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RESEARCH ARTICLE

Greenhouse gas emissions, soil quality, and crop productivity from a mono-rice cultivation system as influenced by fallow season straw management

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Abstract Straw management during fallow season may influence crop productivity, soil quality, and greenhouse gas (GHG) emissions from rice field. A 3-year field experiment was carried out in central China to examine the influence of different fallow season straw management practices on rice yield, soil properties, and emissions of methane (CH_4) and nitrous oxide (N_2O) from a mono-rice cultivation system. The treatments comprised an unfertilized control (CK), inorganic fertilization (NPK), rice straw burning in situ (NPK+RSB), rice straw mulching (NPK+RSM), and rice straw strip mulching with green manuring (NPK+RSM+GM). The maximum rice yield, soil organic carbon, soil total nitrogen, and available potassium were observed in NPK+RSM+GM treatment. Compared with NPK, the NPK+RSM+GM recorded 9 % higher grain yield averaged across 3 years. However, NPK+RSM and NPK+RSB were statistically similar with NPK regarding grain yield. The NPK+RSM and NPK+RSM+GM recorded significantly higher CH_4 emission during rice growing season as well as winter fallow; however, the response of N_2O emissions was variable. The NPK+RSM and NPK+RSM+GM were statistically similar for annual cumulative CH_4 and N_2O emissions. The NPK+RSM+GM recorded 103 and 72 % higher straw-induced net economic benefits and soil organic carbon sequestration rate, and reduced net global warming potential by 27 % as compared with NPK+RSM. Considering the benefits of soil fertility, higher crop productivity, and environmental safety, the NPK+RSM+GM could be the most feasible and sustainable option for mono-rice cultivation system in central China.

Keywords Global warming potential · Greenhouse gas emissions · Rice productivity · Soil organic carbon · Straw management · Winter fallow

Introduction

Rice (*Oryza sativa* L.) is the most prominent cereal crop and the staple food for more than half of the world's population. Annually, it is grown on approximately 153 million hectares worldwide comprising 11 % of total arable lands (FAO 2011). China is one of the leading producers of rice contributing more than 28 % of total global rice production; therefore, stability of rice production in China is critical for global food security (FAO 2011; Liu et al. 2015). The global demand for rice is predicted to increase by 24 % in the next 20 years (Van Nguyen and Ferrero 2006), which necessitates amid global efforts to increase rice production in order to ensure food security.

Rice is considered as the one of the major causes for greenhouse gas (GHG) emissions in agriculture, as rice fields contribute about 30 and 11 % of global agricultural methane (CH_4) and nitrous oxide (N_2O) emissions, respectively (IPCC 2007). The global warming potential (GWP) of CH_4 and N_2O is 25 and 298 times higher than that of carbon

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dioxide, respectively (IPCC 2007). The CH_4 production occurs by organic matter decomposition in anoxic flooded rice cultures by the process of methanogenesis. On the other hand, N_2O is produced by the microbial transformation of nitrogen (N) in soils and manures and often boosted with the availability of excess N particularly under wet conditions (Chen et al. 1997; Zou et al. 2007, 2009).

In rice fields, the emissions of CH_4 and N_2O mainly depend on crop management practices like irrigation, soil tillage, fertilizer application, and organic additives; therefore, changes in these management practices also offer possibilities for mitigation (Hussain et al. 2015). In paddy fields, fluxes of CH_4 and N_2O emissions often remain complex due to trade-off between these two gases. Therefore, an overall balance between the net gas exchange is often expressed as global warming potential (GWP) of the system based on CO_2 equivalent (Shang et al. 2011).

With the gradual decrease of organic manure application, rice soils mainly depend upon straw recycling to overcome C losses caused by harvesting of crop and soil cultivation (Singh et al. 2005; Zhang et al. 2012). Moreover, plantation of winter green manure crops like Chinese milk vetch (*Astragalus sinicus* L.) is also common particularly in rice cultivation system. The available reports of organic additives on GHG emissions in paddy soils are more conflicting. Soil amendment with organic additives, such as crop residue (Ma et al. 2008) and green manure incorporation (Lee et al. 2010), has been reported to increase CH_4 emission in paddy soils. Xiong et al. (2002) also observed higher N_2O emissions when Chinese milk vetch residue and inorganic N were applied together. A meta-analysis of 26 long-term paddy field experiments concluded that the rice straw retention increased the soil organic carbon (SOC) by 0.41 t ha^{-1} $year^{-1}$ (Rui and Zhang 2010). Nevertheless, the soil incorporation of rice straw may also lead to enhanced CH_4 emissions from flooded rice fields, thus contributing to global warming (IPCC 2001). Crop residue amendment can mitigate GHG emissions due to increase in SOC (Verma and Bhagat 1992; Jensen 1997). It also accelerates higher CH_4 emissions under flooded paddy fields as residue provides readily available C and N (Xu et al. 2000; Zhang et al. 2011) and tends to reduce (Zou et al. 2005) or stimulate (Liang et al. 2007) N_2O emissions. Although burning of rice straw is a common practice as it ensures the quick seedbed preparation to farmers, incomplete C combustion adversely affects air quality and enhances GHG emissions (Beri et al. 1995; Khaliq et al. 2013; Hussain et al. 2015). In addition, burning of straw also results in losses of N (up to 80 %), phosphorus (25 %), potassium (21 %), and sulfur (4–60 %) depriving soils of organic matter and causes air pollution (CO_2 13 t ha^{-1}) (Mandal et al. 2004). Mineral N application can also increase (e.g., Lindau et al. 1991; Li et al. 2012) or decrease (Zou et al. 2005) CH_4 emissions or has no effects (Hou et al. 2000). But, it leads to a proportionate increase in N_2O emissions because of enhanced N availability (Xing et al. 2002). To reduce CH_4 emission, straw incorporation in winter instead of that in the rice growth season (Xu et al. 2000), or partial or complete strip mulching onto the field surface (Harada et al. 2005; Ma et al. 2009) has been recommended. Aerobic conditions and low temperature during decomposition of straw are the possible reasons for lower CH_4 emission from winter straw incorporation (Ma et al. 2009; Hussain et al. 2015).

However, few studies have examined the effects of fallow season straw management especially the combined effects of rice straw recycling and green manuring on crop productivity and annual GHG emissions in a mono-rice cultivation system. Therefore, the present study was conducted, (a) to ascertain the influence of different fallow season straw management practices on soil physico-chemical properties and productivity of rice, (b) to quantify CH_4 and N_2O emissions over the whole annual cycle of rice–fallow system including winter fallow period, land preparation period before rice transplantation, and rice growing period, (c) to evaluate the net global warming potential (NGWP) and net economic benefits (NBEs) of different straw management practices in mono-rice cultivation system of central China, and (d) to identify the most feasible and adoptable treatment that can improve crop productivity and soil health along with mitigating GHG emission.

