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RESEARCH ARTICLE

CH_4 and N_2O emissions from double-rice cropping system as affected by Chinese milk vetch and straw incorporation in southern China

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Abstract Chinese milk vetch (CMV) and rice straw (RS) were incorporated into soil to substitute for synthetic N fertilizers and to maintain soil fertility. However, little is known about the integrated impacts of CMV and RS incorporation on CH_4 and N_2O emissions in double-rice cropping systems in southern China. A field experiment was conducted to estimate the integrated impacts of CMV and RS incorporation in the early- and late-rice seasons on CH_4 and N_2O emissions. All treatments received uniform N inputs, 6%–37% of which was replaced by CMV and RS crop residue. CMV and/or RS incorporation produced equivalent or slightly more grain yield, while reducing N_2O emissions by 3%–43%. However, both CMV and RS incorporation increased CH_4 emissions. Annual CH_4 emissions ranged from 321 to 614 $kg \cdot hm^{-2}$ from CMV and RS amendment treatments, which were 1.5–2.9 times higher than that from synthetic N. Compared with single synthetic N fertilizer, incorporation of CMV and/or RS increased GWP and yield-scaled GWP by 45%–164% and 45%–153%, respectively. Our results demonstrate CMV and RS amendments replacing N fertilizer, maintained stable yield, mitigated N_2O emission, but enhanced CH_4 emission. Further study is needed on crop residue management in double-cropping rice systems.

Keywords Chinese milk vetch, CH_4, double-rice cropping system, grain yield, N_2O, rice straw

1 Introduction

Methane and nitrous oxide are long-lived greenhouse gases second only to carbon dioxide in contributing to the greenhouse effect, which causes environmental changes such as global warming, disturbance to the stratospheric ozone, and the present environmental crisis[1,2]. Globally, anthropogenic sources of CH_4 and N_2O are dominated by agriculture, and agricultural CH_4 and N_2O emissions have increased by approximately 17% from 1990 to 2005, according to the IPCC (Intergovernmental Panel on Climate Change)[3]. Flooded rice paddies are an important source of anthropogenic greenhouse gas (GHG) that account almost for 30% and 11% of global agricultural CH_4 and nitrous oxide N_2O emissions, respectively[3].

Rice is the most important staple food in China, and the production and planting area of rice in China accounts for approximately 35% and 20% of the world total[4], respectively. At the same time, food demand is on the increase with population growth, and total world consumption of rice expected to increase by over 50% in 2030[5]. A considerable rice yield will be required, necessitating an increasing intensity of rice production. This intensified rice cultivation may lead to additional chemical fertilization. However, excessive use of synthetic fertilizer causes a series of environmental concerns, such as eutrophication, greenhouse gas (GHG) emissions and soil acidification[6], which have been a focus for scientists and governments in recent years, especially in rice producing countries like China.

As the Chinese are becoming increasingly concerned about the degradation of the agricultural environment due to excessive use of chemicals, green manure use is being advocated as a sustainable agricultural practice to regenerate depleted soil resources, reduce application rate

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of synthetic fertilizers and maintain yields. Aulakh et al.[7] reported that cultivation of leguminous plant species such as vetch as green manure crops improved soil fertility, and these plants are commonly preferred by rice farmers because of their characteristics of high nitrogen fixing capabilities and rapid biomass accumulation. In southern China, Chinese milk vetch (CMV, *Astragalus sinicus,*) is the most popular green manure during the fallow seasons in double-rice cropping systems. However, nowadays, the farmers are less willing to plant green manure CMV in the winter fallow period, which is due primarily to the scarcity of labor and preference for chemical fertilizer.

Crop production inevitably results in large amounts of crop residues. On average, 20% of the crop residues in China are processed burnt in the field[8]. Straw is the major type of crop residue and is generally removed by burning, as part of the field preparation for the next crop. This open-field burning of crop straw results in a loss of organic matter, air pollution and safety risks[9]. Therefore, the Chinese government is implementing a strict policy banning crop straw burning. Considering the huge amount of rice straw (RS) produced annually in China, straw incorporation *in situ* is a highly recommended alternative management practice to increase soil fertility and soil organic carbon storage.

In double-rice cropping systems, direct incorporation of CMV and/or RS into rice field is an important practice to dispose of residues and to improve soil physicochemical properties and increase crop yield. Proper management of crop residues introduces organic carbon into the soil, increasing the soil organic matter[10] as well as improving its physicochemical properties[11], and maintaining rice production[12]. However, the incorporation of CMV and RS produces undesired consequences, such as GHG emissions. Most studies have demonstrated that the incorporation of CMV into rice soil significantly increased CH_4 emissions[13,14]. Likewise, RS amendment resulted in higher CH_4 emissions from rice paddies[10,15–17]. However, little is known about the comprehensive impacts of both CMV and RS incorporation on GHGs emissions in double rice cropping systems of southern China.

The objectives of this study were to characterize and quantify CH_4 and N_2O emissions from a rice field following CMV and RS incorporation and to assess the combined climatic effect of CH_4 and N_2O emissions as influenced by incorporation of crop residues. Such information is expected to be helpful in sustainable production of rice and to lay the foundation for further research on the rational use of CMV and RS.

