Does replacing chemical fertilizer with ryegrass (Lolium multiflorum Lam.) mitigate CH4 and N2O emissions and reduce global warming potential from paddy soil?

Wei Yang (1813671233@qq.com)
Yangtze University
Lai Yao
Xueru Ji
Mengzhen Zhu
Chengwei Li
Shaoqiu Li
Bin Wang
Zhangyong Liu
Bo Zhu

Research Article

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Abstract

(*Purpose*)

The incorporation of ryegrass (*Lolium multiflorum* Lam.; RG), a winter grass manure, could partly replace chemical N and reduce N loss during the succeeding rice seasons, but little is known about its impact on greenhouse gas emission. This study investigated the effect of different RG-urea substitution ratios (0%, 25%, 50%, 75% and 100%) on C and N release, CH_4 and N_2O emissions in a paddy soil.

(*Methods*)

Gas samples for CH_4 and N_2O fluxes measurement were collected by using a closed chamber and determined by chromatograph method. C and N release from the incorporated RG residue were tested by a mesh bag method.

(*Results*)

C and N release from RG followed a single exponential decay model, with 95.5%-97.8% of the original C and 98.7%-99.3% of N released during 192 days. RG-urea substitution ratio increased CH_4 emission, but was negatively correlated with N_2O emission. In comparison with 0% substitution, global warming potential (GWP) and greenhouse gas intensity (GHGI) were not significantly different for the 25% and 50% RG substitutions, but were significantly higher for the 75% and 100% substitutions (P<0.05). Soil redox, C and N remaining in litter residue were key characteristics explaining CH_4 emission, while NH_4^+-N and NO_3^--N concentrations were correlated with the variation of N_2O emission.

(*Conclusion*)

The increased CH_4 emission by RG incorporation could be offset by the reduced N_2O emission when RG-urea substitution ratio was 50% or less.

Introduction

Methane (CH_4) and nitrous oxide (N_2O) are important greenhouse gases (GHGs) responsible for global climate change (Stocker 2014). Rice paddy soil is one of the important sources for CH_4 and N_2O production, and accounts for a significant proportion of global GHG emissions (Carter et al. 2014). Rice paddies are responsible for 48% of total anthropogenic CH_4 emission from agriculture (Carlson et al. 2016), while N_2O emission from paddy soils contributes 19%-25% of the of the global N_2O emissions (Van Groenigen et al. 2011). Therefore, it is crucial to mitigate GHG emissions from paddy soils in most rice production regions to maintain a sustainable grain food supply.

Green manure incorporation and chemical nitrogen (N) fertilizer applications are common soil management practices that may impact CH_4 and N_2O emissions. First, the release of organic carbon (C) and inorganic N from these fertilizers determines the availability of substrates for CH_4 and N_2O releasing microorganisms, such as methanogenic bacteria (Liu et al. 2022) and methanogenic *Archaea* (Zhang et al. 2018), ammonia oxidizers (Gao et al. 2020) and denitrifiers (Huang et al. 2020). Several studies have reported increased CH_4 emission after organic amendments such as green manure (Haque et al. 2012), crop residue and animal manure incorporation (Bhattacharyya et al. 2012; Nguyen et al. 2020). N_2O emission peaks are usually observed immediately after intensive chemical N fertilizer application (Shaukat et al. 2019). Meanwhile, soil conditions that drive CH_4 and N_2O formation and consumption may be greatly changed following organic matter returning and fertilizer application. For example, during the early stage of organic matter decomposition, the reduced dissolved oxygen concentration and soil pH and the increased dissolved organic C availability in the paddy soil (Xu et al. 2017) provide a favorable condition for methanogens, thereby enhancing CH_4 production during the rice growing seasons (Zhou et al. 2020).

The rapidly rising soil NH_4^+-N and NO_3^--N concentrations after chemical N fertilizer application benefit nitrification and denitrification, and increase the potential of N loss in the form of N_2O (Cecilio et al. 2022; Zhu et al. 2013). Replacing chemical N with green manures has potential to reduce N_2O emission because inorganic N release from the incorporated organic matter is much slower than from chemical fertilizers (Mehnaz et al. 2019; Zhu et al. 2014). However, acetate released during anaerobic decomposition of organic matter acts as a terminal electron acceptor for respiration and provides substrate for methanogens activities, resulting in increased CH_4 emissions (Amin et al. 2021).