Materials and methods

Site description

The present study was conducted at the Agricultural Research Station in Datonghu Administration District, Jingzhou City, Hubei Province (30° 05′ N, 113° 45′ E), China. The region belongs to Jianghan Plain with an altitude of 24 m above sea level and has subtropical humid climate. The annual mean temperature is 17.2 °C, and the average annual precipitation is 1446 mm over the last 30 years. About 70 % of precipitation occurs between March and August. The monthly precipitation and mean air temperature during the 3 experiment years from October 2010 to September 2013 are presented in Fig. 1. Soil of the experimental field was derived from alluvial sediments of Yangtze River and classified as fluvo-aquic soil with a silty clay loam texture. The basic physico-chemical properties of experimental soil at 0–20-cm depth were as follows: pH (1:2.5 H_2O) 7.84, soil organic carbon 18.25 g kg^{-1}, total N 1.97 g kg^{-1}, available P (Olsen extractable) 5.22 mg kg^{-1},

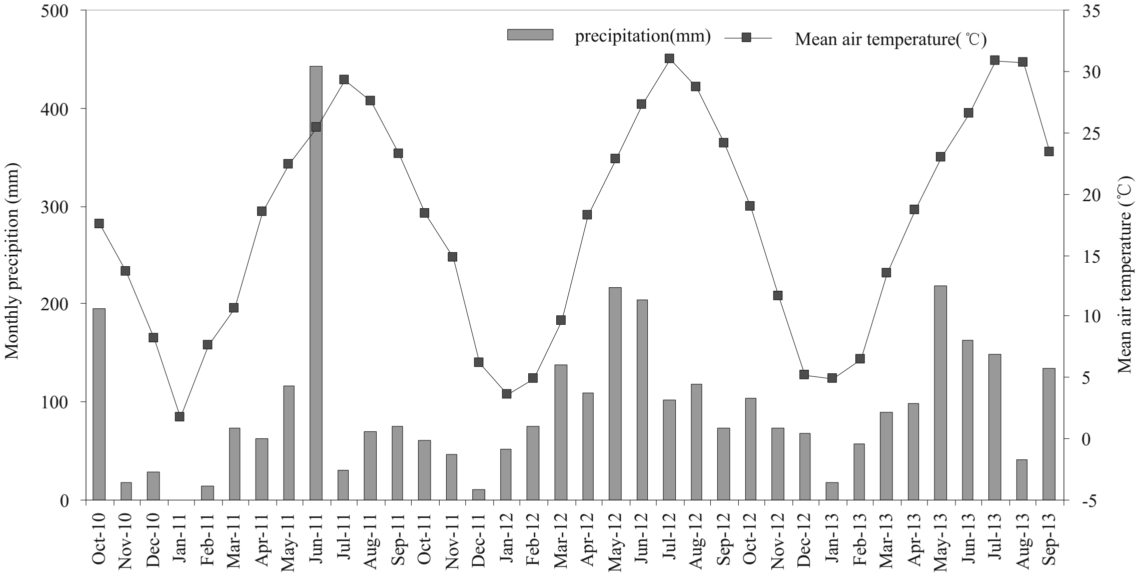

Fig. 1 Mean monthly precipitation and air temperature during the three annual experiment periods from 2010 to 2013 at the experiment site

available K (NH_4OAc extractable) 101.69 mg kg^{-1}, and soil bulk density 1.218 g cm^{-3}.

Experimentation

The proposed study was laid out in a randomized complete block design replicated three times, and the area of each experimental plot was 20 m^2 (4 m×5 m). The experiment was comprised of five treatments as follows: (1) CK [control; without any fertilizers and straw amendments], (2) NPK [without straw amendments, local recommended dose of chemical fertilizer (165 kg N ha^{-1}, 45 kg P_2O_5 ha^{-1}, and 75 kg K_2O ha^{-1}) was applied in rice growing season], (3) NPK+RSB [rice straw burning in situ during fallow season, recommended dose of chemical fertilizer was applied in rice growing season], (4) NPK+RSM [rice straw mulching in the fallow season, recommended dose of chemical fertilizer was applied in rice growing season], and (5) NPK+RSM+GM [rice straw strip mulching, and Chinese milk vetch was planted during the fallow season, recommended dose of chemical fertilizer was applied in rice growing season]. In NPK+RSB, NPK+RSM, and NPK+RSM+GM treatments, an equal amount of rice straw at 8.65 t ha^{-1} on dry weight (equivalent to the total amount of previously harvested rice straw yield) was either burnt or applied as surface mulch after harvesting. In NPK+RSM+GM plots, seed of Chinese milk vetch was broadcasted at the rate of 30 kg ha^{-1} in late September of each year. The aboveground fresh yield of Chinese milk vetch was 11.38±0.74, 12.43±0.59, and 14.28±0.19 t ha^{-1} during 2011, 2012, and 2013, respectively. The mean N, P, and K contents in rice straw were 0.60, 0.06, and 2.79 %, and in fresh Chinese milk vetch were 0.37, 0.02, and 0.40 %, respectively. The respective C/N ratios of rice straw and Chinese milk vetch were 49.49 and 17.88. In rice growing season, the same amount of fertilizer was applied in all the plots except CK according to the local recommended practice. The basal chemical fertilizers applied 1 day before rice transplanting were 82.5 kg N ha^{-1} (in the form of urea), 45 kg P_2O_5 ha^{-1} (in the form of super phosphate), and 37.5 kg K_2O ha^{-1} (in the form of potassium chloride). Tillering fertilizer (41.25 kg N ha^{-1}) was applied about 2 weeks after rice transplanting and panicle fertilizer (41.25 kg N ha^{-1}, 37.5 kg K_2O ha^{-1}) on 5 weeks after rice transplanting.

Consistent with local farmers' practice, all plots were ploughed in early May of each year, and about 2 weeks later, the land was harrowed and puddled. Rotary tillage concomitant with basal fertilizer for rice transplanting was carried out. Thirty-day-old rice seedlings (cv. *Huaan 3*) were transplanted at hill spacing of 16.7 cm×20 cm with two seedlings per hill. During the winter fallow season, the fields were naturally drained. Before land preparation (at end of April), the rain water was conserved in the field. During the rice growing season, the water regime was under the flooding–midseason drainage–reflooding–moist by intermittent irrigation but without waterlogged conditions (F-D-F-M) mode. The fields were irrigated after every 5–7 days during the rice growing season except at the midseason drainage (about 4 to 5 weeks after rice transplanting) and maturity (2 weeks prior to rice harvesting). The detailed schedule of field operations during the entire experiment is shown in Table 1.

