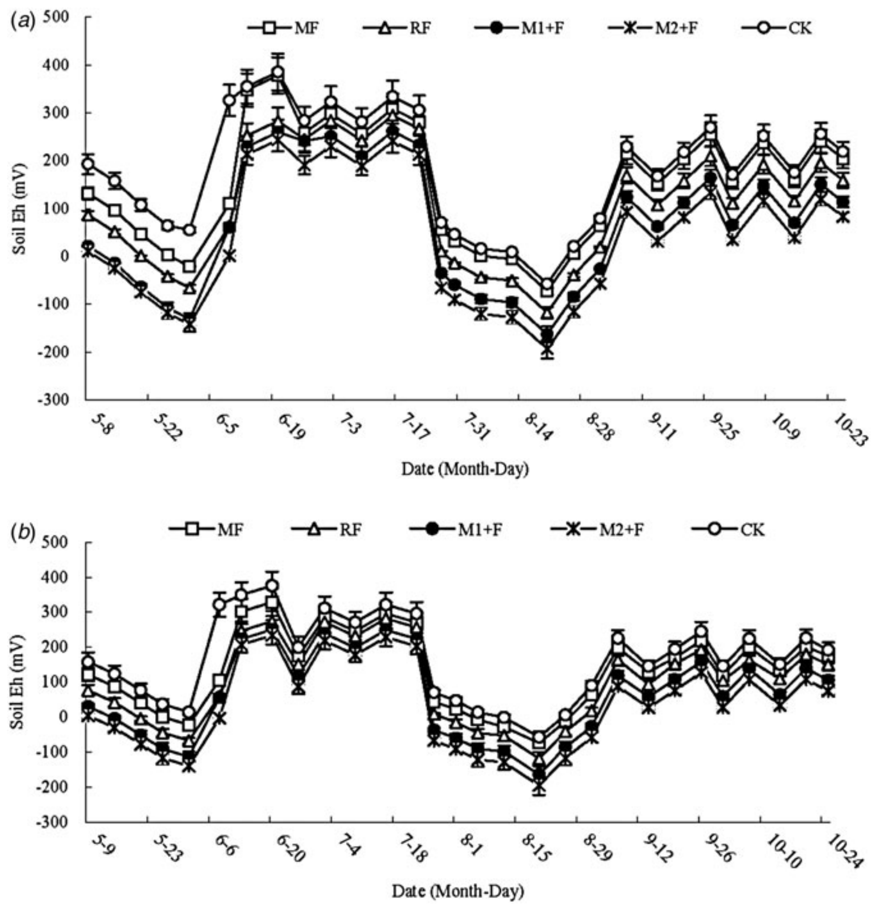

Fig. 3. Soil redox potential (Eh) at 10 cm depth in paddy field during early and late cropped rice in (*a*) 2013 and (*b*) 2014. MF, mineral fertilizer alone; RF, crop residue + mineral fertilizer; M1 + F, low manure rate + mineral fertilizer; M2 + F, high manure rate + mineral fertilizer; CK, without fertilizer. Bars show S.D.

CK during the period from transplanting to field drainage, and RF > M2 + F > M1 + F > M F > CK during the alternating wetting–drying irrigation period. The N_2O flux in early paddy rice reached the highest peak at 37 and 35 days after transplanting in 2013 and 2014, respectively (Fig. 5).

In the late rice crop, N_2O emissions increased from field drainage to full heading stage (GS 50–60), and was mainly focused at the booting stage (GS 41–47). The order of N_2O emission fluxes among different treatments was MF > M2 + F > M1 + F > RF > CK during the period from transplanting to field drainage, and RF > M2 + F > M1 + F > MF > CK during the alternating wetting–drying irrigation period. In 2013, the average N_2O fluxes in the late rice growing season were 20·13, 20·37, 15·44, 17·98 and 11·68 $\mu g/m^2/h$ in MF, RF, M1 + F, M2 + F and CK, respectively. In 2014, the average N_2O fluxes in the late rice growing season were 21·05, 21·33, 18·46, 20·50 and 14·68 $\mu g/m^2/h$ in MF, RF, M1 + F, M2 + F and CK, respectively.

Total methane and nitrous oxide emission from paddy fields of early rice and late rice

The cumulative CH_4 emission of CK was significantly lower than MF, RF, M1 + F and M2 + F during the early rice crop ($P < 0·05$), and the sequence of treatments was M2 + F > M1 + F > RF > MF > CK (Table 2). In 2013, the total CH_4 emissions from paddy fields covering the whole late rice growth cycle were 3·35, 4·27, 5·86, 8·43 and 2·65 g/m^2 in MF, RF, M1 + F, M2 + F and CK, respectively. In 2014, the total CH_4 emissions from paddy fields during the whole late rice growth cycle were 3·21, 3·96, 4·88, 6·10 and 2·55 g/m^2 in MF, RF, M1 + F, M2 + F and CK, respectively. The sequence of treatments with respect to total CH_4 emission was M2 + F > M1 + F > RF > MF > CK (Table 2).