2 Materials and methods

2.1 Field site

In 2013, a field experiment was conducted at the experimental station of Soil and Fertilizer Institute of Hunan Province, located in Huarong County (29°57′ N, 112°49′ E, 30 m), Hunan Province, China. The study area, which is situated in the Dongting Lake Plain, has a subtropical monsoon climate with an annual average temperature of 17°C and annual precipitation of 1450 mm. Daily mean temperatures and rainfall in 2013 are shown in Fig. 1. The initial properties of the topsoil were as followed: pH 7.7, soil organic matter 49.2 g·kg^{-1}, total nitrogen 3.11 g·kg^{-1}, available phosphorus

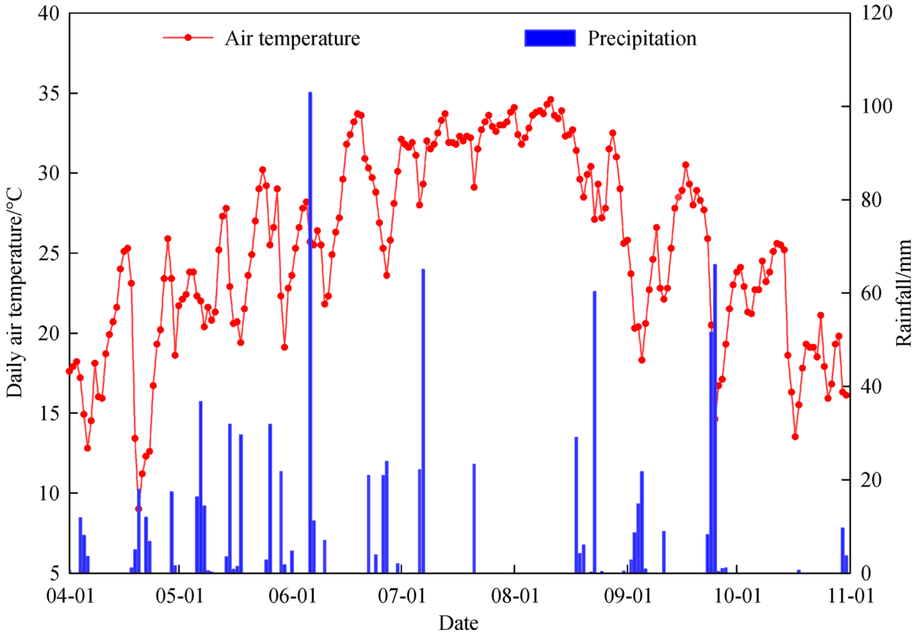

Fig. 1 Daily air temperature and precipitation during Date double-rice growing season from April to late October in 2013

16.4 mg·kg^{-1}, exchangeable potassium 69.0 mg·kg^{-1}, clay (< 0.002 mm) 17.8%, silt (0.002–0.02 mm) 48.6% and sand (0.02–2 mm) 33.6%.

2.2 Field experimental design

In the early-rice season, an experiment with a completely randomized block design was conducted in plots of 10×6 m^2. Fresh CMV was applied at rates of 15000, 22500 and 30000 kg·hm^{-2} for treatment T1, T2 and T3, respectively, with standard chemical fertilizer as the control. Each treatment had three replicates.

After early-rice harvest, each plot was subdivided into two equal subplots, one of which was selected randomly for incorporation of RS (S2) and the other received no RS (S0). Thus, the late-rice trial had 24 plots (each 5 m × 6 m), laid down as a randomized block design. Based on the four original treatments in the early-rice season, the second experiment was composed of eight treatments with three replications. Specific treatments were as follows: the four treatments S0T1, S0T2, S0T3 and S0CF without RS were based on early-rice season treatments, T1, T2, T3 and CF, respectively. The remaining four treatments S2T1, S2T2, S2T3 and S2CF amended with straw from T1, T2, T3 and CF, respectively. The RS dry weight was applied at 3000 kg·hm^{-2} and incorporated one week prior to transplanting rice.

Each plot was uniformly fertilized with 200 kg·hm^{-2} N per crop season. The N content of CMV and RS was deducted from the amount of fertilizer N applied. In both crop seasons, urea was used as the fertilizer N and broadcast on the fields, with 70% as basal fertilizer and 30% top dressed at the late tillering stage. For each plot, 85 kg·hm^{-2} P_2O_5 (calcium superphosphate) and 100 kg·hm^{-2} K_2O (potassium chloride) were also applied as basal fertilizer per season. The field management closely followed the local agronomic practices, including cultivation, irrigation and pest and weed control. During the rice growing season, a local typical water regime of flooding-midseason drainage-reflooding-moist intermittent irrigation but without waterlogging (F-D-F-M) was employed for all field plots.

2.3 Crop management practices

Seed of Chinese milk vetch cv. Xiangfei 3 was broadcast at the rate of 37.5 kg·hm^{-2} in late September and fresh CMV was incorporated at the full-bloom stage, about 20 days prior to early-rice transplanting. The aboveground biomass of fresh vetch was collected from neighboring fields and mixed completely before incorporation. The treated soil was mixed mechanically to a depth of 15 cm, and then flooded to a depth of 5–10 cm. The 30-day-old early-rice cv. T-Liangyou 705 seedliings were transplanted in late April and harvested in mid-July and the 32-day-old late-rice cv. Yueyou 9113 seedlings were transplanted in late July and harvested in late October. When early-rice was harvested 10 cm high stubble was left. All the rice straw from three replicate plots was collected, weighed and mixed uniformly and a small subsample was collected and oven-dried to analysis N content.