CH_4 and N_2O measurements

The CH_4 and N_2O emissions were measured from May 2011 to April 2013 using the static closed chamber method. Before the field was initially flooded in May 2011, a PVC frame with

Table 1 Field operations during the three annual experiment periods from 2010 to 2013

Field operations	Year		
	2010–2011	2011–2012	2012–2013
Straw management	1 October 2010	20 September 2011	2 September 2012
Winter fallow period	1 October 2010–3 May 2011	19 September 2011 to 3 May 2012	1 September 2012 to 2 May 2013
Field tillage	4 May 2011	4 May 2012	3 May 2013
Land preparation period	4 May to 1 June 2011	4 May to 19 May 2012	3 May to 18 May 2013
Basal fertilizer application	1 June 2011	19 May 2012	18 May 2013
Rice transplantation	2 June 2011	20 May 2012	19 May 2013
Tillering fertilizer application	18 June 2011	2 June 2012	30 May 2013
Midseason drainage	1–8 July 2011	20–24 June 2012	12–19 June 2013
Panicle fertilizer application	9 July 2011	8 July 2012	20 June 2013
Final drainage	1 September 2011	18 August 2012	16 August 2013
Grain harvesting	18 September 2011	30 August 2012	1 September 2013
Rice growing period	2 June to 18 September 2011	20 May to 30 August 2012	19 May to 1 September 2013
Gas collection		4 May 2011 to 28 April 2013	

a groove (for water filling to seal the rim of the chamber) was permanently fixed in a random site for each plot. The static chamber with 60-cm diameter and 60- or 120-cm height (depending of rice plant height) was made of 0.5-mm stainless steel and was wrapped with a layer of sponge and aluminum foil to minimize air temperature changes inside the chamber during sampling. Two small fans were installed on the top of the chamber to ensure an even mixing of air in the chamber. Gas samples were collected at 8:30 a.m. to 11:30 a.m., at 3–7-day intervals during the land preparation period before rice transplanting (P_{BRT}) and the rice growing period (P_{R}), and about 7–14-day intervals during the period of winter fallow (P_{WF}). A 60-mL plastic syringe fitted with three-way stopcock was used to extract air at 0-, 10-, 20-, and 30-min intervals and 0-, 7-, 14-, and 21-min intervals after closing the chamber in 2011–2012 and 2012–2013, respectively. The collected gas samples were transferred into 40-mL air-evacuated glass vials sealed with butyl rubber septum. The gas samples of CH_4 and N_2O concentrations were analyzed with a modified gas chromatograph (Agilent 7890, USA) equipped with a flame ionization detector (FID) and an electron capture detector (ECD). The CH_4 was detected by FID, while N_2O was detected by ECD. The oven temperature was controlled at 55 °C, and the temperatures of the FID and ECD were set at 200 and 330 °C, respectively (Wang and Wang 2003).

Soil sampling and analysis

The top soil (0–20-cm depth) from experimental field was sampled prior to experimentation. Moreover, soil samples from the upper layer (0–20-cm depth) of each plot were also collected after rice harvesting in each year. Soil was analyzed for basic physico-chemical properties using the procedures as described in Bao (2000). Briefly, the soil bulk density was determined using cylinders of 100 cm^{-3} in volume. The soil pH was measured with distilled water at a volume ratio of 1:2.5 (soil-to-water ratio) using a pH detector. The soil organic carbon (SOC) was measured by wet digestion with H_2SO_4-$K_2Cr_2O_7$. Total N was determined by semi-micro Kjeldahl digestion using Se, $CuSO_4$, and K_2SO_4 as catalysts. Available P was recorded by extracting samples with 0.5 mol L^{-1} $NaHCO_3$ and determining P colorimetrically using molybdate. Available K was measured by extracting soil with a solution of 1 mol L^{-1} NH_4OAc (1:10, soil to solution *v*/*v*) at 25 °C and determined by a flame photometer (FP640).

Data analysis

The fluxes of CH_4 and N_2O were calculated using the following equations:

$$F = \rho \times H \times \frac{\Delta c}{\Delta t} \times \frac{273}{T}$$

where F is the CH_4 flux (mg CH_4-C m^{-2} h^{-1}) or N_2O flux (μg N_2O-N m^{-2} h^{-1}), ρ is the gas density of CH_4 or N_2O at standard state (mg cm^{-3}), H is the height of the chamber (m), $\Delta c/\Delta t$ is the rate of CH_4 or N_2O gas accumulation in the chamber (mg m^{-3} h^{-1} for CH_4, μg m^{-3} h^{-1} for N_2O), and T is the absolute temperature (273+mean temperature in the chamber, °C).

The seasonal cumulative emissions of CH_4 and N_2O from different periods were calculated from the emissions averaged on every two adjacent intervals of the measurements.

The soil organic carbon density (SOCD, kg C ha^{-1}) and the soil organic carbon sequestration rate (SOCSR, kg C ha^{-1} year^{-1}) were computed according to the following equation:

$$SOCD = SOC \times \rho \times \mathrm{H} \times 10,000$$

$$SOCSR = \frac{SOCD2013 - SOCD2010}{T}$$

where SOC refers to the soil organic carbon content (g kg^{-1}), ρ is the soil bulk density (g cm^{-3}), and H is the depth of the plough horizon (0.2 m). $SOCD_{2013}$ and $SOCD_{2010}$ refer to the SOCD in 2013 and the initial year, respectively, and T (3 years) refers to the duration of experiment. Global warming potential (GWP, kg CO$_2$-eq ha^{-1} year^{-1}), the net global warming potential (NGWP, kg CO$_2$-eq ha^{-1} year^{-1}), and the straw-induced net economic benefits (NEB, RMB year^{-1}) were calculated by using the following equations as described by Xia et al. (2014):

$$GWP = 25 \times CH_4 + 298 \times N_2O$$

$$NGWP = GWP - SOCSR \times \frac{44}{12}$$

$$GWP\ \text{straw-induced} = GWP\ \text{NPK} + \text{RSB or NPK} + \text{RSM or NPK} + \text{RSM} + \text{GM} - GWP\ \text{NPK}$$

$$SOCSR\ \text{straw-induced} = SOCSR\ \text{NPK} + \text{RSB or NPK} + \text{RSM or NPK} + \text{RSM} + \text{GM} - SOCSR\ \text{NPK}$$

$$NGWP\ \text{straw-induced} = NGWP\ \text{NPK} + \text{RSB or NPK} + \text{RSM or NPK} + \text{RSM} + \text{GM} - NGWP\ \text{NPK}$$

$$NEB\ \text{straw-induced} = RGYC\ \text{straw-induced} \times 3.0 - NGWP\ \text{straw-induced} \times 24.0$$

where RGYC is the straw-induced rice grain yield change (kg ha^{-1}), 3.0 RMB kg^{-1} is for the rice grain price, and 24.0 RMB Mg^{-1} CO$_2$-eq is for the carbon price in this region (http://www.tanpaifang.com/).

Statistical analysis

Data were statistically analyzed following analysis of variance using SPSS 11.5 analytical software package (Statistical Graphics Corp., Princeton NJ, USA). The mean value±standard error (SE) and least significant difference (LSD) at the 0.05 probability level were calculated for comparison of the treatment means.

Results

Rice yield and soil properties

The rice grain yield (Table 2) was significantly ($P<0.05$) higher in all the soil amendment treatments (NPK, NPK+RSB, NPK+RSM, and NPK+RSM+GM) compared with CK during 3 years. When compared with NPK, the rice grain yield in NPK+RSM and NPK+RSM+GM treatments was increased by 5.4 and 6.0 % in 2011, 3.9 and 13.4 % in 2012, and 4.8 and 7.1 % in 2013, respectively (Table 2). Averaged across 3 years, the NPK+RSM+GM outperformed all other treatments regarding rice grain yield. Compared with those in NPK, rice grain yields in NPK+RSB treatment were slightly reduced in 2011 by 4.8 %, but increased by 4.4 % in 2012, and 5.1 % in 2013, respectively. Nonetheless, these two treatments were statistically similar in 3 years for rice grain yield (Table 4).