Compared with CK, other treatments increased total N_2O emissions in the early rice crop with emissions increasing by 0·008 g/m^2 (88·89%) in MF, 0·007 g/m^2 (77·78%) in RF, 0·005 g/m^2 (55·56%) in M1 + F and

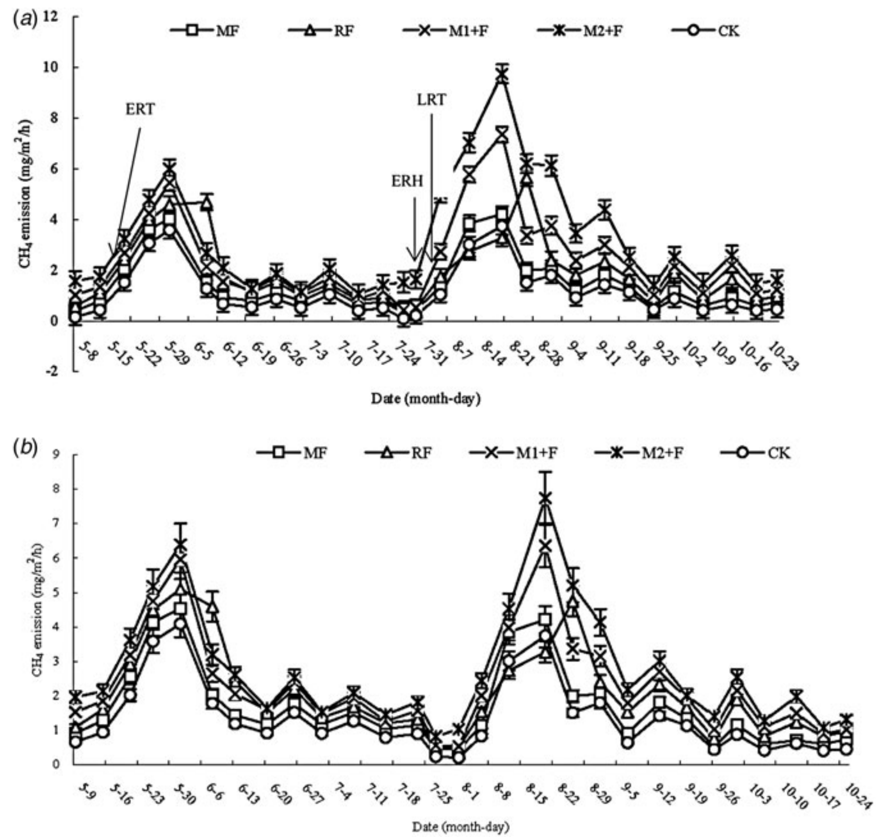

Fig. 4. Methane (CH_4) fluxes from the soils affected by long-term fertilizer management during early and late cropped rice in (*a*) 2013 and (*b*) 2014. MF, mineral fertilizer alone; RF, crop residue + mineral fertilizer; M1 + F, low manure rate + mineral fertilizer; M2 + F, high manure rate + mineral fertilizer; CK, without fertilizer; ERT, early rice transplanting; ERH, early rice harvesting; LRT, late rice transplanting. Methane emission rate is the mean of values measured within each treatment ($n = 3$). Bars show S.D.

0·007 g/m^2 (77·78%) in M2 + F in 2013, and by 0·009 g/m^2 (81·82%) in MF, 0·009 g/m^2 (81·82%) in RF, 0·007 g/m^2 (63·64%) in M1 + F and 0·008 g/m^2 (72·73%) in M2 + F in 2014 (Table 2). Similar results were observed in the late rice crop in both the seasons. Total N_2O emissions increased by 0·053 g/m^2 (151·43%) in MF, 0·052 g/m^2 (148·57%) in RF, 0·039 g/m^2 (111·43%) in M1 + F and 0·047 g/m^2 (134·29%) in M2 + F in 2013, and by 0·055 g/m^2 (127·91%) in MF, 0·055 g/m^2 (127·91%) in RF, 0·047 g/m^2 (109·30%) in M1 + F and 0·053 g/m^2 (123·26%) in M2 + F in 2014 (Table 2).

Global warming potentials of methane and nitrous oxide

Treatment M2 + F had larger total CH_4 emissions than other treatments across the double rice cropping period, while MF and RF had the largest total N_2O emissions with quantities of 0·062 and 0·061 g/m^2 in 2013, and 0·064 and 0·064 g/m^2 in 2014, respectively (Tables 2 and 3).

Global warming potential reflects the relative effect of a GHG, with the GWP of CO_2 being defined as 1. In the present study, the GWP of CH_4 and N_2O from double-cropping paddy fields varied with different fertilizer management, with the trend M2 + F > M1 + F > RF > MF > CK. In 2013, M2 + F had the largest GWP (3320·60 kg CO_2-equivalent/ha) of total CH_4 and N_2O from double-cropping paddy fields, followed by M1 + F (2496·57 kg CO_2-equivalent/ha), RF (2124·63 kg CO_2-equivalent/ha) and CK (1257·93 kg CO_2-equivalent/ha). In 2014, M2 + F again had the largest GWP (2982·57 kg CO_2-equivalent/ha), followed by M1 + F (2521·55 kg CO_2-equivalent/ha), RF (2289·11 kg CO_2-equivalent/ha) and CK (1489·78 kg CO_2-equivalent/ha). According to GWP, the contribution of CH_4 from double-cropping paddy fields to global warming was greater than that of N_2O (Table 3). Double rice grain yield was highest for RF and lowest for CK (Table 3).