2.4 Measurement of CH_4 and N_2O fluxes

CH_4 and N_2O fluxes were simultaneously monitored using the closed-static chamber method following the procedure described by Zou et al.[16]. The chamber (0.45 m × 0.45 m × 1 m) covered four hills of rice in the field. Plastic bases (0.45 m × 0.45 m × 0.15 m) for the chambers were permanently installed in all plots 3 days after rice transplanting and remained there until rice harvest. The air temperature inside the chamber headspace was measured with a thermocouple. Wooden bridges (2 m long) were set up well before gas sampling to avoid soil disturbance. Gas samples were taken from 9:00 through 11:00 because the soil temperature during this period was close to the mean daily temperature[12,16,18]. For each plot, four gas samples were manually extracted from the headspace of the chamber through a three-way stopcock using a 30-mL airtight syringe at 10 min intervals (0, 10, 20 and 30 min after chamber closure) and then transferred to 18 mL evacuated vials for storage. After each sampling event, the chambers were removed from the rice fields.

The gas concentrations were analyzed using a modified gas chromatograph (Agilent 7890A, California, USA) equipped with a flame ionization detector (FID) for CH_4 analyses and electron capture detector (ECD) for N_2O analyses. The oven was operated at 55°C, the ECD at 330°C, and the FID at 200°C. The carrier gas (N_2) flow rate was 30 mL·min^{-1}. The following equation was used to estimate the CH_4 and N_2O fluxes from each treatment:

$$F = \rho \times (V/A) \times (\Delta c/\Delta t) \times 273/(273 + T) \qquad (1)$$

where F is the CH_4 flux (mg·m^{-2}·h^{-1}) or N_2O flux (μg·m^{-2}·h^{-1}), ρ is the gas density of CH_4 or N_2O under a standard state (mg·m^{-3}), V is the volume of the chamber (m^3), A is the chamber area (m^2), $\Delta c/\Delta t$ 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), being the calculated slope of the curve of gas concentration versus sampling time (0, 10, 20 and 30 min during the time of chamber closure), and T is mean temperature in the chamber (°C).

The seasonal CH_4 and N_2O emission for the entire cropping period were calculated using the following equation:

$$T_{CH_4 \text{ or } N_2O} = \sum_{i=1}^{n}(Fi \times 24 \times Di) \qquad (2)$$

where Fi stands for CH_4 or N_2O average flux in the ith sampling intervals (mg·m^{-2}·h^{-1}); Di is the number of days in the ith sampling intervals (d); n means the number of sampling intervals; 24 is the number of hours per day.

Global warming potential (GWP) is an index defined as the cumulative radiative forcing between the present and some chosen later time 'horizon' caused by a unit mass of gas emitted now. In general, CO_2 is typically taken as the reference gas, and CH_4 and N_2O are converted into 'CO_2-equivalents' through their GWPs. GWP over a 100-year period was calculated by multiplying seasonal CH_4 emissions by a factor of 25 and seasonal N_2O by a factor of 298[3].

$$\mathrm{GWP} = T_{\mathrm{CH}_4} \times 25 + T_{\mathrm{N}_2\mathrm{O}} \times 298 \tag{3}$$

2.5 Statistical analysis

All of the statistical analyses were performed with SAS 9.3 (SAS Institute Inc., North Carolina, USA) and Sigmaplot 12.5 (SSI, San Jose, California, USA). Least significant difference (LSD) tests were used to compare means between treatments. Differences were considered statistically significantly at $P < 0.05$. Normal distribution and variance uniformity of all collected data were checked and all collected data were fit for the variance uniformity ($P > 0.05$) in the current experiment.

3 Results

3.1 N contribution of incorporated Chinese milk vetch and rice straw

The fresh CMV held 0.4% N. In the early-rice season, when CMV was incorporated at the rate of 15000, 22500 and 30000 kg·hm^{-2}, it could provide 60, 90 and 120 kg·hm^{-2} N for the rice plants, accounting for 30%, 45% and 60% of total N input (200 kg·hm^{-2} N) (Table 1). After the early-rice harvest, the N content of rice straw derived from treatment T1, T2, T3 and CF was determined to be 1.04%, 1.09%, 0.89% and 0.77% DW, respectively. As RS was incorporated into the late-rice field at the same rate of 3000 kg·hm^{-2}, this represented 23–33 kg·hm^{-2} N, corresponding to 12%–17% of the total 200 kg·hm^{-2} N (Table 1). Therefore, CMV and RS amendments decreased the synthetic fertilizer N applied by 6%–37% during a double-rice growing season (Table 1).

3.2 Effect of CMV and RS incorporation on CH_4

There were similar temporal trends in each crop season, but varying amplitudes of CH_4 fluxes for all plots (Fig. 2). CH_4 fluxes varied between 1.7 and 44.6 mg·m^{-2}·h^{-1} in the early-rice season (Fig. 2a), and 0.22 and 79.48 mg·m^{-2}·h^{-1} in the late-rice season (Fig. 2b, Fig. 2c). Two distinct peaks of CH_4 flux, one at the tillering stage and the other at the heading stage, were observed across all treatments, and the first peaks were significantly higher than the second peaks (Fig. 2). At the initial stage, CH_4 fluxes in all treatments were low. Subsequently, CH_4 fluxes gradually increased with rice growth and reached the first major peaks 21 and 14 days after transplanting for early- and late-rice respectively, up to midseason drainage (MSD). CH_4 emissions were relatively high during the flooding period and then sharply dropped during MSD. At the end of MSD, paddy fields were re-flooded. Thereafter, CH_4 fluxes remained at relatively low levels until rice harvest.