The ratio of substitution of organic for chemical fertilizer is an important factor for determining C and N dynamics after fertilization (Lashermes et al. 2010) as well as the consequent changes in soil environment (Hou et al. 2022). In addition, the complex interaction between organic material and inorganic N under different organic-chemical N substitution ratio greatly affects CH_4 and N_2O emissions (Zou et al. 2009).

An important aspect concerning GHG production in paddy soil is the comparison of radiative forcing from different GHGs. The global warming potential (GWP) calculation integrates the radiative forcing of CH_4 and N_2O emissions into “CO_2-equivalents” (Robertson and Grace 2004). Greenhouse gas intensity (GHGI) is calculated by dividing GWP by grain yield and is used to relate GHG emission and food production (Shang et al. 2011).

Ryegrass (*Lolium multiflorum* Lam.; RG), a commonly used green manure in paddy soils, has the potential to partly replace chemical N fertilizers in most Asian countries. Increased rice yield and N use efficiency have been observed after ryegrass incorporation alone or in combination with urea (Asagi and Ueno 2009; Zhu et al. 2014). However, the impacts of RG-urea substitution ratio on CH_4 and N_2O emissions remains poorly understood. The objectives of this study were to: (1) estimate changes in CH_4 and N_2O emissions during rice growing seasons under different RG-urea substitution ratios; (2) quantify C and N release from RG residue under different RG-urea substitution ratios; (3) measure the relationship between GHGs and soil properties after RG incorporation.

Materials And Methods

Experimental description

Two open glasshouse pot experiments were conducted at the experimental station of Yangtze University, Jingzhou, Hubei Province, China (30°20'N, 112°12'E) in 2021. The regional climate was subtropical with annual mean air temperature 16.5°C and precipitation 1200 mm. The paddy soil (0-15cm) was collected from a nearby farmer's paddy field followed by manual removal of stems, roots, stones, etc. The soil was then air-dried and sieved to pass 2 cm mesh. Soil properties were: sand 265 g kg^{-1}, clay 134 g kg^{-1}, silt 601 g kg^{-1}, pH 6.2, total N 1.4 g kg^{-1}, organic C content of 14.2 g kg^{-1}, available phosphorus 15.6 mg kg^{-1} and available potassium 87.0 mg kg^{-1}. The fresh RG (*cv*. Muteli) aboveground litter had moisture content 79%, dry matter N content 4.94% and dry matter C content 38.1%.

Experiment 1: effects of RG-urea substitution ratio on CH_4 and N_2O emission

The experiment comprised five RG-urea substitution ratios: 0%, 25%, 50%, 75% and 100% with 3 replicates for each treatment. All the treatments received a total amount N at a rate of 100 mg N kg^{-1} air-dried soil. The details for RG and urea application amount in each treatment were shown in Table 1. Plastic pots (20 cm in diameter and 15 cm in height), each containing 3 kg air-dried soil was used. The aboveground litter of RG was weighed, cut into 2–3 cm pieces and thoroughly mixed with soil in mid-April 2021. Superphosphate and potassium chloride were applied at 0.61 g kg^{-1} and 0.21 g kg^{-1} air-dried soil, respectively. On April 25, three rice seedlings (cv. Tianliangyou 616, 30 d old) were transplanted per pot. The seedlings were watered to 2 cm flooding depth and received no topdressing fertilizer during the whole growing season. The plants were harvested at 40 cm cutting height for the first maturity, leaving the stubbles for ratooning to get a second harvest.

Table 1
The amount of C and N contributions for each treatment by RG or urea application

Treatment	**N applied from urea (g pot^{-1})**	**N applied from RG (g pot^{-1})**	**C applied from RG (g pot^{-1})**
0% RG	0.3	0	0
25% RG	0.225	0.075	0.58
50% RG	0.15	0.15	1.16
75% RG	0.075	0.225	1.74
100% RG	0	0	2.31

Experiment 2: C and N release during RG decomposition

In experiment 2, the mesh bag method (Zhu et al. 2014) was used to measure C and N release dynamics from the incorporated RG litter. Treatments were the same as in experiment 1. RG aboveground litter was cut and placed in 0.5mm mesh size nylon bags (10 cm × 10 cm) and buried in the soil with 39 replications for each treatment.