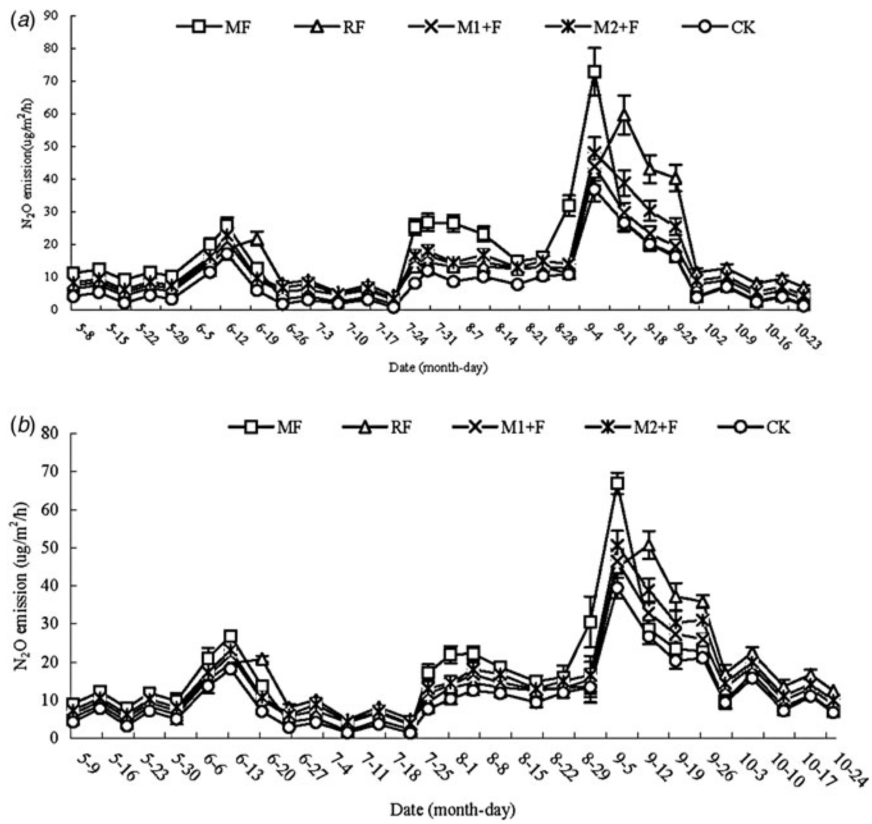

Fig. 5. Nitrous oxide (N_2O) fluxes from the soils affected by long-term fertilizer management during early and late cropped rice in (*a*) 2013 and (*b*) 2014. MF, mineral fertilizer alone; RF, crop residue + mineral fertilizer; M1 + F, low manure rate + mineral fertilizer; M2 + F, high manure rate + mineral fertilizer; CK, without fertilizer; ERT, early rice transplanting; ERH, early rice harvesting; LRT, late rice transplanting. Nitrous oxide emission rate is the mean of values measured within each treatment ($n = 3$). Bars show S.D.

DISCUSSION

Methane emission

Methane emission is a complex process including production, oxidation and emission. Chu *et al*. (2007) reported that N fertilizer application decreased atmospheric CH_4 uptake and resulted in positive emissions from the soil. In the present study, the CH_4 flux and total CH_4 emissions from paddy fields during the early and late cropped rice were much larger in M2 + F, M1 + F and RF compared with CK, which was similar to the results of Wang *et al*. (2013). The reasons for this may be: (i) microbial activities were improved after returning crop residue/manure to the soil, due to the supplementation of carbon (C) sources and energy for microbial activities to accelerate consumption of soil oxygen and decrease soil redox potential (Eh); (ii) methanogens became active due to the large quantities of C sources, which provided reactive substrates for CH_4 emission from paddy fields. Meanwhile, higher CH_4 emission in RF, M1 + F and M2 + F during the early and late cropped rice suggests higher root growth due to increased N supply by mineral fertilizer, manure or crop residue, which probably stimulated the activity of methanogens that produce CH_4. When N was supplied with mineral fertilizer alone, as in the MF treatment, CH_4 emission was probably reduced because of the excessive soil inorganic N level. Reduced root growth due to lower levels of soil inorganic N as a result of the absence of fertilization with organic N probably also reduced methanotroph activity, thereby resulting in lower CH_4 emission in MF. Several researchers (Bronson & Mosier 1994; Powlson *et al*. 1997) have reported that inorganic N fertilization reduced soil CH_4 emission compared with organic N fertilization, while others (Amos *et al*. 2005; Mosier *et al*. 2006) did not observe the effects of N fertilization on emissions.

Methane production has been shown to increase with increasing temperature (Bergman *et al*. 1998), while CH_4 oxidation is less temperature-dependent

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Table 2. *Effects of long-term fertilizer managements on methane (CH_4) and nitrous oxide (N_2O) emission from rice fields during whole growth period of early and late rice (g/m^2)*

		CH_4			N_2O		
Years	Treatment	Early rice	Late rice	Total	Early rice	Late rice	Total
2013	MF	2·30 ± 0·12*	3·40 ± 0·24	5·90 ± 0·36	0·017 ± 0·0011	0·044 ± 0·0014	0·062 ± 0·0023
	RF	3·50 ± 0·10	4·30 ± 0·17	7·80 ± 0·27	0·016 ± 0·0012	0·045 ± 0·0014	0·061 ± 0·0022
	M1 + F	3·50 ± 0·10	5·90 ± 0·12	9·40 ± 0·22	0·014 ± 0·0011	0·034 ± 0·0012	0·048 ± 0·0021
	M2 + F	4·17 ± 0·073	8·43 ± 0·097	12·60 ± 0·17	0·016 ± 0·0012	0·040 ± 0·0013	0·056 ± 0·0018
	CK	1·96 ± 0·057	2·65 ± 0·077	4·60 ± 0·13	0·009 ± 0·0009	0·026 ± 0·0011	0·035 ± 0·0014
2014	MF	3·50 ± 0·15	3·20 ± 0·18	6·70 ± 0·32	0·018 ± 0·0012	0·046 ± 0·0014	0·064 ± 0·0024
	RF	4·40 ± 0·13	4·00 ± 0·14	8·40 ± 0·27	0·018 ± 0·0012	0·047 ± 0·0014	0·064 ± 0·0024
	M1 + F	4·50 ± 0·13	4·91 ± 0·11	9·40 ± 0·24	0·016 ± 0·0011	0·040 ± 0·0012	0·056 ± 0·0023
	M2 + F	5·10 ± 0·10	6·10 ± 0·093	11·20 ± 0·19	0·017 ± 0·0011	0·045 ± 0·0013	0·062 ± 0·0025
	CK	2·89 ± 0·083	2·558 ± 0·074	5·40 ± 0·16	0·011 ± 0·0010	0·032 ± 0·0011	0·043 ± 0·0016