Seasonal cumulative emissions of CH_4 from the fields are shown in Table 2. In the early-rice season, the cumulative CH_4 emissions ranged from 76.1 to 280 kg·hm^{-2} (Table 2). On average, CMV incorporation significantly stimulated CH_4 emissions, which were 3.3

Table 1 N contribution from Chinese milk vetch (CMV) and rice straw (RS) incorporation

Season	Treatment[a]	Crop residue	N content/%	Incorporated amount /(kg·hm^{-2})	N rate /(kg·hm^{-2})	Urea-N /(kg·hm^{-2})	Total N /(kg·hm^{-2})	Percentage /%
Early rice	T1	CMV	0.4	15000	60	140	200	30
	T2			22500	90	110	200	45
	T3			30000	120	80	200	60
	CF		–	–	–	200	200	–
Late rice	S2T1	RS	1.04	3000	31	169	200	16
	S2T2		1.09	3000	33	167	200	17
	S2T3		0.89	3000	27	172	200	14
	S2CF		0.77	3000	23	177	200	12
	S0T1		–	–	–	200	200	–
	S0T2		–	–	–	200	200	–
	S0T3		–	–	–	200	200	–
	S0CF		–	–	–	200	200	–

Note: [a], T1, T2 and T3 represent 15000, 22500 and 30000 kg·hm^{-2} fresh CMV with fertilizer, respectively, CF represents application of synthetic N fertilizer at a rate of 200 kg·hm^{-2} N. S2 and S0 represent treatment with and without RS incorporation in the late-rice season, respectively; [b], Percentage represents the ratio of crop residue N to total N.

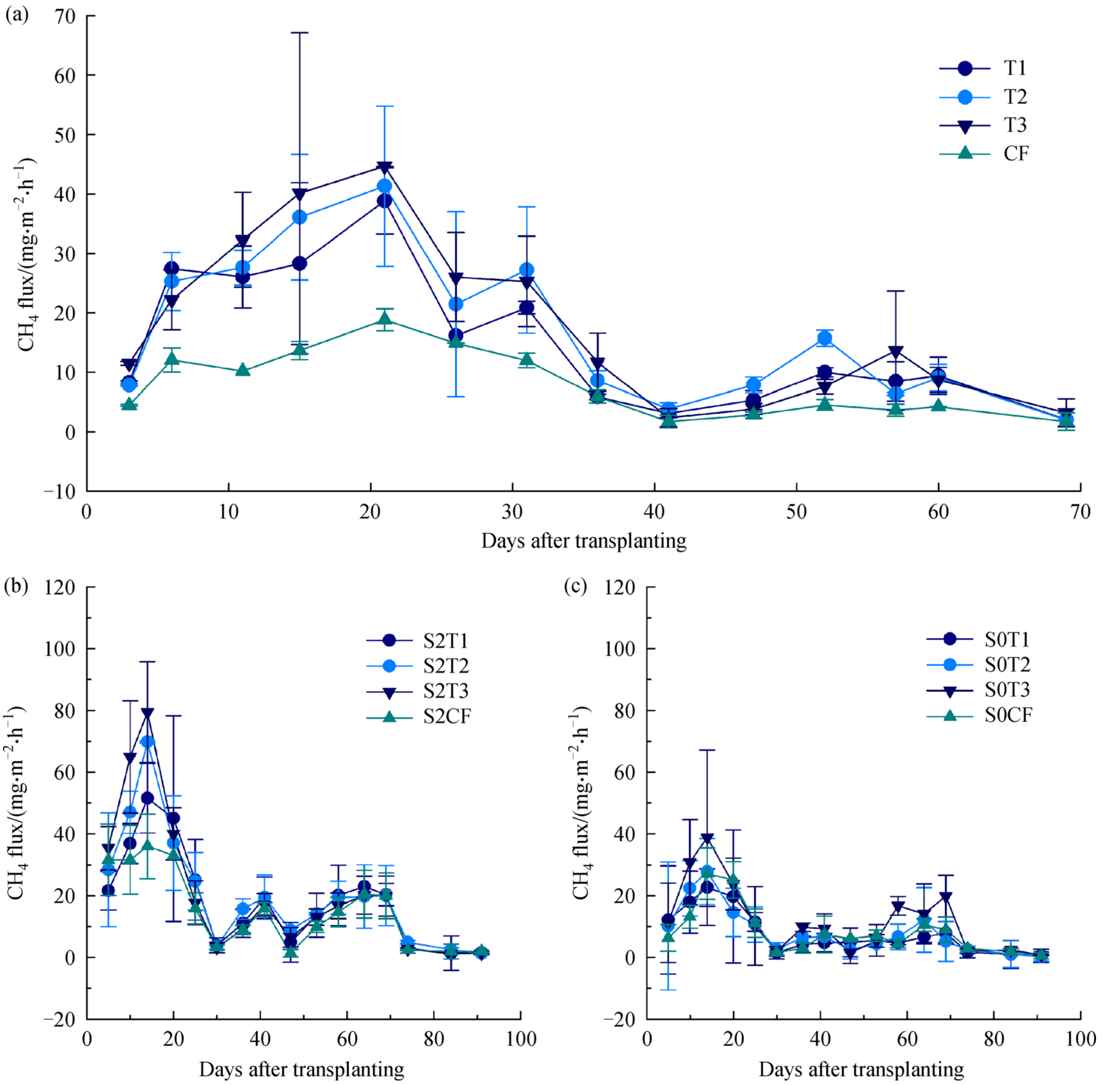

Fig. 2 Temporal variations of CH$_4$ flux from paddy soils under different treatments during the early-rice (a) and late-rice (b, c) growing season in double-rice cropping system. Error bars indicate the standard deviation of the means. See Table 1 for treatment codes.