Sampling and analysis

In Experiment 1, gas samples for CH_4 and N_2O fluxes measurement were collected using a static chamber (Zhang et al. 2020) at 3–7 d intervals after RG incorporation until the harvest of the ratoon crop. The pot with plant was placed in a closed PVP pipe chamber (height 110 cm, diameter 25 cm). An electric fan at the top of the chamber was used to mix the air in the chamber. The gas samples were collected from the chamber at 0, 10 and 20 min between 9:00 and 11:00 am and transferred to 0.5 L sample bags. CH_4 and N_2O concentrations were determined by gas chromatography (Agilent 7890 B, USA) with a flame ionization detector (FID) at 200°C and an electron capture detector (ECD) at 330°C, respectively. Soil pH and redox state (Eh) were simultaneously measured by pH meter (Leici PHS-25, China) and ORP meter (Leici TR-901, China), respectively.

In Experiment 2, RG residue in nylon mesh bags was collected 14, 24, 29, 34, 42, 48, 55, 69, 83, 111, 139, 167 and 192 days after incorporation (n = 3). The residue was carefully washed with tap water, oven-dried at 80°C to constant weight, weighed, ground and sieved (100 mesh). C and N contents in RG residue were determined by an elemental analyzer (Costech ECS4010, Italy). Soil samples were collected at three random locations for each pot and mixed thoroughly for ammonium (NH_4^+-N) and nitrate (NO_3^--N) concentrations measurements by using a UV spectrophotometer (Hash DR6000, China) after extraction with 2 mol L^{-1} KCl.

Calculations

The CH_4 and N_2O fluxes were calculated in detail as follows:

$$F = p \times h \times dc/dt \times 273/(273 + T)$$

where *F* is CH_4 flux (mg m^{-2} h^{-1}) or N_2O flux (μg m^{-2} h^{-1}); *p* is density of CH_4 or N_2O under the standard temperature and pressure (CH_4 0.714 kg/m^3, N_2O 1.964 kg/m^3); *h* is the height of the chamber (cm); *dc/dt* is the change of CH_4 or N_2O concentration (mg m^{-3}) over time (h); *T* is the air temperature inside the chamber (°C).

The seasonal CH_4 or N_2O emission was calculated as follows:

$$\text{SeasonalCH}_4\text{orN}_2\text{Ocumulativeemissions} = \sum_{i=1}^{n} \frac{F_i + F_{i-1}}{2} \times (D_{i+1} - D_i)$$

where F is the CH_4 ($mg\ m^{-2}\ h^{-1}$) or N_2O ($\mu g\ m^{-2}\ h^{-1}$) flux, i is the sampling time, D_{i+1}-D_i is the number of days between two adjacent sampling time (h), and n is the total number of sampling intervals.

Global warming potential (GWP) was calculated as the sum of N_2O (GWP_{N2O}) and CH_4 (GWP_{CH4}) as IPCC (2021):

$$\mathrm{GWP}(\mathrm{gCO_2-eq}m^{-2}) = 29.8 \times \mathrm{CH_4}\left(\mathrm{gm^{-2}}\right) + 273 \times \mathrm{N_2O}\left(\mathrm{gm^{-2}}\right)$$

The greenhouse gas intensity (GHGI) was calculated as follows:

$$\mathrm{GHGI(gGWPpergofyield)} = \mathrm{GWP}(\mathrm{gCO_2-eq}m^{-2})\,/\,\mathrm{grainyield}\left(\mathrm{g}m^{-2}\right)$$

Percentage of C and N remaining in RG residues were calculated as described by Zhu et al. (2014):

$$\mathrm{Yc}(\%) = \frac{\mathrm{Yt}}{\mathrm{Yi}} \times 100$$

where Yc is the C or N remaining percent of RG residue, Yt is the C or N content of RG residues at each sampling time, Yi is the original C or N content in RG.

An exponential decay model was used to describe C and N release from RG litter over time as follows:

$$\mathrm{YR} = \mathrm{exp}^{-\mathrm{kt}} \times 100$$

where YR is C or N remaining in RG residue at time t and k is the C (k_C) or N (k_N) release rate.