CK, without fertilizer; MF, mineral fertilizer alone; RF, crop residue plus mineral fertilizer; M1 + F, low manure rate plus mineral fertilizer; M2 + F, high manure rate plus mineral fertilizer.
* Values are presented as mean ± s.e. ($n = 3$).

than CH_4 production (Dunfield *et al.* 1993). The higher CH_4 emissions in all treatments may result from higher CH_4 production than the consumption rate under the elevated soil temperature, and could partially explain why CH_4 emissions increased in late rice growth season than that of the early rice growth season. In the present study, CH_4 emissions increased during the early and late cropped rice when soil Eh decreased, and there are differences in CH_4 emissions observed among the different fertilizer management practices. As soil Eh increased during the early and late cropped rice, CH_4 emissions decreased.

Hu *et al.* (2002) similarly observed significant CH_4 emissions in paddy fields and significantly higher CH_4 emissions with N fertilization. In the present study, CH_4 fluxes from the control were low in the early and late cropped rice. When N was supplied jointly by manure, crop residue and mineral fertilizer, such as in M2 + F with high manure rate plus mineral fertilizer, M1 + F with low manure rate plus mineral fertilizer and RF with crop residue plus mineral fertilizer, CH_4 emissions were probably increased because of the high levels of soil organic N. Therefore, during the early and late cropped rice, the CH_4 emission increased gradually with the decomposition of organic matters and growth of rice after transplanting, and reached the peak value at tillering stage in all treatments. However, CH_4 emissions in both rice seasons were reduced to a large extent after field drying, because soil aeration was improved during this period, and the activities of methanogens were therefore restricted, and the physiological activity of rice plants decreased, thereby limiting the ability for transportation and emission of CH_4. Compared with the RF, M1 + F and M2 + F, it was also observed that MF decreased CH_4 emissions from the paddy soil. These results indicated that in paddy soils, where there is high precipitation and high soil temperature, CH_4 production may occur.

Nitrous oxide emission

Nitrous oxide is emitted by soils as a result of denitrification in anaerobic soil and nitrification in aerobic soil, with the anaerobic production considered to be more important. In the present study, N_2O fluxes from the control were lower than those from the organic–inorganic mixed mineral fertilizer treatments throughout the whole experimental period. The greater N_2O flux in MF and RF than in the control during early and late cropped rice, however, probably resulted from increased N substrate availability from both crop residue and mineral fertilizer. Increased N substrate availability due to N fertilization has been known to increase N_2O flux due to enhanced nitrification (Drury *et al.* 2006; Mosier *et al.* 2006; Dusenbury *et al.* 2008). Increased emissions of N_2O from paddy fields by organic–inorganic mixed fertilization management practices have also been reported in other studies (Akiyama *et al.* 2000; Yan *et al.* 2001; Akiyama & Tsuruta 2002; Li *et al.* 2002; Chu *et al.* 2007). In the present study, organic–inorganic mixed

Table 3. *Double rice grain yield, global warming potentials (GWP) of methane (CH_4) and nitrous oxide (N_2O) and per yield GWP from rice fields under long-term fertilizer managements*

Years	Treatment	CH_4 emission (g/m^2)	N_2O emission (g/m^2)	GWP of CH_4 (kg CO_2/ha)	GWP of N_2O (kg CO_2/ha)	GWP of CH_4 and N_2O (kg CO_2/ha)	Early and late rice grain yield (kg/ha)	Per yield GWP CO_2 (kg/kg)
2013	MF	5·90 ± 0·36*	0·06 ± 0·002	1470 ± 91	185 ± 5·3	1655 ± 96	10364 ± 312·5	0·16 ± 0·007
	RF	7·80 ± 0·27	0·06 ± 0·002	1942 ± 68	183 ± 5·3	2125 ± 72	11473 ± 299·2	0·19 ± 0·009
	M1 + F	9·40 ± 0·22	0·05 ± 0·002	2352 ± 56	145 ± 4·8	2497 ± 61	10691 ± 308·6	0·23 ± 0·007
	M2 + F	12·60 ± 0·17	0·06 ± 0·001	3154 ± 43	166 ± 4·2	3321 ± 48	10824 ± 331·2	0·31 ± 0·005
	CK	4·60 ± 0·13	0·04 ± 0·001	1155 ± 33	103 ± 3·0	1258 ± 36	5069 ± 146·3	0·25 ± 0·006
2014	MF	6·70 ± 0·32	0·06 ± 0·002	1673 ± 81	192 ± 5·5	1865 ± 86	10480 ± 318·7	0·18 ± 0·011
	RF	8·40 ± 0·27	0·06 ± 0·002	2098 ± 68	191 ± 5·5	2289 ± 73	12098 ± 302·5	0·19 ± 0·012
	M1 + F	9·40 ± 0·24	0·06 ± 0·002	2354 ± 61	168 ± 5·4	2522 ± 66	10936 ± 315·7	0·23 ± 0·015
	M2 + F	11·20 ± 0·19	0·06 ± 0·002	2797 ± 48	186 ± 4·9	2983 ± 54	11039 ± 349·2	0·27 ± 0·016
	CK	5·4 ± 0·16	0·043 ± 0·001	1361 ± 39·3	129 ± 3·7	1490 ± 43·0	5723 ± 165·2	0·26 ± 0·015

CK, without fertilizer; MF, mineral fertilizer alone; RF, crop residue plus mineral fertilizer; M1 + F, low manure rate plus mineral fertilizer; M2 + F, high manure rate plus mineral fertilizer.