Compared with CK, all the soil amendment treatments significantly ($P<0.05$) increased the soil available P and soil available K contents after rice harvest during 3 years (Table 2). The NPK+RSM+GM treatment recorded the highest SOC and total N contents than all other treatments. Compared with CK, the NPK+RSM+GM treatment increased the SOC and total N content by 6.5 and 7.8 % in 2011, 8.5 and 7.3 % in 2012, and 9.9 and 8.8 % in 2013 and decreased the soil bulk density by 0.034 g cm^{-3} in 2011, 0.040 g cm^{-3} in 2012, and 0.030 g cm^{-3} in 2013. In 2011, the NPK+RSM was statistically similar ($P>0.05$) with CK regarding SOC and total N content; nevertheless, in 2012 and 2013, both of these attributes were significantly ($P<0.05$) increased in NPK+RSM compared with the CK (Table 2). The NPK+RSB treatment did not influence SOC and total N contents but significantly ($P<0.05$) increased the soil pH. However, the other treatments, viz., NPK, NPK+RSM, and NPK+RSM+GM, were statistically similar ($P>0.05$) with CK regarding soil pH in 3 years (Table 2).

CH_4 and N_2O emissions

Consistent with local farmers' practice, our observations of two annual cycles on CH$_4$ and N$_2$O emissions consisted of three parts (Table 1): the land preparation period before rice transplantation (P_{BRT}; 29 vs. 15 days in 2011 and 2012, respectively), rice growing period (P_R; 108 vs. 102 days in 2011

Table 2 Effect of different fallow season straw management treatments on rice yield and soil quality in 2011, 2012, and 2013

Year	Treatment	Grain yield (t ha^{-1})	SOC (g kg^{-1})	Total N (g kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})	pH (1:2.5 H_2O)	Bulk density (g cm^{-3})
2011	CK	5.00±0.14 d	18.55±0.26 b	1.93±0.02 bc	4.71±0.12 b	83.65±3.81 c	7.92±0.06 b	1.225±0.004 a
	NPK	8.57±0.16 bc	18.84±0.14 ab	1.92±0.05 c	5.92±0.51 a	93.32±1.80 b	7.99±0.03 ab	1.219±0.008 a
	NPK+RSB	8.15±0.17 c	19.02±0.44 ab	1.95±0.01 bc	6.36±0.33 a	102.69±4.23 a	8.08±0.04 a	1.203±0.008 a
	NPK+RSM	9.02±0.19 ab	19.20±0.16 ab	2.06±0.04 ab	6.36±0.47 a	96.19±0.91 ab	7.95±0.04 b	1.205±0.013 a
	NPK+RSM+GM	9.08±0.14 a	19.76±0.38 a	2.08±0.06 a	6.32±0.32 a	100.67±0.95 ab	7.98±0.04 ab	1.191±0.022 a
2012	CK	4.54±0.21 c	18.30±0.05 c	1.93±0.04 b	4.31±0.23 b	82.59±1.83 c	7.93±0.01 b	1.222±0.005 a
	NPK	8.46±0.29 b	19.00±0.05 bc	1.97±0.03 b	5.17±0.24 ab	89.98±3.81 b	7.92±0.03 b	1.208±0.010 ab
	NPK+RSB	8.83±0.20 b	19.12±0.33 ab	1.96±0.03 b	5.58±0.48 a	99.51±1.06 a	8.06±0.01 a	1.197±0.009 ab
	NPK+RSM	8.79±0.14 b	19.65±0.29 ab	2.07±0.02 a	5.24±0.14 a	95.91±0.92 a	7.87±0.04 b	1.185±0.010 b
	NPK+RSM+GM	9.59±0.10 a	19.86±0.37 a	2.10±0.03 a	5.51±0.20 a	96.90±0.77 a	7.91±0.03 b	1.182±0.005 b
2013	CK	3.87±0.27 c	18.34±0.15 d	1.94±0.02 d	4.05±0.32 c	82.05±0.91 c	7.76±0.01 b	1.223±0.002 a
	NPK	8.70±0.20 b	19.06±0.10 bc	2.02±0.01 bc	5.01±0.22 b	92.57±1.05 b	7.76±0.03 b	1.207±0.006 ab
	NPK+RSB	9.09±0.26 a	18.91±0.20 cd	1.97±0.02 cd	5.65±0.23 ab	97.80±2.77 ab	7.88±0.02 a	1.200±0.009 b
	NPK+RSM	9.12±0.13 a	19.69±0.17 ab	2.07±0.04 ab	5.84±0.27 a	94.66±2.77 b	7.70±0.04 b	1.199±0.006 b
	NPK+RSM+GM	9.32±0.10 a	20.16±0.33 a	2.11±0.03 a	5.69±0.15 ab	103.56±3.66 a	7.74±0.03 b	1.193±0.003 b

The soil samples were collected from the depth of 0–20 cm. Values are presented as mean±SE (n=3); different letters in the same column indicate significant differences at $P<0.05$ level

CK no straw return or chemical fertilizers applied; *NPK* no straw return, chemical N, P, and K fertilizers applied in rice growing season; *NPK+ RSB* rice straw burning in situ after rice harvest and chemical fertilizers applied in rice growing season; *NPK+ RSM* rice straw mulching in winter fallow then incorporated into soil before rice transplantation, and chemical fertilizers applied in rice growing season; *NPK+ RSM+ GM* rice straw strip mulching plus green manuring in winter fallow then incorporated into soil before rice transplantation, and chemical fertilizers applied in rice growing season; *SOC* soil organic carbon

and 2012, respectively), and the period of winter fallow (P_{WF}; 227 vs. 240 days in 2011–2012 and 2012–2013, respectively).

As apparent from Fig. 2, the net CH_4 fluxes were prominent during the P_{BRT} and P_{R} (May to August/September) but negligible during the P_{WF} (October to April). In both years, higher CH_4 emission peaks were observed in middle May (about 7–14 days after land preparation), and in the early growth stage of rice. Afterward, the CH_4 emission was lower except at the heading stage of rice growth. During the 2011 and 2012 P_{BRT}, the CH_4 fluxes from all the treatments ranged from 0.10 to 18.27 mg CH_4-C m^{-2} h^{-1} and 0.07 to 57.79 mg CH_4-C m^{-2} h^{-1}, respectively (Fig. 2). During the P_{R}, the CH_4 fluxes from all the treatments ranged from −0.16 to 29.78 mg CH_4-C m^{-2} h^{-1} in 2011 and 0.06 to 96.61 mg CH_4-C m^{-2} h^{-1} in 2012, respectively. During the 2011–2012 and 2012–2013 P_{WF}, the CH_4 fluxes ranged from −0.91 to 3.40 mg C m^{-2} h^{-1} and −0.89 to 17.84 mg C m^{-2} h^{-1}, respectively. In both years, the highest CH_4 flux during P_{BRT} was recorded in NPK+RSM+GM. However, during P_{R} and P_{WF}, the highest CH_4 flux was observed in NPK+RSM treatment, followed by NPK+RSM+GM.