Statistical analysis

Analysis of variance (ANOVA) for RG substitution ratio on CH_4 and N_2O emission fluxes, GWP, GHGI, grain yield and soil properties was conducted with SPSS Statistics 19.0 (IBM Co., NY, USA). The multiple comparisons significant differences were set at $P < 0.05$. Pearson correlation analysis was used to examine the correlation between greenhouse gas emissions and soil properties. Canoco 5 (Beijing Huanzhong Ruichi Technology Co., LTD, China) was used to make the redundancy analysis (RDA) between GHG emissions and soil properties.

Result

CH_4 and N_2O emissions

A major peak was observed at 38 d after urea and RG application for CH_4 emissions (Fig. 1a), and at 17 d for N_2O emissions (Fig. 2a). Several minor peaks were also detected for CH_4 and N_2O emissions during the whole observing seasons. The highest CH_4 peaks were found in the 100% RG treatment (41.3 mg m^{-2}

h^{-1}), followed by 75% RG, 50% RG, 25% RG and 0% RG (Fig. 1a). By contrast, N_2O peaks were observed to be highest in 0% RG (784.9 μg m^{-2} h^{-1}) and decreased with the rising RG-urea substitution ratio (Fig. 2a).

Most of the CH_4 (54.3%-63.7%) was emitted before the tillering stage and 73.7%-82.1% of the CH_4 emission took place before the first season maturity. Regression analysis showed that there was a significant quadratic relationship between RG-urea substitution ratio and total CH_4 emission (R^2 = 0.99, $p < 0.01$; Fig. 1b). When it came to N_2O, 65.4%-79.6% of the seasonal emissions occurred before the tillering stage and 91.5%-98.3% of the total emissions were contributed before the first season maturity. A significant quadratic relationship was identified between RG-urea substitution ratio and total N_2O emission (Fig. 2b; R^2 = 0.99, $p < 0.01$).

Global warming potential and greenhouse gas intensity

The GWP for seasonal CH_4 and N_2O emissions showed a significant quadratic relationship with RG-urea substitution ratio (Fig. 3a; R^2 = 0.99, $p < 0.05$). The values for GWP were lowest in the 25% and 50% RG treatments (6.3% and 6.5% lower than 0% RG, respectively), which were significantly lower than those in 75% and 100% RG. As shown in Table 2, contribution of CH_4 emission to the GWP (71.7%-96.7%) was much higher than that from N_2O emission (3.3%-28.3%). CH_4 and N_2O emissions from the first 45 d of the experiment accounted for 47.5%-56.4% of the total GWP while comparable total GWP (43.6%-52.5%) were detected in the relatively longer following 46–125 d (Fig. 3b).

Table 2
Total global warming potential (GWP), CH_4 and N_2O-induced GWP, grain yield, greenhouse gas intensity (GHGI) as affected by ryegrass (RG)-urea substitution

Treatment	CH_4-induced GWP[a]		N_2O -induced GWP[b]		Total GWP (g CO_2-eq m^{-2})	Grain yield (g m^{-2})	GHGI (kg CO_2-eq kg^{-1} yield)
	GWP (g CO_2-eq m^{-2})	Account for total GWP[c] (%)	GWP (g CO_2-eq m^{-2})	Account for total GWP (%)			
0% RG	277.1 d[d]	71.7	109.4 a	28.3	386.5 c	796.3 a	0.49 c
25% RG	291.6 d	80.5	70.5 b	19.5	362.1 c	773.7 a	0.47 c
50% RG	323.0 c	89.3	38.5 c	10.7	361.5 c	747.2 a	0.48 c
75% RG	455.0 b	93.7	30.8 c	6.3	485.8 b	639.2 b	0.76 b
100% RG	595.6 a	96.7	20.6 c	3.3	616.2 a	594.9 b	1.04 a

[a]Global warming potential calculated from CH_4 emission

[b]Global warming potential calculated from N_2O emission

[c]The percentage of CH_4 or N_2O induced GWP to the total GWP

[d]Different letters within the same column mean significant differences at $p < 0.05$ level.