Table 2 Seasonal emissions of CH$_4$ and N$_2$O from a double-rice cropping system with different amounts of Chinese milk vetch (CMV) and/or rice straw (RS) treatments with fertilizer

Early-rice season			Late-rice season			Double rice system	
Treatment	CH$_4$/(kg·hm^{-2})	N$_2$O/(kg·hm^{-2})	Treatment	CH$_4$/(kg·hm^{-2})	N$_2$O/(kg·hm^{-2})	CH$_4$/(kg·hm^{-2})	N$_2$O/(kg·hm^{-2})
T1	227.7 b	0.75 b	S2T1	322 a	0.85 de	550 ab	1.60 c
			S0T1	191 bc	1.13 bc	419 d	1.88 ab
T2	251.9 ab	0.52 c	S2T2	351 a	0.65 de	603 a	1.18 d
			S0T2	208 bc	1.21 b	460 dc	1.73 bc
T3	279.5 a	0.41 c	S2T3	335 a	0.76 de	614 a	1.17 d
			S0T3	224 b	1.59 a	504 bc	2.00 a
CF	76.1 c	0.99 a	S2CF	245 b	0.95 cd	321 e	1.94 ab
			S0CF	137 c	1.08 bc	214 f	2.07 a

Note: Means with the same letter within a column are not significantly different according to LSD (0.05). See Table 1 for treatment codes.

times higher than the CF treatment (76.1 kg·hm^{-2}) (Table 2). The CH_4 emission amount increased with the increases in CMV incorporation. However, no significant difference was observed between the treatments amended with CMV ($P > 0.05$).

However, in the late-rice seasonal, the RS incorporation had significant effects on the seasonal CH_4 emission ($P < 0.05$) (Table 2). The cumulative CH_4 emissions from the plots with RS averaged 313 kg·hm^{-2}, which was 1.6 times higher than those without RS, which averaged 190 kg·hm^{-2} (Table 2). CMV incorporation still stimulated CH_4 emission during the late-rice season. The treatments incorporated equal quantities of CMV into the fields in the early-rice season, those amended with RS emitted more CH_4 than those without RS incorporation ($P < 0.05$). A seasonal total CH_4 flux of 137 kg·hm^{-2} was recorded in the S0CF treatment. In this double-rice cropping system, the combined impacts of CMV and/or RS on CH_4 emissions were estimated in this study (Table 2). The annual cumulative CH_4 emission varied from 214 to 614 kg·hm^{-2}. Late-rice had significantly higher seasonal CH_4 emissions than early-rice: cumulative CH_4 emissions for late-rice were 1.2 times higher than those for early-rice (Table 2). CH_4 cumulative emissions during early- and late-rice seasons contributed 24%–55% and 45%–76% to the annual total CH_4 emissions, respectively (Table 2), which largely depended upon organic matter in the rice-growing season.

3.3 Effect of CMV and RS incorporation on N_2O

As shown in Fig. 3, similar temporal patterns of N_2O fluxes during the rice-growing season were observed across all the treatments, which were highly dependent on the water regime of the rice field. There was an initial flush of N_2O due to the input N fertilizer. Little N_2O was emitted during