The seasonal CH_4 emissions varied significantly ($P<0.05$) under the influence of different soil amendment treatments and the year (Table 3). The average CH_4 emissions were significantly lower in the 2011 P_{R} and 2011–2012 P_{WF} than in the 2012 P_{R} and 2012–2013 P_{WF}, respectively. Annual cumulative CH_4 emissions in 2011–2012 cycle was ranked in the order of NPK+RSM> NPK+RSM+GM>NPK>NPK+RSB>CK. Likewise, in the 2012–2013 cycle, annual cumulative CH_4 emissions followed almost a similar trend, NPK+RSM>NPK+RSM+GM>NPK>CK>NPK+RSB. No significant variations were observed among CK, NPK, and NPK+RSB treatments regarding annual cumulative CH_4 emissions in both years. The NPK+RSM and NPK+RSM+GM treatments had significantly higher annual cumulative CH_4 emissions compared with CK, NPK+RSB, and NPK treatments in both years (Table 3).

The pattern of seasonal variations in N_2O flux rates from the paddy soil was different from that of the CH_4 flux, in which sporadic and pulse-like emissions were observed (Fig. 2). Prominent N_2O emission peaks were observed immediately after soil preparation, after the midseason drainage, and at final drainage (rice harvest stage). The highest N_2O flux in both annual cycles was observed in the NPK+RSM+GM plot, which was recorded as 84.90 μg N_2O-N m^{-2} h^{-1} immediately after soil preparation in 2011–2012 cycle and 78.70 μg N_2O-

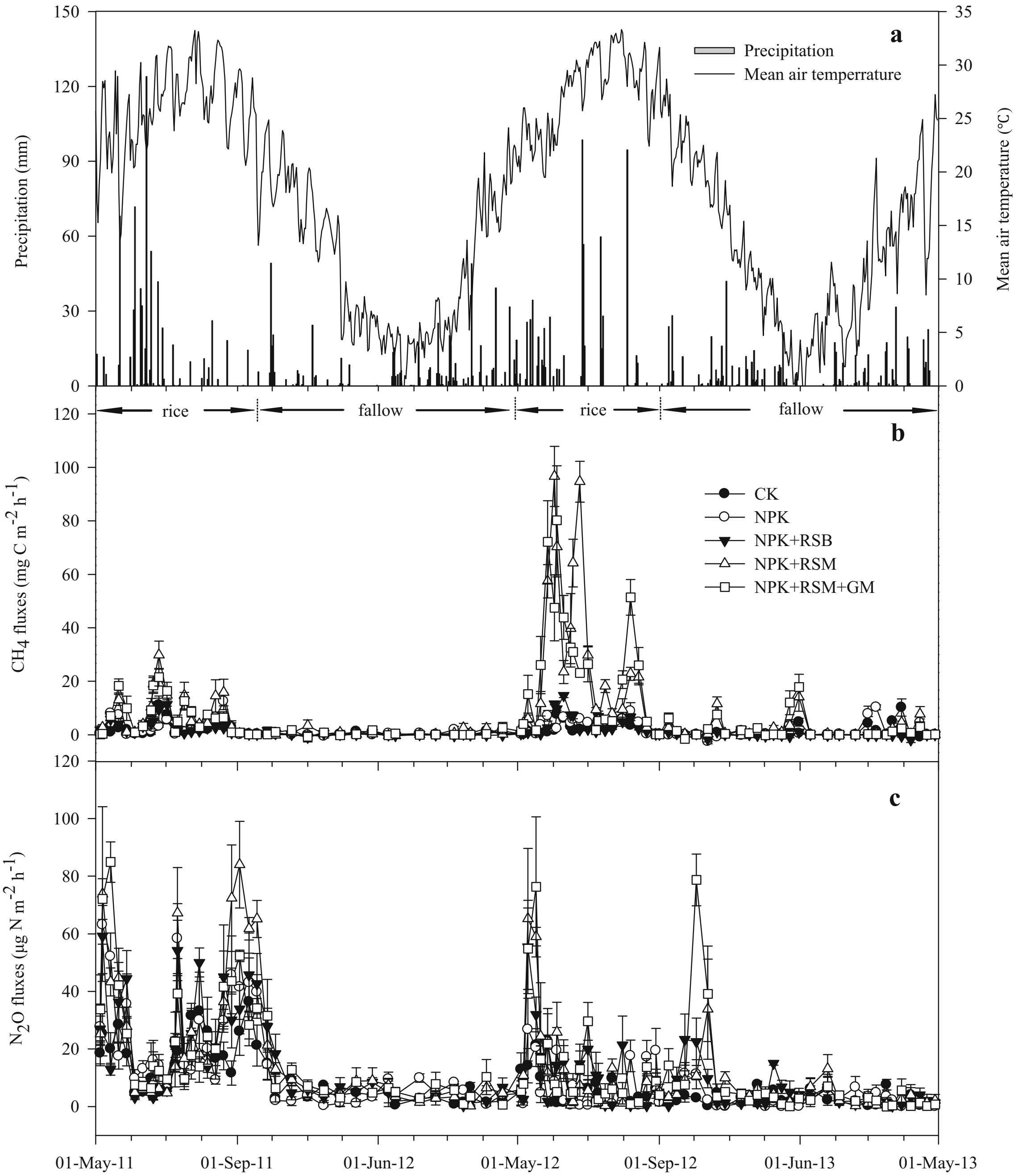

Fig. 2 Daily mean air temperature and precipitation (**a**), seasonal variations of CH_4 (**b**) and N_2O (**c**) emission fluxes over the two annual cycles from 2011 to 2013 under different straw management practices. *CK*: no straw return or chemical fertilizers applied; *NPK*: no straw return, chemical N, P, and K fertilizers applied in rice growing season; *NPK+ RSB*: rice straw burning in situ after rice harvest and chemical fertilizers applied in rice growing season; *NPK+RSM*: rice straw mulching in winter fallow then incorporated into soil before rice transplantation, and chemical fertilizers applied in rice growing season; *NPK+RSM+GM*: rice straw strip mulching plus green manuring in winter fallow then incorporated into soil before rice transplantation, and chemical fertilizers applied in rice growing season. *Vertical bars* represent standard errors of the three replicates

N m^{-2} h^{-1} at the beginning of winter fallow period in 2012–2013 cycle.