Rice grain yield in the 25% and 50% RG treatments was not significantly different from that in the 0% RG treatment, but was significantly higher than that in the 75% and 100% RG treatments (Table 2; $p < 0.05$). Similar as GWP, GHGI was higher in the 75% and 100% RG treatments as compared to the 0%, 25% and 50% RG treatments (Table 2).

C and N release from RG residue

The majority of C (83.2%-86.9%) and N (97.4%-97.5%) from the incorporated RG residue was released during the first 29 d after start of the experiment (Figs. 4a and b). At the end of experiment, less than 4.5% of C and 1.3% of N remaining remained in RG residue. The decay exponential model successfully described C ($R^2 = 0.92–0.94$, $p < 0.05$) and N ($R^2 = 0.98–0.99$, $p < 0.05$) release dynamics after RG incorporation in the paddy soil (Table 3). The values for k_N were generally higher than for k_C (0.0877–

0.1368 *vs* 0.0689-0.0800), indicating N release from RG residue was faster than C release. The values for k_N increased with higher RG-urea substitution ratio while the opposite was true for k_C (Table 3).

Table 3
The rate of C (k_C) and N releases (k_N) from ryegrass (RG) residue under different RG-urea substitution ratios, estimated using a single exponential model

Treatment	K_C	r^2	K_N	r^2
25% RG	0.0800	0.9177	0.0877	0.9791
50% RG	0.0697	0.9400	0.1104	0.9948
75% RG	0.0706	0.9255	0.1368	0.9978
100% RG	0.0689	0.9251	0.1254	0.9975

Importance of soil properties for CH_4 and N_2O emissions

Soil NH_4^+-N concentrations were much higher than NO_3^--N concentrations during the experiment (Figs. 5a and b). Both NH_4^+-N and NO_3^--N increased steadily and peaked 14–29 d after RG and urea application. NH_4^+-N and NO_3^--N appeared to be highest in 0% RG and lowest in 100% RG treatment. Redox state (Eh value) decreased gradually within 30–40 d after the start of the experiment and increased steadily thereafter. Lower Eh values tended to be observed in higher RG-urea substitution ratios (Fig. 5c). Soil pH was reduced during the first two months especially for the 25%, 50% and 100% RG treatments (Fig. 5d).

Distance-based RDA showed that the first two components accounted for 99.5% of the variation in CH_4 and N_2O emissions (Figs. 6a and c). C remaining ($F = 49.8$, $p = 0.002$), N remaining ($F = 7.8$, $p = 0.014$) and soil Eh ($F = 6.9$, $p = 0.032$) had a significant impact on CH_4 emission when NH_4^+-N ($F = 15.4$, $p = 0.004$) and NO_3^--N ($F = 6.6$, $p = 0.034$) showed a significant impact on N_2O emission (Table 4). Variance decomposition showed that 90.3% of the variance of CH_4 emission could be explained by C and N remaining in RG residue, soil Eh and other indicators (Fig. 6b), while 84% of the variance of N_2O emission was explained by soil NH_4^+-N, NO_3^--N and C remaining in RG residue (Fig. 6d).

Table 4
Results of ANOVA RDA model

Soil factors	CH_4		N_2O	
	F	*p*	F	*p*
Eh	6.9	0.032*[a]	3.6	0.092
pH	0.8	0.402	0.3	0.568
NH_4^+-N	1.8	0.214	15.4	0.004**
NO_3^--N	0.6	0.402	6.6	0.034*
C remaining	49.8	0.002**[b]	5.1	0.056
N remaining	7.8	0.014*	1.5	0.276

[a]Significant differences at $p < 0.05$ level

[b]Significant differences at $p < 0.01$ level

Discussion

Effects of RG-urea substitution ratio on CH_4 emission

Incorporation of organic amendments such as green manure and crop straw in an important soil practice to increase biological C fixing in agricultural fields, but the enhanced active C input may stimulate CH_4 production in paddy soils (Fu et al. 2018). This was confirmed by the rapidly increasing CH_4 emission after RG incorporation, especially in the treatments with high RG-urea substitution ratios (Fig. 1). Dramatically increased CH_4 emissions have also been reported in flooded paddy soils with fresh green manure incorporation (Lee et al. 2010; Liu et al. 2019). In this study, major CH_4 emissions took place at the time of rapid C release from RG residue, suggesting that C input by RG incorporation was an important source for CH_4 production (Fig. 1a, Fig. 4a). RG-urea substitution ratio affected the rate of green manure decomposition, which consequently determined the availability of soil C substrates for methanogens (Dalal et al. 2008; Xu et al. 2017).