* Values are presented as mean ± S.E. ($n = 3$).

fertilization management practices increased emissions of N_2O during the early and late cropped rice. The greater N_2O flux in M2 + F and M1 + F was probably due to both the organic and the inorganic mineral fertilization and the flux in early and late cropped rice was probably a result of substantial precipitation and/or increased soil temperature. It has been suggested that the accumulation of manure and crop residue material in the soil during growing of early and late rice enhanced N_2O production (Christensen & Christensen 1991).

Several researchers have noted increased N_2O flux immediately after N fertilization and/or substantial precipitation (Mosier *et al.* 2006; Dusenbury *et al.* 2008; Liebig *et al.* 2010). In the present study, greater N_2O flux in MF than in M2 + F, M1 + F and RF during the rice growing season may have resulted from increased N contribution from mineral fertilizer, due to its higher N concentration. Greater N_2O flux in M2 + F, M1 + F and RF than in the control during the early and late cropped rice may have resulted either from increased N contribution from crop residue due to the higher N concentration in RF and increased organic N mineralization due to manure application during rice growing season in M2 + F and M1 + F. The reasons for greater N_2O flux in M2 + F, M1 + F and RF in late rice growth period were also likely to be a result of increased microbial activity and soil temperature. Meanwhile, compared with M1 + F, the greater N_2O flux in M2 + F with high manure rate plus mineral fertilizer probably resulted from increased N substrate availability from both high manure and mineral fertilizer. Increased N substrate availability due to N fertilization has been confirmed to increase N_2O flux due to enhanced nitrification (Drury *et al.* 2006; Mosier *et al.* 2006; Dusenbury *et al.* 2008).

Effects of methane and nitrous oxide flux factors

A considerable number of studies have shown that some soil or environmental factors can influence CH_4 and N_2O emission. For example, CH_4 and N_2O production is regulated by vegetation type, soil temperature, soil moisture, root activity and many other factors (Parkin & Kaspar 2003; Wassmann *et al.* 2004; Ma *et al.* 2008; Kallenbach *et al.* 2010), and soil temperature, soil moisture and soil Eh have been determined to be the most crucial regulators (Kudo *et al.* 2014). Yu *et al.* (2007) reported that CH_4 emission showed an exponential decrease when Eh increased. In the present study, during the early and late cropped rice, the soil Eh rapidly increased simultaneously with rapid CH_4 emission decrease. In the present study, crop residues and manure were incorporated into the soil in the RF, M1 + F, M2 + F treatments and their decomposition consumed limited soil-dissolved oxygen. All these factors resulted in decreased Eh and consequently increased CH_4 emission under RF, M1 + F and M2 + F.

The soil temperature had a predictive functional relationship with CH_4 emission. Khalil *et al.* (1998) observed an increase in CH_4 emissions from paddy fields with increasing soil temperature and Zhu *et al.* (2007) reported a strong correlation between CH_4 emission and soil temperature. The current results also found that there was a relationship between CH_4 emission and soil temperature, with soil temperature found to be a major factor affecting CH_4 emission. In general MF decreased soil temperature, especially during the hotter days, and this may have been partly responsible for lower CH_4 emissions when compared with other treatments. Temperature was also the major reason for differences in the CH_4 emission pattern between the early and late cropped rice. In the current experimental area, the late rice season was the hottest time of the summer and high temperatures enhanced the decomposition rate of crop residues and manure in the moist environment. During decomposition, a large number of organic compounds are produced and oxygen is consumed, thus decreasing soil Eh and leading to increased CH_4 emission. In contrast to the warm temperatures of the late rice season, air temperatures in the early rice season were lower, which resulted in slower crop residue and manure decomposition and therefore little CH_4-substrate. Hence, these differences in weather factors (e.g. temperature) resulted in the different characteristics of CH_4 between the early and late cropped rice.

The N_2O emission was influenced strongly by external factors and many emission peaks occurred during the rice growing season. The emission of N_2O was different between the early and late cropped rice, possibly due to the variations in weather. Some studies show that extreme precipitation and drying could increase N_2O emission (Zona *et al.* 2011). Hao *et al.* (2001) reported that aeration and water flooding led to 'outbreaks' of emissions. In the present study, precipitation in the early rice growing season was much higher than that in the late season. This precipitation difference may explain the fluctuations of N_2O emissions between the seasons.

In addition, similar to CH_4, N_2O emission is also influenced by soil Eh. Weier *et al.* (1993) reported that the rate of N_2O emission decreased with increasing soil reducibility. In the present study, crop residues and manure in RF, M1 + F, M2 + F were mainly distributed within the plough layer (0–20 cm) and had a strong redox potential due to decomposition of crop residues and manure. Therefore, compared with the MF, N_2O produced from RF, M1 + F, M2 + F soils tended to be further deoxidized to nitrogen gas (N_2), which consequently decreased N_2O emission. Meanwhile, the greater N_2O flux in the late rice growing season than in the season was probably due to increased soil temperature, since increased temperature can stimulate microbial activity and N mineralization (Parkin & Kaspar 2003; Dusenbury *et al.* 2008; Liebig *et al.* 2010).