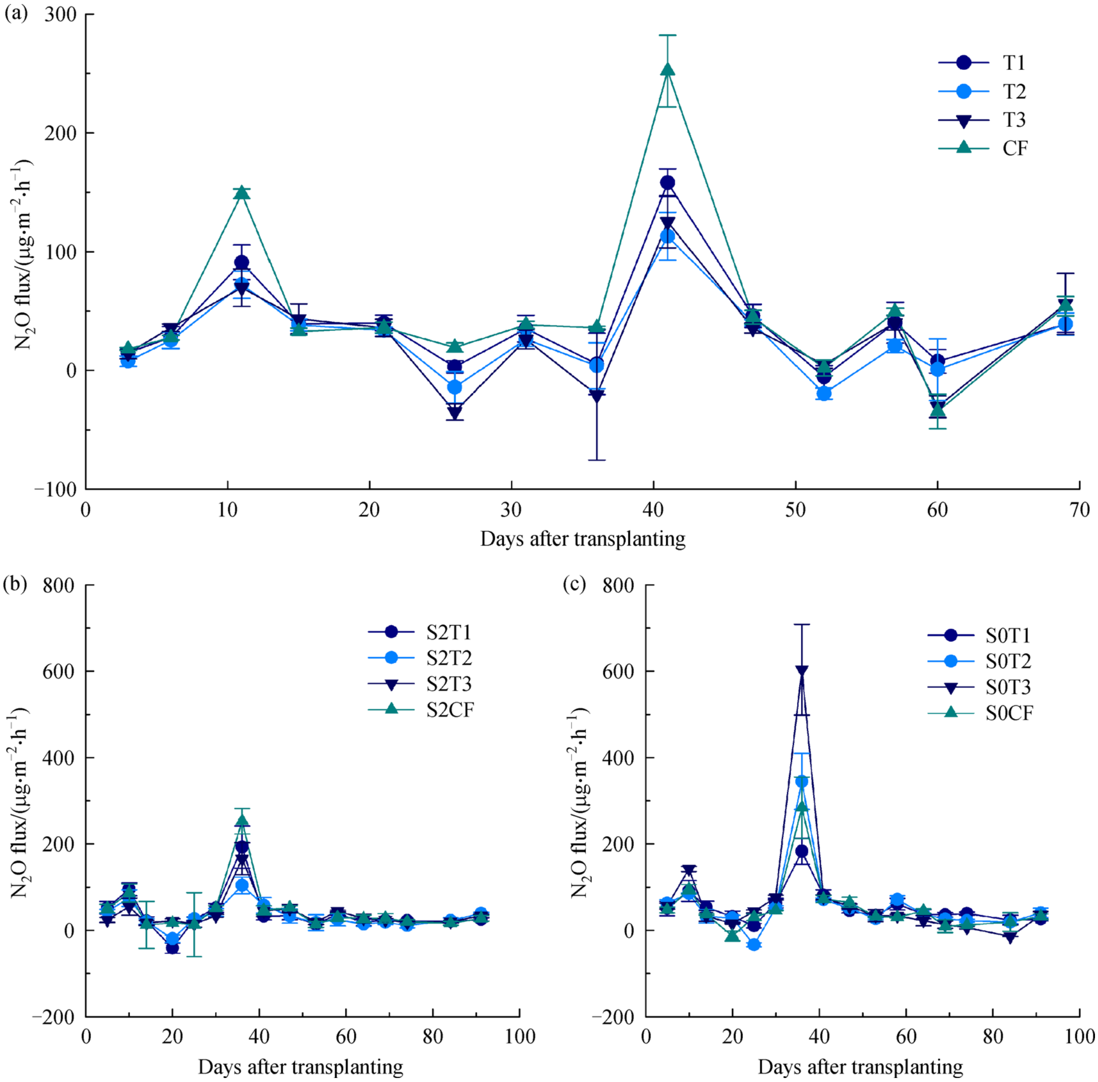

Fig. 3 Temporal variations of N_2O flux from paddy soils under different treatments during the early-rice (a) and late-rice (b, c) growing season in the double-rice cropping system. Error bars indicates the standard deviation of the means. See Table 1 for treatment codes.

the continuously flooded period. Negative values of N_2O flux were observed among all the treatments during the early- and late-rice growing seasons (Fig. 3). The two major peaks for all treatments were observed in each season, one soon after application of basal fertilizer and the other during MSD (Fig. 3). In the early-rice season, N_2O emissions varied between -35 and 307 $\mu g \cdot m^{-2} \cdot h^{-1}$. In the late-rice season, although the magnitude of emissions varied, N_2O emission followed similar patterns in treatments with straw and without RS. The N_2O fluxes ranged from -6.2 to 311 $\mu g \cdot m^{-2} \cdot h^{-1}$ in treatments with RS and from -61.5 to 789 $\mu g \cdot m^{-2} \cdot h^{-1}$ in those without RS (Fig. 3b, Fig. 3c). Obviously, the N_2O fluxes fluctuated more profoundly in treatments with RS than those without RS.

The cumulative emission of N_2O is given in Table 2. N_2O emissions were significantly affected by CMV and RS incorporation in this double rice cropping system. In the early-rice season, compared with the treatment CF, treatments amended with CMV produced less N_2O. The N_2O emissions from plots amended with CMV were mitigated by 24%–59%, which was significantly lower than CF (0.99 $kg \cdot hm^{-2}$) (Table 2). In the late-rice season, cumulative N_2O emissions differed greatly in all the treatments, ranging from 0.65 to 0.95 $kg \cdot hm^{-2}$ in the treatments with RS and from 1.08 to 1.59 $kg \cdot hm^{-2}$ in those without RS (Table 2). The addition of RS decreased N_2O emission by 36% compared to the treatments without RS (Table 2). Of all the treatments, the minimum of cumulative N_2O emission was recorded in the treatment S2T2 (0.65 $kg \cdot hm^{-2}$) and maximum in the treatment S0T3 (1.59 $kg \cdot hm^{-2}$) (Table 2). The N_2O emissions over the double-rice cropping year in all CMV- and RS-amended treatments were low, and annual cumulative N_2O emission did not exceed 1.6 $kg \cdot hm^{-2}$. The maximum of annual N_2O emissions over the double-rice growing year was observed in CF + S0CF (2.07 $kg \cdot hm^{-2}$).

3.4 Rice grain yields

Rice grain yields are given in Table 3. In the early-rice season, grain yields were influenced by CMV as well as application of inorganic fertilizer. Grain yields in plots amended with CMV were significantly higher than the control. In contrast to the control (5.07 $Mg \cdot hm^{-2}$), T1, T2 and T3 increased the early-rice grain yields by 11.6%, 9.9% and 6.5%, respectively (Table 3). However, no significant differences in the grain yields were found among the treatments with various rates of CMV. In the late-rice season, grain yields with RS amendment averaged 7.86 $Mg \cdot hm^{-2}$, a small increase of 0.6% compared to the treatments without RS (Table 3). No significant differences were observed with or without RS incorporation under the initial treatment in the early-rice season ($P > 0.05$) (Table 3). Over the whole year, CMV and/or RS addition increased grain yields by 0.4%–8.9% relative to mineral nitrogen alone. The maximum grain yield was observed in T2 + S2T2 (13.7 $Mg \cdot hm^{-2}$) and the minimum in the CF + S0CF treatment (12.6 $Mg \cdot hm^{-2}$).

3.5 Global warming potential and yield-scaled GWP

The GWP of CH_4 and N_2O over a 100-year horizon of the double-rice cropping system are shown in Table 4. The contribution of the annual cumulated CH_4 emission to the total GWP was 89.5%–97.8%, but the estimated N_2O flux contribution was low (Table 4). Among all the treatments in this double-rice cropping system, the minimum total GWP was recorded for CF + S0CF (5.95 $Mg \cdot hm^{-2}$ CO_2-eq) and the maximum with T3 + S2T3 (15.7 $Mg \cdot hm^{-2}$ CO_2-eq) in both seasons. Addition of CMV and/or RS increased GWP by 45%–139% (Table 4). Thus, the comprehensive impacts of CMV and RS incorporation on GWP was much higher than single application of synthetic N fertilizer.