Soil condition is another factor affecting the activity of methanogens and methane-oxidizing bacteria which are responsible for CH_4 production and consumption in the soil. In the present study, Effects of soil condition changes by RG-urea substitution ratio on GHG emission could be better measured in a pot study than in field experiments, because some undesirable interferences such as rainfall and leaching could be well prevented. In the present study, rapid decomposition of RG litter may have reduced dissolved oxygen concentration in the flooded paddy soil, resulting in a decrease of soil Eh (Fig. 5c). A low Eh provides a suitable condition for methanogens and reduces CH_4 oxidation in the soil (Muhammad et al. 2020). Significantly higher CH_4 emissions in low redox soils have also been reported by Fan et al. (2020) and Xu et al. (2017). About 5% of the variance in CH_4 emission was explained by changes in soil Eh while 0.6% was explained by pH (Fig. 6b). Decreased soil pH by RG incorporation (Fig. 5d) was attributed to the formation of small organic acids such as acetic acid and butanoic acid during the process of RG fermentation. This lower pH and increased acetic acid availability stimulates the activity of methanogens (Baumann et al. 2009; Qualls 2005).

Effects of RG-urea substitution ratio on N_2O emission

Green manure applied alone or in conjunction with chemical fertilizers has been reported to improve total N use efficiency and decrease N losses into the environment (Gao et al. 2020; Liang et al. 2022; Zhu et al. 2012). However, the results of observations on N_2O emission, a form of gaseous N loss in paddy fields, are inconsistent. Some reported significant N_2O emissions after fertilization with chemical N (Shaukat et al. 2019; Xu et al. 2022). Others found negligible N_2O emissions over the entire rice growing season (Chen et al. 2021; Cowan et al. 2021). In the current study, a major N_2O peak was detected following urea application while several minor peaks were afterwards (Fig. 2a). Similar as with Zhang et al. (2020), both the major peak and seasonal N_2O emissions were significantly decreased with the increase of RG-urea substitution ratio, in spite that the soils received a same amount of total N input (Fig. 2). Soil mineral N concentrations, especially NH_4^+-N content, were significantly decreased with RG-urea substitution ratio in the peaking stage (Fig. 5a). This may result in a reduced N available for nitrification or coupled nitrification-denitrification which are the main mechanisms for N_2O production in agricultural soils (Gao et al. 2020; Nie et al. 2021). In addition, the lower redox condition which may reduce the activity of ammonia oxidizers (Tao et al. 2018). These results supported the beneficial effect of replacing chemical N with green manure on N_2O mitigation. To trace N_2O production from different N sources in a paddy ecosystem, ^{15}N labeled green manure or chemical fertilizer should be used in further studies.

Global warming potential and greenhouse gas intensity

The assessment of GWP is important because of the dramatically different effects of RG substitution on CH_4 and N_2O emissions in this study. The majority of GWP (71.7%-96.7%) were caused by CH_4 emission, confirming that CH_4 is the dominant GHG responsible for radiative forcing in the studied paddy soil (Peyron et al. 2016; Wang et al. 2016). Nevertheless, GWP in 25% and 50% RG-urea substitution ratios were slightly decreased when compared with 0% RG (361.5-362.1g CO_2-eq m^{-2} *vs* 386.5 g CO_2-eq m^{-2}) while CH_4-induced GWP increased with RG-urea substitution ratio (Table 2). This confirms a positive trade-off between CH_4 emission and N_2O emission for the 25% and 50% RG-urea substitution treatments (Shang et al. 2011). However, RG-urea substitution ratios higher than 50% tended to increase GWP due to the rising CH_4 emission. Nearly half of the GWP was observed during the first 45 d after fertilization (Fig. 3b), suggesting that GHG mitigation strategies in paddy soil with organic matter incorporation should be focused on the early stages of organic material decomposition and rice growth. Shang et al. (2011) suggest incorporating organic matter when the soil is drained and before rice is planted in order to minimize CH_4 and N_2O emissions. Because rice grain yields were not significantly decreased by 25% and 50% RG-urea substitution ratios, their GHGI values were comparable with 0% RG (Table 2). The increased GHGI under 75% and 100% RG-urea substitution could both be attributed to the promoted GWP and the reduced grain yields.