Annual cumulative N_2O emissions in 2011–2012 were 1.57–3.11 times greater than those in 2012–2013 (Table 3). In 2011–2012 cycle, the annual cumulative N_2O emissions ranked in the order of NPK+RSB>NPK+RSM>NPK+RSM+GM>NPK>CK. While during 2012–2013 cycle, the annual cumulative N_2O emissions were in the order of NPK+RSM+GM>NPK+RSM>NPK+RSB>NPK>CK. Averaged across two annual cycles, the annual cumulative N_2O emissions

Table 3 Cumulative CH_4 and N_2O emissions from different straw management treatments during the land preparation period before rice transplanting (P_{BRT}), the periods of rice growing (P_R), and winter fallow (P_{WF}) in the two annual cycles of 2011–2012 and 2012–2013

Season	Treatment	CH_4 emission (kg CH_4-C ha^{-1})				N_2O emission (kg N_2O-N ha^{-1})			
		P_{BRT}	P_R	P_{WF}	Total	P_{BRT}	P_R	P_{WF}	Total
2011–2012	CK	10.08±1.41	73.62±12.46	1.45±0.31	85.15±13.96	0.16±0.03	0.46±0.05	0.19±0.04	0.81±0.05
	NPK	28.21±3.78	72.85±10.03	1.55±0.57	102.61±12.65	0.28±0.02	0.63±0.02	0.28±0.05	1.19±0.04
	NPK+RSB	22.83±7.29	74.66±15.96	1.80±0.86	99.30±8.11	0.25±0.02	0.62±0.05	1.23±0.29	2.10±0.33
	NPK+RSM	38.49±3.38	208.20±12.96	12.60±3.88	259.28±15.89	0.31±0.03	0.77±0.05	0.57±0.04	1.66±0.06
	NPK+RSM+GM	58.23±8.81	170.53±6.44	9.52±1.62	238.28±7.32	0.38±0.02	0.59±0.01	0.60±0.09	1.57±0.08
2012–2013	CK	3.25±0.44	61.65±12.90	31.15±3.46	96.05±15.19	0.06±0.01	0.14±0.02	0.17±0.01	0.36±0.02
	NPK	2.59±0.31	82.06±15.21	31.75±5.28	116.40±15.39	0.06±0.02	0.17±0.02	0.20±0.03	0.43±0.06
	NPK+RSB	3.24±0.66	80.71±6.13	5.21±2.64	89.16±9.28	0.12±0.02	0.25±0.04	0.29±0.03	0.66±0.04
	NPK+RSM	15.44±3.59	449.02±26.86	64.38±5.18	528.84±29.68	0.17±0.03	0.24±0.07	0.32±0.02	0.73±0.05
	NPK+RSM+GM	33.86±19.80	416.09±10.50	62.70±10.53	512.65±19.69	0.18±0.01	0.32±0.12	0.46±0.06	0.96±0.14
Mean	CK	6.66±0.52 b	67.63±12.65 b	16.30±1.87 b	90.60±14.47 b	0.11±0.02 c	0.30±0.03 b	0.18±0.02 d	0.58±0.03 b
	NPK	15.40±1.75 b	77.45±6.11 b	16.65±2.40 b	109.51±9.25 b	0.17±0.01 b	0.40±0.02 ab	0.24±0.02 cd	0.81±0.02 b
	NPK+RSB	13.03±3.43 b	77.69±10.68 b	3.51±0.94 c	94.23±8.14 b	0.18±0.01 b	0.43±0.04 a	0.76±0.14 a	1.38±0.19 a
	NPK+RSM	26.96±2.02 ab	328.61±19.24 a	38.49±2.13 a	394.06±22.78 a	0.24±0.02 a	0.51±0.02 a	0.45±0.01 bc	1.19±0.03 a
	NPK+RSM+GM	46.04±14.27 a	293.31±3.16 a	36.11±5.38 a	375.46±12.46 a	0.28±0.01 a	0.46±0.06 a	0.53±0.07 b	1.26±0.09 a

Values are presented as mean±SE (n=3); different letters in the same column indicate significant differences at $P < 0.05$ level

CK no straw return or chemical fertilizers applied; *NPK* no straw return, chemical N, P, and K fertilizers applied in rice growing season; *NPK+ RSB* rice straw burning in situ after rice harvest and chemical fertilizers applied in rice growing season; *NPK+ RSM* rice straw mulching in winter fallow then incorporated into soil before rice transplantation, and chemical fertilizers applied in rice growing season; *NPK+ RSM+ GM* rice straw strip mulching plus green manuring in winter fallow then incorporated into soil before rice transplantation, and chemical fertilizers applied in rice growing season in NPK+RSB, NPK+RSM, and NPK+RSM+GM treatments were statistically similar ($P > 0.05$) with each other, but significantly higher those that in NPK or CK treatments.

SOC sequestration

The annual soil organic carbon sequestration rates (SOCSRs) over 3 years (from 2010 to 2013) ranged from 0.13 to 1.20 t C ha^{-1} year^{-1} across the different treatments (Table 4). Compared with NPK, the NPK+RSM+GM and NPK+RSM treatments enhanced the SOCSR. The highest SOCSR was observed in NPK+RSM+GM, which was 32 % higher than that in NPK+RSM. The SOCSR in CK, NPK, and NPK+RSB treatments was similar with each other (Table 4).

NGWP and straw-induced NEB

The GWP from the annual CH_4 and N_2O emissions was primarily based on CH_4 emissions, which accounted for 85.1–96.5 % of total GWP over the two annual cycles (Table 3 and Fig. 2). Considering the SOCSR, the NGWP ranged from 1136 to 6867 kg CO_2-eq ha^{-1} across different treatments (Table 4). Among the different soil amendment treatments, the NGWP was the highest in NPK+RSM treatment, followed by NPK+RSM+GM. The NGWP in the NPK+RSB treatment was similar to that in NPK or CK treatments (Table 4).

The straw-induced CH_4 and N_2O emissions exceeded the SOCSR. The straw-induced GWP was 7230 and 6786 kg CO_2-eq ha^{-1} for the NPK+RSM and NPK+RSM+GM treatments, respectively (Table 5). The straw-induced NEB was based on the rice grain price and the carbon price. Based on our observations in this region, the rice grain price and carbon price are 3.0 RMB kg^{-1} and 24.0 RMB Mg^{-1} CO_2-eq, respectively, in recent years. The rice straw management treatments recorded a positive NEB (Table 5). The highest NEB was observed for NPK+RSM+GM treatment (2161 RMB kg^{-1} year^{-1}), which was 2.04 and 6.49 times higher than that recorded for the NPK+RSM and NPK+RSB treatments, respectively (Table 5).

Discussion

Effects of fallow season straw management on soil quality and rice productivity

Results of the present study depicted significant variations in soil fertility and rice grain yield under the influence of different straw management practices during winter fallow season (Table 2). Compared with straw removal (NPK), rice straw burning in situ (NPK+RSB) had no positive effect on soil nutrients but significantly increased the soil pH. Although the NPK+RSM treatment increased the SOC and total N

Table 4 Mean grain yield, soil organic carbon sequestration rates (SOCSR), annual CH_4 and N_2O emissions, and their estimated global warming potentials (GWPs) under different fallow season straw management practices

Treatment	Grain yield (t ha^{-1})	SOCSR (t C ha^{-1} year^{-1})	CH_4 (kg CH_4-C ha^{-1} year^{-1})	N_2O (kg N_2O-N ha^{-1} year^{-1})	GWP of CH_4 (kg CO_2-eq ha^{-1} year^{-1})	GWP of N_2O (kg CO_2-eq ha^{-1} year^{-1})	GWP of CH_4 and N_2O (kg CO_2-eq ha^{-1} year^{-1})	NGWP (kg CO_2-eq ha^{-1} year^{-1})
CK	4.47±0.16 c	0.13±0.09 c	90.60±14.47 b	0.58±0.03 b	2265±362 b	174±10 b	2439±353 b	1979±283 c
NPK	8.58±0.07 b	0.50±0.07 bc	109.51±9.25 b	0.81±0.02 b	2738±231 b	241±6 b	2978±235 b	1136±111 c
NPK+RSB	8.69±0.16 b	0.31±0.06 c	94.23±8.14 b	1.38±0.19 a	2356±204 b	411±55 a	2767±177 b	1644±235 c
NPK+RSM	8.98±0.14 ab	0.91±0.11 ab	394.06±22.78 a	1.19±0.03 a	9852±569 a	356±8 a	10208±575 a	6867±154 a
NPK+RSM+GM	9.33±0.07 a	1.20±0.27 a	375.46±12.46 a	1.26±0.09 a	9387±312 a	377±27 a	9764±333 a	4833±677 b