The combined impacts of CMV and RS on GHG emissions and grain yields were evaluated by comparing the yield-scaled GWP (Table 4), which ranged from 0.47 to 1.19 Mg CO_2-eq per Mg grain yield. The CMV and RS addition significantly increased the yield-scaled GWP by 45%–153% compared with CF + S0CF (0.47 Mg CO_2-eq per Mg grain yield).

Table 3 Rice grain yields in a double rice cropping system

Early-rice season		Late-rice season		Double rice system
Treatment	Grain yield/($Mg \cdot hm^{-2}$)	Treatment	Grain yield/($Mg \cdot hm^{-2}$)	Grain yield/($Mg \cdot hm^{-2}$)
1	5.65 a	S2T1	7.93 bc	13.6 ab
		S0T1	7.88 c	13.5 b
T2	5.57 ab	S2T2	8.16 a	13.7 a
		S0T2	8.11 ab	13.7 ab
T2	5.41 b	S2T3	7.77 cd	13.2 c
		S0T3	7.72 cde	13.1 c
CF	5.07 c	S2CF	7.59 de	12.7 d
		S0CF	7.54 e	12.6 d

Note: Means with the same letter within a column are not significantly different according to LSD (0.05). See Table 1 for treatment codes.

Table 4 GWP over the 100 year horizon and yield-scaled GWP from rice system under different treatments

Treatment	CH_4		N_2O		Total GWP CO_2-eq CO_2 (Mg·hm^{-2} CO_2-eq)	Yield-scaled GWP (Mg CO_2-eq per Mg grain yield)
	CO_2-eq CO_2 (Mg·hm^{-2} CO_2-eq)	Percentage/%	CO_2-eq CO_2 (Mg·hm^{-2} CO_2-eq)	Percentage/%		
T1 + S2T1	13.7 ab	96.6 b	0.48 c	3.4 d	14.20 ab	1.05 b
T1 + S0T1	10.5 d	94.9 c	0.56 ab	5.1 c	11.00 d	0.81 de
T2 + S2T2	15.1 a	97.7 a	0.35 d	2.3 e	15.40 a	1.12 ab
T2 + S0T2	11.5 cd	95.7 bc	0.52 bc	4.3 cd	12.00 cd	0.88 cd
T3 + S2T3	15.4 a	97.8 a	0.35 d	2.2 e	15.70 a	1.19 a
T2 + S0T3	12.6 bc	95.5 c	0.60 a	4.5 c	13.20 bc	1.00 bc
CF + S2CF	8.0 e	93.3 d	0.58 ab	6.7 b	8.60 e	0.68 e
CF + S0CF	5.3 f	89.5 e	0.62 a	10.5 a	5.95 f	0.47 f

Note: For T1 + S2T1, T2 + S2T2 and T3 + S2T3, 15000, 22500 and 30000 kg·hm^{-2} Chinese milk vetch were incorporated in the early-rice season plus 2000 kg·hm^{-2} rice straw incorporation *in situ* in the late-rice season; T1 + S0T1, T2 + S0T2 and T3 + S0T3 represent 15000, 22500 and 30000 kg·hm^{-2} Chinese milk vetch incorporated in the early-rice season plus no rice straw incorporation in the late-rice season; CF + S2CF represents application of synthetic N fertilizer at a rate of 200 kg·hm^{-2} N in the early-rice season plus 2000 kg·hm^{-2} RS incorporation *in situ* after early-rice harvest; CF + S0CF represents application of synthetic N fertilizer at a rate of 200 kg·hm^{-2} N in each season. Means with the same letter within a column are not significantly different according to LSD (0.05).

4 Discussion

4.1 Effect on CH_4 emission

Organic fertilizers effect on CH_4 emissions have been extensively discussed in the literature. Previous studies have suggested that addition of organic materials to the rice soil increases the availability of methanogenic substrates and thereby enhances CH_4 emissions[15,19–21]. In this study, CMV and RS incorporation considerably increased CH_4 emission from rice paddies. In the current study, there were significant increases in CH_4 emissions after CMV and RS incorporation, which were supported by the observations of Lee et al.[13], Zhu et al.[14] and Zou et al.[16]. In comparison with a single application of synthetic N fertilizer in both seasons, the treatments amended with CMV and/or RS produced about 1.5–2.9 times more CH_4 emissions (Table 2). Moreover, in the early-rice season, seasonal CH_4 emissions ranged from 228–280 kg·hm^{-2} in the plots with CMV, which is in close accordance with a previous study[14]. In the late-rice season, CH_4 fluxes were significantly higher in the treatments with rice straw than without rice straw (on average, 313 vs. 190 kg·hm^{-2}) (Table 2). The reason for the increases in CH_4 emissions is because the CMV and RS incorporation provided much organic matter. As we know, biogenic methane production is exclusively accomplished by methanogens that can metabolize in the strict absence of oxygen. The incorporation of CMV and RS provide abundant C substrates via the decomposition of organic matters in the anaerobic soil and enhance CH_4 production[14,22–24]. Consequently, the abundant substrates largely favor methane-producing microbial activity in paddy soil, resulting in a great CH_4 emission flux. Given the spatial and temporal distribution of the CMV and RS, these seasonal totals are reasonably consistent with the quantities of organic materials added in each treatment (Fig. 2, Table 2).