Global warming potentials of methane and nitrous oxide

Global warming potential can be used as an index to estimate the potential effects of different GHGs on the global climate system. Tang *et al.* (2014) estimated that GWP of double-cropping rice systems increased through the return of straw from winter cover crops. Zhu *et al.* (2012) reported that the highest GWP was found for incorporation of Chinese milk vetch in a double-cropping rice system, which was 21–325% higher than the other treatments they studied. In the present study, the GWP of CH_4, N_2O or both had different orders. For a comprehensive consideration, GWP of both CH_4 and N_2O is an important method to assess the effect of a farming system on climate warming. Therefore, it is necessary to make a combined estimate of global warming effects of CH_4 and N_2O emitted from each treatment. Thus, GWP and GWP per yield were introduced into the present study for global warming calculations. It was found that the CH_4 and N_2O GWP for M2 + F and M1 + F were higher than for RF and MF, due to their greater CH_4 emissions. Manure and crop residue addition increased early and late rice grain production compared with the control. Therefore, the control without fertilizer may mitigate GHG emissions but may not sustain rice yields. The total of early and late rice production was significantly higher in the M2 + F, M1 + F and RF than in the control, but the GWP per yield of RF was significantly lower than the control, M2 + F and M1 + F. Therefore, application of the crop residue and mineral fertilizer pattern is recommended for double-cropping rice areas in the Middle and Lower reaches of Yangtze River in China, which corresponds to RF as a management option under an intensive cropping system. Further studies are under way to examine whether RF with reduced N fertilization rate might mitigate GHG emissions and sustain crop yields. Other benefits of applying crop rotation rather than mono-cropping include reduced infestation of weeds, diseases and pests. However, for evaluating the GWP of management systems, it would be mandatory to consider the soil C dynamics associated with crop production inputs and machinery use.

CONCLUSIONS

Greenhouse gas emissions from large paddy fields and excessive fertilizer application can contribute significantly to global warming. Managing fertilizer application is one of the feasible ways of limiting GHG emissions from paddy areas. Low fertilizer application results in low-energy consumption, which can contribute to the reduction of GHG and lessen global warming. The current results show that mineral fertilizer application stimulates N_2O emission during the early and late cropped rice. Meanwhile, the results indicate that with the same N application rate, different organic–inorganic mixed fertilizer application, such as RF, M1 + F and M2 + F, caused substantial CH_4 emissions during the early and late cropped rice compared with those from the conventional MF treatment. However, it significantly increased rice grain yields in both RF, M1 + F and M2 + F production systems. The GWP of both CH_4 and N_2O resulted in a significantly lower yield-scaled GWP compared with the control treatments. The increased use of organic inputs greatly affected CH_4 and N_2O emission; however, the inputs were necessary for maintaining soil fertility and are a crucial source of nutrient input for small-scale farmers in paddy fields who cannot rely solely on mineral fertilizer. The combined use of organic inputs and mineral fertilizer is therefore suggested as a potential for intensifying rice production in paddy soil under intensive cropping systems. Nevertheless, future research is necessity to provide a complete insight into the effects of recently developed practices on soil C dynamics.

This study was supported by the National Natural Science Foundation of China (Grant numbers 31201178 and 31571591) and technology innovation platform project of Hunan Province.

REFERENCES

AKIYAMA, H. & TSURUTA, H. (2002). Effect of chemical fertilizer form on N_2O, NO and NO_2 fluxes from Andisol field. *Nutrient Cycling in Agroecosystems* **63**, 219–230.

AKIYAMA, H., TSURUTA, H. & WATANABE, T. (2000). N_2O and NO emissions from soils after the application of different chemical fertilizers. *Chemosphere – Global Change Science* **2**, 313–320.

AL-KAISI, M. M. & YIN, X. (2005). Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn–soybean rotation. *Journal of Environmental Quality* **34**, 437–445.

AMOS, B., ARKEBAUER, T. J. & DORAN, J. W. (2005). Soil surface fluxes of greenhouse gases in an irrigated maize-based agroecosystem. *Soil Science Society of America Journal* **69**, 387–395.

BERGMAN, I., SEVENSSON, B. O. H. & NILSSON, M. (1998). Regulation of methane production in a Swedish acid mire by pH, temperature and substrate. *Soil Biology & Biochemistry* **30**, 729–741.

BHATIA, A., PATHAK, H., JAIN, N., SINGH, P. K. & SINGH, A. K. (2005). Global warming potential of manure amended soils under rice-wheat system in the Indo-Gangetic plains. *Atmospheric Environment* **39**, 6976–6984.

BRONSON, K. F. & MOSIER, A. R. (1994). Suppression of methane oxidation in aerobic soil by nitrogen fertilizers, nitrification inhibitors, and urease inhibitors. *Biology and Fertility of Soils* **17**, 263–268.

CHRISTENSEN, S. & CHRISTENSEN, B. T. (1991). Organic matter available for denitrification in different soil fractions: effect of freeze/thaw cycles and straw disposal. *Journal of Soil Science* **42**, 637–647.

CHU, H. Y., HOSEN, Y. K. & YAGI, K. Y. (2007). NO, N_2O, CH_4 and CO_2 fluxes in winter barley field of Japanese Andisol as affected by N fertilizer management. *Soil Biology & Biochemistry* **39**, 330–339.

CURTIN, D., WANG, H., SELLES, F., MCCONKEY, B. G. & CAMPBELL, C. A. (2000). Tillage effects on carbon fluxes in continuous wheat and fallow-wheat rotations. *Soil Science Society of America Journal* **64**, 2080–2086.