Values are presented as mean±SE (n=3); different letters in the same column indicate significant differences at $P < 0.05$ level. Mean grain yield and SOCSR was calculated as the average of 3 years, whereas annual CH_4 emissions, N_2O emissions, and their GWPs were the average of two annual cycles from 2011 to 2013

CK no straw return or chemical fertilizers applied; *NPK* no straw return, chemical N, P, and K fertilizers applied in rice growing season; *NPK+ RSB* rice straw burning in situ after rice harvest and chemical fertilizers applied in rice growing season; *NPK+ RSM* rice straw mulching in winter fallow then incorporated into soil before rice transplantation, and chemical fertilizers applied in rice growing season; *NPK+ RSM+ GM* rice straw strip mulching plus green manuring in winter fallow then incorporated into soil before rice transplantation, and chemical fertilizers applied in rice growing season

Table 5 Effect of different straw management practices on straw induced net global warming potentials (NGWPs) and net economic benefit (NEB) in mono-rice cultivation system

Treatment	$RGYC_{\text{straw-induced}}$ (kg ha^{-1} $year^{-1}$)	$GWP_{\text{straw-induced}}$ (kg CO_2-eq ha^{-1} $year^{-1}$)	$SOCSR_{\text{straw-induced}}$ (kg CO_2-eq ha^{-1} $year^{-1}$)	$NGWP_{\text{straw-induced}}$ (kg CO_2-eq ha^{-1} $year^{-1}$)	$NEB_{\text{straw-induced}}$ (RMB ha^{-1})
NPK+RSB	115	−211	−721	508	333
NPK+RSM	400	7230	1498	5731	1062
NPK+RSM+GM	754	6786	2573	4211	2161

$RGYC_{\text{straw-induced}}$=Yield $_{\text{NPK+RSB or NPK+RSM or NPK+RSM+GM}}$ − Yield $_{\text{NPK}}$

CK no straw return or chemical fertilizers applied; *NPK* no straw return, chemical N, P, and K fertilizers applied in rice growing season; *NPK+ RSB* rice straw burning in situ after rice harvest and chemical fertilizers applied in rice growing season; *NPK+ RSM* rice straw mulching in winter fallow then incorporated into soil before rice transplantation, and chemical fertilizers applied in rice growing season; *NPK+ RSM+ GM* rice straw strip mulching plus green manuring in winter fallow then incorporated into soil before rice transplantation, and chemical fertilizers applied in rice growing season. *RGYC* rice grain yield change; $RGYC_{straw\text{-}induced}$ straw-induced rice grain yield change

contents as compared with NPK+RSB and NPK (Table 2); nevertheless, this treatment could not significantly enhance the rice productivity and was statistically similar with NPK+RSB and NPK treatments for average rice grain yield across 3 years. Previously, several studies conducted in subtropical China have reported no significant effect of straw return on rice grain yield (Xia et al. 2014; Zhang et al. 2015). After reviewing a number of published studies, Singh et al. (2005) reported that the straw incorporation did not produce any significant effect on grain yield in rice-based cropping systems. However, in a long-term 16-year study, Shang et al. (2011) observed that continuous straw incorporation at a full rate increased the grain yield of early rice by 15.98 % and suggested that the positive effects of straw return on the crop yields become more obvious after long-term incorporation.

The present results indicated that rice straw mulching along with green manuring (NPK+RSM+GM) during the fallow season significantly enhanced the rice yield compared with either straw removal (NPK) or burning of straw (NPK+RSB) over the 3 years. The superiority of NPK+RSM+GM to all other treatments might be attributed to the availability of additional nutrients especially N from green manure crop as well as rice straw. Similar results have been reported by Liu and Shen (1992) in double-rice cropping system of China and Aulakh et al. (2001) in rice–wheat cropping system in India. Less effectiveness of NPK+RSM treatment for rice yield might be attributed to higher C/N ratio of rice straw. On the other hand, plantation of green manure crop NPK+RSM+GM might have reduced the C/N ratio. Singh et al. (2005) stated that incorporation of residues with low N contents (such as rice, wheat, and barley) could accelerate immobilization of N causing N deficiency to the following crop, lower C/N ratio, and higher amount of N in the crop residue resulting in higher mineralization of N (Norman et al. 1990). Haque et al. (2013) indicated that plantation of hairy vetch with barley crop during winter reduced the C/N ratio and favored the mineralization of organic substrates in soil and thus increased rice plant growth and yield. Kim et al. (2013) also observed that higher rice yield in NPK+milk vetch plots compared with NPK+rye was due to lower C/N ratio of milk vetch residue than rye. Moreover, Caballero et al. (1996) also attributed the crop yield enhancement by vetch application to presence of organic and inorganic nutrients such as N, P, and K.

Effects of fallow season straw management on CH_4 emissions

Many research studies (Wang et al. 1992; Le Mer and Roger 2001; Singh et al. 2005) have demonstrated that organic C from crop residues, organic manures, soil organic matter, and/or rice plant roots is the major driving force for CH_4 production in rice-based cropping systems. In the present study, less CH_4 production occurred in rice straw removal (CK and NPK) and rice straw burning (NPK+RSB) plots during the whole rice–fallow period, which might be due to lack of organic materials in these plots. Addition of rice straw alone or along with green manure crop enhanced the CH_4 fluxes, especially during the 1–2 weeks after land preparation and the early vegetative growth stage of rice plant (Fig. 2), which was consistent with many previous studies (Ma et al. 2009; Qin et al. 2010; Wang et al. 2013; Das and Adhya 2014). The higher CH_4 peaks after land preparation could be related to increased availability of labile organic matter, while occurrence of intense reducing conditions in the rhizosphere due to flooding could be the reason for higher CH_4 emissions in early vegetative growth stage of rice (Lauren et al. 1994; Bronson et al. 1997; Lee et al. 2010; Yao et al. 2013). In the present study, seasonal total CH_4 emission especially during the rice season (including 15–29 days of land preparation period before rice transplanting (P_{BRT}) and 102–108 days of rice growing period (P_{R})) was significantly enhanced by the incorporation of rice straw or rice straw plus green manuring (NPK+RSM and NPK+RSM+GM, Table 3). Many researchers have previously reported that the application of organic materials considerably increased CH_4 emissions from paddy fields, because they provided a source of readily available C and N and a predominant source of methanogenic substrates (Lauren et al. 1994; Bronson et al. 1997; Lee et al. 2010; Yao et al. 2013).