4.2 Effect on N_2O emission

In the current study, the combined application of CMV and/or RS with synthetic N fertilizer significantly mitigated seasonal N_2O emissions in comparison with synthetic N only fertilizer (Table 3), irrespective of equal N inputs in each plot. In the early-rice season, the treatments amended with CMV inhibited N_2O emissions, ranging from 1.10 to 1.63 kg·hm^{-2}, which were obviously lower compared to CF (2.18 kg·hm^{-2}). Similarly, Zhu et al. reported that CMV in combination with synthetic fertilizer N significantly decreased N_2O emissions compared with pure synthetic fertilizer N[14]. In the late-rice season, the treatments amended with RS also decreased N_2O emission by 10%–30% relative to synthetic N fertilizer. This might be attributed to: (1) the decomposition of CMV and RS accelerates O_2 consumption in the aerobic soil layer and in the rhizospheres, generating a strictly aerobic environment, which is favorable for the N_2O transformed into N_2 through denitrification[16]; (2) the decomposition of straw with high C/N ratio may result in less N available for nitrification and denitrification, reducing N_2O production. However, a meta-analysis quantitatively suggested that returning crop residue to the soil has no obvious effect on N_2O emission compared with control[25]. In agricultural systems, N_2O is primarily produced in the soil through microbial nitrification and denitrification processes that are mainly affected by N substrate availability[26], which is greatly dependent on N inputs[25]. The mechanisms affecting N_2O emissions following crop residue incorporation involve very complex processes. Therefore, further research is required to determine the micro-processes in the soil associated with N_2O emission when crop residues are applied.

4.3 Effect on grain yields and aggregate emissions of CH_4 and N_2O

The current study has demonstrated that CMV as a green manure amendment can serve as an alternative to chemical fertilization to improve rice productivity. In the early-rice season, grain yields were significantly enhanced by CMV addition. The treatments amended with CMV attained significantly higher grain yields than the control. The findings were consistent with the result of Zhu et al.[14]. In the late-rice season, no significant differences were observed between treatments with and without RS with the same treatments in the early-rice. Likewise, Ma et al.[12] reported there were no differences in grain yield between treatments with and without wheat straw addition. Over the whole double-rice year, CMV and/or RS incorporation increased grain yield by 0.4%–8.9% relative to synthetic N fertilizer alone.

A trade-off relationship between the emission of CH_4 and N_2O was found during the rice-growing seasons (Fig. 2, Fig. 3), which was consistent with the results reported for other studies[14,17,27]. In contrast to pure fertilizer application, the plots amended with crop residues emitted more CH_4, but N_2O emissions were reduced. However, over the rice growing year, the amount of N_2O emission was negligible compared to the amount of CH_4 emission (Table 4). Accordingly, efforts to reduce GWP should focus primarily on CH_4 rather than N_2O in double-rice cropping systems.

To access better the combined climatic impacts from CH_4 and N_2O under various treatments, the aggregate emissions of CH_4 and N_2O were expressed in CO_2 equivalents. When CH_4 and N_2O emissions were expressed as CO_2 equivalents, the major contributor to GWP over the whole growing year was clearly CH_4, which represented most of the total GWP across the year (Table 4). This result was consistent with the findings of previous studies in rice paddies[14,18].

The CMV and RS incorporation did increase the GWP compared to pure synthetic N fertilizer by 45%–139% over the double-rice cropping year (Table 4). This result is supported by numerous studies on rice production systems differing in fertilizer application[10,14]. Combining GWP (CH_4 and N_2O) and grain yield, this study provided yield-scale GWP for organic and inorganic fertilizer application in typical double-rice cropping systems. In the current study, grain yields and CH_4 emissions both increased with the application of organic and inorganic fertilizer. In contrast, the treatments with CMV and/or RS incorporation mitigated N_2O emission. However, the quantity of N_2O emission was negligible compared to the amount of CH_4 emission. The minimum of yield-scaled GWP was found with the synthetic N fertilizer only treatment (0.47 Mg CO_2-eq per Mg grain yield). The CMV and/or RS addition significantly increased the yield-scaled GWP by 45%–153% compared with CF + S0CF. Similarly, Shang et al.[28] observed that the combined inorganic and organic fertilizer application greatly increased yield-scaled GWP. Based on the results of grain yields, GHG emissions, GWP and yield-scaled GWP, balanced fertilizer application, especially N nutrient supplement, and proper crop residues management is needed to sustain soil fertility, increase soil organic matter, reduce the amount of fertilizers applied into field, and contribute to rice production while mitigating GHG emissions[29]. Thus, optimizing agricultural managements could simultaneously improce grain yield and mitigate GHG emissions from rice paddies, which is the critical challenge of agricultural sustainability.

5 Conclusions

CMV and RS incorporation into paddy soil can substitute for a proportion of chemical fertilizer, reducing synthetic N fertilizer application. Although our experiment was relatively short, our results show that crop residues are important factors for GHG emissions. CMV and/or RS incorporation enhanced the CH_4 emissions and mitigated N_2O emissions during the double-rice growing year. The combination of CMV and/or RS with synthetic fertilizer application increased grain yields in double-rice cropping system. Therefore, adopting an effective crop residue management strategy for mitigating climatic impacts requires a complete perspective on the agriculture impacts. Additionally, some management practices associated with crop residues incorporation should be optimized to promote the incorporation of green manure and straw, making the practices simply and feasible. Considering mitigating GHG emissions and promoting grain yield, some specific practices should be taken into account and crop residue management and alternative straw recycling methods deserved more attention.

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