DRURY, C. F., REYNOLDS, W. D., TAN, C. S., WELACKY, T. W., CALDER, W. & MCLAUGHLIN, N. B. (2006). Emissions of nitrous oxide and carbon dioxide: influence of tillage type and nitrogen placement depth. *Soil Science Society of America Journal* **70**, 570–581.

DU, Z. L., LIU, S. F., XIAO, X. P., YANG, G. L. & REN, T. S. (2009). Soil physical quality as influenced by long-term fertilizer management under an intensive cropping system. *International Journal of Agricultural and Biological Engineering* **2**, 19–27.

DUNFIELD, P., KNOWLES, R., DUMONT, R. & MOORE, T. R. (1993). Methane production and consumption in temperate and subarctic peat soils: response to temperature and pH. *Soil Biology & Biochemistry* **25**, 321–326.

Dusenbury, M. P., Engel, R. E., Miller, P. R., Lemke, R. L. & Wallander, R. (2008). Nitrous oxide emissions from a northern Great Plains soil as influenced by nitrogen management and cropping systems. *Journal of Environmental Quality* **37**, 542–550.

Groot, T. T., Van Bodegom, P. M., Harren, F. J. M. & Meijer, H. A. J. (2003). Quantification of methane oxidation in the rice rhizosphere using ^{13}C-labelled methane. *Biogeochemistry* **64**, 355–372.

Hernandez-Ramirez, G., Brouder, S. M., Smith, D. R. & Van Scoyoc, G. E. (2009). Greenhouse gas fluxes in an eastern corn belt soil: weather, nitrogen source, and rotation. *Journal of Environmental Quality* **38**, 841–854.

Hao, X., Chang, C., Carefoot, J. M., Janzen, H. H. & Ellert, B. H. (2001). Nitrous oxide emissions from an irrigated soil as affected by fertilizer and straw management. *Nutrient Cycling in Agroecosystems* **60**, 1–8.

Hu, R., Hatano, R., Kusa, K. & Sawamoto, T. (2002). Effect of nitrogen fertilization on methane flux in a structured clay soil cultivated with onion in central Hokkaido, Japan. *Soil Science and Plant Nutrition* **48**, 797–804.

IPCC (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the IPCC* (Eds. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex & P. M. Midgley). Cambridge, UK and New York, NY: Cambridge University Press.

Kallenbach, C. M., Rolston, D. E. & Horwath, W. R. (2010). Cover cropping affects soil N_2O and CO_2 emissions differently depending on type of irrigation. *Agriculture, Ecosystems & Environment* **137**, 251–260.

Khalil, M. A. K., Rasmussen, R. A., Shearer, M. J., Chen, Z. L., Yao, H. & Yang, J. (1998). Emissions of methane, nitrous oxide, and other trace gases from rice fields in China. *Journal of Geophysical Research: Atmospheres* **103**, 25241–25250.

Kudo, Y. K., Noborio, K. K., Shimoozono, N. & Kuriharab, R. K. (2014). The effective water management practice for mitigating greenhouse gas emissions and maintaining rice yield in central Japan. *Agriculture, Ecosystems & Environment* **186**, 77–85.

Levy, P. E., Mobbs, D. C., Jones, S. K., Milne, R., Campbell, C. & Sutton, M. A. (2007). Simulation of fluxes of greenhouse gases from European grasslands using the DNDC model. *Agriculture, Ecosystems & Environment* **121**, 186–192.

Li, X., Inubushi, K. & Sakamoto, K. (2002). Nitrous oxide concentrations in an Andisol profile and emissions to the atmosphere as influenced by the application of nitrogen fertilizers and manure. *Biology and Fertility of Soils* **35**, 108–113.

Liebig, M. A., Tanaka, D. L. & Gross, J. R. (2010). Fallow effects on soil carbon and greenhouse gas flux in central North Dakota. *Soil Science Society of America Journal* **74**, 358–365.

Liu, H., Zhao, P., Lu, P., Wang, Y. S., Lin, Y. B. & Rao, X. Q. (2008). Greenhouse gas fluxes from soils of different land-use types in a hilly area of South China. *Agriculture, Ecosystems & Environment* **124**, 125–135.

Lokupitiya, E. & Paustian, K. (2006). Agricultural soil greenhouse gas emissions: a review of national inventory methods. *Journal of Environmental Quality* **35**, 1413–1427.

Ma, J., Xu, H., Yagi, K. & Cai, Z. C. (2008). Methane emission from paddy soils as affected by wheat straw returning mode. *Plant and Soil* **313**, 167–174.

Mosier, A. R., Halvorson, A. D., Reule, C. A. & Liu, X. J. (2006). Net global warming potential and greenhouse gas intensity in irrigated cropping systems in northeastern Colorado. *Journal of Environmental Quality* **35**, 1584–1598.

Parashar, D. C., Gupta, P. K., Rai, J., Sharma, R. C. & Singh, N. (1993). Effect of soil temperature on methane emission from paddy field. *Chemosphere* **26**, 247–250.

Parkin, T. B. & Kaspar, T. C. (2003). Temperature controls on diurnal carbon dioxide flux: Implications for estimating soil carbon loss. *Soil Science Society of America Journal* **67**, 1763–1772.

Powlson, D. S., Goulding, K. W. T., Willison, T. W., Webster, C. P. & Hutsch, B. W. (1997). The effect of agriculture on methane oxidation in soil. *Nutrient Cycling in Agroecosystems* **49**, 59–70.

Robertson, G. P. & Vitousek, P. M. (2009). Nitrogen in agriculture: balancing the cost of an essential resource. *Annual Review of Environment and Resources* **34**, 97–125.