Our results showed that annual CH_4 emissions ranged from 85.15 to 528.84 kg CH_4-C ha^{-1} (Table 3), which was comparable to previous research studies in rice-based cropping systems of subtropical China (Yan et al. 2005; Yang et al. 2010; Shang et al. 2011; Zhang et al. 2013). The highest seasonal CH_4 emission during the P_{BRT} in 2 years was found in NPK+RSM+GM treatment. It might be possible that rice straw mixed with green manure has influenced the decomposition rate of organic matter and the activity of CH_4 production or oxidizing microbes (Singh et al. 2005; Bhattacharyya et al. 2012; Zhang et al. 2013). Mishra et al. (2001) observed that plantation of green manure crop accelerated the decomposition of wheat straw by lowering the C/N ratio of the decomposing material and by stimulating the microbial population to carry out the decomposition. In the present study, the CH_4 emissions during the P_R and P_{WF} were slightly lower in NPK+RSM+GM treatment compared with those in NPK+RSM (Table 3). However, the annual CH_4 emissions were similar between NPK+RSM+GM and NPK+RSM treatments.

Effects of fallow season straw management on N_2O emission

The N_2O fluxes from soil are mainly driven by microbial activity, through nitrification and denitrification processes (Granli and Bockman 1994). Paddy fields are also considered as the source of atmospheric N_2O emissions, depending on the other management practices like irrigation, N fertilizer, and organic amendments (Cai et al. 1997; Stevens and Laughlin 1998; Xing et al. 2009). The N_2O is formed by nitrifying and denitrifying bacteria in upland or aerobic soils and is boosted by excess N availability, but under flooded conditions, the N_2O is reduced to N_2 leading to less emissions (Granli and Bockman 1994). Soil moisture is known to regulate the soil aeration and to influence the nitrification and denitrification processes that produce N_2O (Bollmann and Ralf 1998). Therefore, soil nitrate content and soil water content are the key factors affecting denitrification and N_2O emissions from rice paddy fields (Xiong et al. 2007). In the present study, fluxes of N_2O emission showed a great fluctuation, and prominent N_2O emission peaks were observed during the soil preparation before rice transplanting period, after the midseason drainage and the final drainage at rice harvest stage (Fig. 2). During land preparation period, the dry–wet cycles of soil were more conducive to N_2O production. Moreover, incorporation of organic materials (straw, green manuring) at the time of land preparation might have also triggered microbial activity (Zelenev et al. 2005), and rapid decomposition of organic materials also had created a pool of readily available N and therefore induced N_2O emissions. Higher N_2O emissions after midseason drainage and final drainage might be because of N application at panicle stage (between midseason and final drainage), high temperature, and aerobic environment during this period.

In our study, the seasonal total N_2O emissions during the rice season (including P_{BRT} and P_R) ranged from 0.36 to 2.10 kg N_2O-N ha^{-1} (Table 3), and this range was almost similar with rice–wheat cropping systems in other regions of subtropic China (Xu et al. 1997; Ma et al. 2009; He et al. 2013). But, it was lower than some early observations from rice–wheat cropping systems in Jiangsu Province (Zou et al. 2005; Xia et al. 2014) which might be due to high N input in their studies and different weather conditions.

Effects of fallow season straw management on SOCSR, NGWP, and NEB

The SOC sequestration in cropping systems has been considered as a cost-effective and eco-friendly strategy for sequestrating anthropogenic CO_2 emission. In the past, several studies (e.g., Shang et al. 2011; Zhang et al. 2012; Xia et al. 2014; Tian et al. 2015) have documented the beneficial role of straw return for SOC sequestration. For instance, Yan et al. (2007) estimated that the SOCSR of 100 % crop residue recycling in middle and lower reaches of Yangtze River region of China, was about 0.30–0.40 t C ha^{-1} year^{-1} for 20-year duration. Lu et al. (2009) pointed out that the annual carbon sequestration potential induced by the straw return could increase from the current level of 9.76 to 34.4 Tg, if the practice of straw return grows in terms of its popularity.

In present study, we found that NPK+RSM and NPK+RSM+GM treatments significantly increased SOC contents compared with NPK, and both of these treatments were beneficial for SOC sequestration. The highest SOCSR was observed in NPK+RSM+GM than in all other treatments. It might be attributed to the fact that green manure crop with a narrow C/N ratio decomposed very rapidly in the soil and might have promoted soil microbial activities and thus enhanced SOC sequestration. Zhang et al. (2012) also observed similar results in a long-term (1981–2007) experiment while studying in double-rice cropping system of east China. Organic amendments may benefit SOC sequestration in three ways; first, organic additives directly integrate the organic material into the soil; second, organic fertilizers increase the input of the root exudate by stimulating the crop growth; and finally, organic fertilizers improve the physical conditions of the soil and subsequently enhance the root development. In addition to increasing the SOC and sequestering of the atmospheric C, organic additives like straw and green manure crops can improve soil fertility by providing macronutrients and micronutrients, and by improving the physico-chemical properties of the soil (Yan et al. 2013).

In the present study, the annual SOC sequestration rates under different soil amendment treatments over the 3 years ranged from 0.13 t C ha^{-1} $year^{-1}$ in CK plot to 1.20 t C ha^{-1} $year^{-1}$ in NPK+RSM+GM plot with an average of 0.61 t C ha^{-1} $year^{-1}$ (Table 4), and this range falls within the estimated value (from 0.1 to 2 t C ha^{-1} $year^{-1}$) in Chinese rice paddies given by Pan and Zhao (2005) but was higher than the estimated value (0.195–0.255 t C ha^{-1} $year^{-1}$) reported by Xia et al. (2014) under a long-term (22 years) straw incorporation in a rice–wheat cropping system. The higher annual SOC sequestration rate values in our study might be due to the application of straw in greater amount (8.65 t ha^{-1}), single cropping system (only one season of rice), and short-term straw incorporation.

Considering the SOC sequestration rate and the annual emissions of CH_4 and N_2O, the NGWP in the study region ranged from 1136 kg CO_2-eq ha^{-1} $year^{-1}$ in the NPK to 6867 kg CO_2-eq ha^{-1} $year^{-1}$ in the NPK+RSM (Table 4). The NGWP of NPK+RSM+GM treatment was significantly lower, while NEB was almost two times compared with NPK+RSM. Higher rice productivity and higher NEB by rice straw mulching and green manuring during the fallow season suggested that traditional method of direct straw incorporation can be easily replaced by NPK+RSM+GM in mono-rice cultivation system.

Conclusions

The present study demonstrated that rice straw mulching in combination with green manuring of Chinese milk vetch (NPK+RSM+GM) during winter fallow was the most effective treatment to increase rice productivity and soil health, and stabilize GHG emissions. Across 3 years, NPK+RSM+GM recorded higher grain yield, SOC, and TN than NPK+RSM or NPK alone. Nevertheless, annual cumulative CH_4 and N_2O emissions were similar in NPK+RSM and NPK+RSM+GM treatments. The NPK+RSM+GM recorded 103 and 72 % higher straw-induced NEB and SOC sequestration rates, while 27 % lower NGWP compared with NPK+RSM. Taking in conjunction the benefits of improved soil health, higher crop yield, and environmental safety, the NPK+RSM+GM could be the most feasible and sustainable option for mono-rice cultivation system in central China. However, future studies may focus on further reducing the GHG emission in NPK+RSM+GM by modifying crop management regimes like irrigation patterns and tillage practices.

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