Saggar, S., Hedley, C. B., Giltrap, D. L. & Lambie, S. M. (2007). Measured and modelled estimates of nitrous oxide emission and methane consumption from a sheep-grazed pasture. *Agriculture, Ecosystems & Environment* **122**, 357–365.

Sainju, U. M., Jabro, J. D. & Stevens, W. B. (2008). Soil carbon dioxide emission and carbon content as affected by irrigation, tillage, cropping system, and nitrogen fertilization. *Journal of Environmental Quality* **37**, 98–106.

SAS Institute (2003). *SAS Version 9.1·2 2002–2003*. Cary: NC, USA: SAS Institute Inc.

Sethunathan, N., Kumaraswamy, S., Rath, A. K., Ramakrishnan, B., Satpathy, S. N., Adhya, T. K. & Rao, V. R. (2000). Methane production, oxidation, and emission from Indian rice soils. *Nutrient Cycling in Agroecosystems* **58**, 377–388.

Singh, J. S., Singh, S., Raghubanshi, A. S., Singh, S. & Kashyap, A. K. (1996). Methane flux from rice/wheat agroecosystem as affected by crop phenology, fertilization and water level. *Plant and Soil* **183**, 323–327.

Tan, Z., Liu, S., Tieszen, L. L. & Tachie-Obeng, E. (2009). Simulated dynamics of carbon stocks driven by changes in land use, management and climate in a tropical moist ecosystem of Ghana. *Agriculture, Ecosystems & Environment* **130**, 171–176.

Tang, H. M., Xiao, X. P., Tang, W. G., Wang, K., Sun, J. M., Li, W. Y. & Yang, G. L. (2014). Effects of winter cover crops straws incorporation on CH_4 and N_2O emission from double-cropping paddy fields in southern China. *PLoS ONE* **9**, e108322. DOI: 10.1371/journal.pone.0108322

Verge, X. P. C., de Kimpe, C. & Desjardins, R. L. (2007). Agricultural production, greenhouse gas emissions and mitigation potential. *Agricultural and Forest Meteorology* **142**, 255–269.

Verma, A., Tyagi, L., Yadav, S. & Singh, S. N. (2006). Temporal changes in N_2O efflux from cropped and fallow agricultural fields. *Agriculture, Ecosystems & Environment* **116**, 209–215.

Vor, T., Dyckmans, J., Loftfield, N., Beese, F. & Flessa, H. (2003). Aeration effects on CO_2, N_2O, and CH_4 emission and leachate composition of a forest soil. *Journal of Plant Nutrition and Soil Science* **166**, 39–45.

Wang, J. Y., Chen, Z. Z., Ma, Y. C., Sun, L. Y., Xiong, Z. Q., Huang, Q. W. & Sheng, Q. R. (2013). Methane and nitrous oxide emissions as affected by organic–inorganic mixed fertilizer from a rice paddy in southeast China. *Journal of Soils and Sediments* **13**, 1408–1417.

Wassmann, R., Neue, H. U., Ladha, J. K. & Aulakh, M. S. (2004). Mitigating greenhouse gas emissions from rice–wheat cropping systems in Asia. *Environment, Development & Sustainability* **6**, 65–90.

Weier, K. L., Doran, J. W., Power, J. F. & Walters, D. T. (1993). Denitrification and the dinitrogen/nitrous oxide ratio as affected by soil water, available carbon, and nitrate. *Soil Science Society of America Journal* **57**, 66–72.

Yagi, K. & Minami, K. (1990). Effect of organic matter application on methane emission from some Japanese paddy fields. *Soil Science and Plant Nutrition* **36**, 599–610.

Yan, X., Hosen, Y. & Yagi, K. (2001). Nitrous oxide and nitric oxide emissions from maize field plots as affected by N fertilizer type and application method. *Biology and Fertility of Soils* **34**, 297–303.

Yao, Z., Zheng, X., Xie, B., Mei, B., Wang, R., Butterbach-Bahl, K., Zhu, J. & Yin, R. (2009). Tillage and crop residue management significantly affects N-trace gas emissions during the non-rice season of a subtropical rice–wheat rotation. *Soil Biology & Biochemistry* **41**, 2131–2140.

Yue, J., Shi, Y., Liang, W., Wu, J., Wang, C. R. & Huang, G. H. (2005). Methane and nitrous oxide emissions from rice field and related microorganism in black soil, northeastern China. *Nutrient Cycling in Agroecosystems* **73**, 293–301.

Yu, K., Böhme, F., Rinklebe, J., Neue, H. U. & DeLaune, R. D. (2007). Major biogeochemical processes in soils – a microcosm incubation from reducing to oxidizing conditions. *Soil Science Society of America Journal* **71**, 1406–1417.

Zadoks, J. C., Chang, T. T. & Konzak, C. F. (1974). A decimal code for the growth stages of cereals. *Weed Research* **14**, 415–421.

Zhu, B., Yi, L. X., Hu, Y. G., Zeng, Z. H., Tang, H. M., Yang, G. L. & Xiao, X. P. (2012). Effects of Chinese Milk Vetch (*Astragalus sinicus* L.) residue incorporation on CH_4 and N_2O emission from a double-rice paddy soil. *Journal of Integrative Agriculture* **11**, 1537–1544.

Zhu, R., Liu, Y., Sun, L. & Xu, H. (2007). Methane emissions from two tundra wetlands in eastern Antarctica. *Atmospheric Environment* **41**, 4711–4722.

Zona, D., Janssens, I. A., Verlinden, M. S., Broeckx, L. S., Cools, J., Gioli, B., Zaldei, A. & Ceulemans, R. (2011). Impact of extreme precipitation and water table change on N_2O fluxed in a bio-energy poplar plantation. *Biogeosciences* **8**, 2057–2092.