Conclusions

This study demonstrated that RG-urea substitution ratio played an important role in CH_4 and N_2O emissions. CH_4 emissions were positively related with RG-urea substitution ratio, while the opposite was true for N_2O emissions. Compared with 0% RG, the increased CH_4 emissions in the 25% RG and 50% RG substitution ratios were offset by decreased N_2O emissions, leading to comparable GWP and GHGI values. The RG-urea substitution ratio affected C and N release from RG residues, which further affected CH_4 and N_2O emissions in the paddy soil. Soil Eh, C and N remaining were key characteristics correlated with CH_4 emission while NH_4^+-N, NO_3^--N and C remaining were main factors on N_2O emissions. As CH_4 was the main contributor to GWP in paddy soils, further studies should be taken to reduce CH_4 fluxes, especially in the early stage of organic matter returning.

Abbreviations

RG, ryegrass; GWP, global warming potential; GHGI, greenhouse gas intensity.

Declarations

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Author Contributions

Bo Zhu and Zhangyong Liu designed the experiments. Wei Yang, Lai Yao, Mengzhen Zhu, Xueru Ji, Chengwei Li and Shaoqiu Li performed the experiments and data collection. Wei Yang and Bin Wang analyzed the data and Bo Zhu wrote the first draft of the manuscript.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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Figures

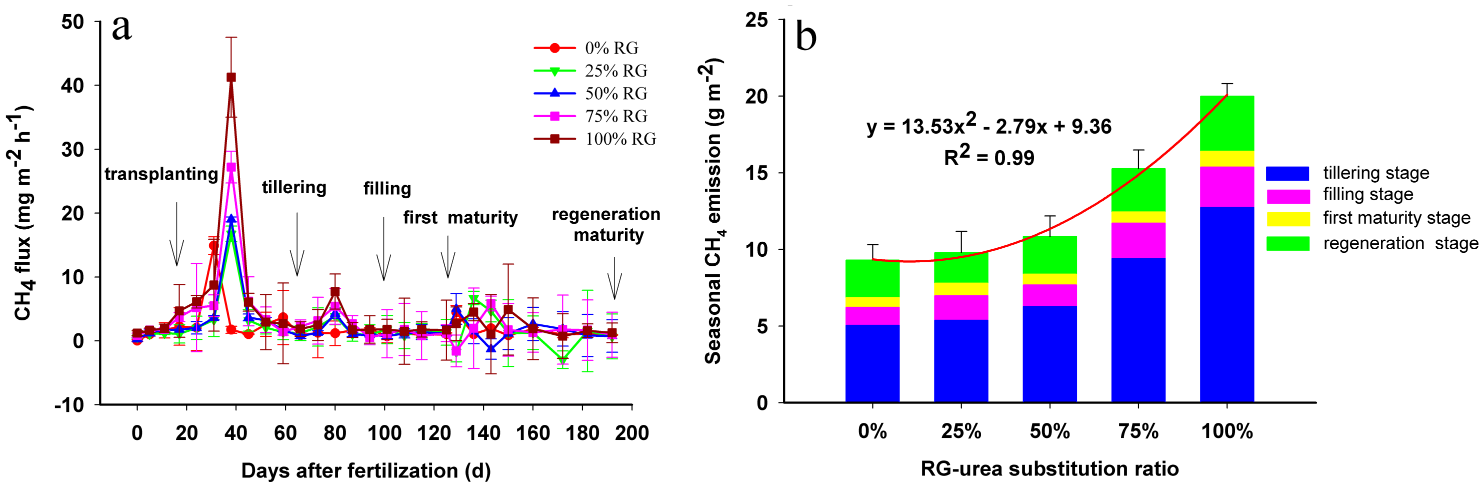

Figure 1

CH_4 emission flux (a) and cumulative CH_4 emissions (b) of different RG-urea substitution ratios: 0% RG, 25% RG, 50% RG, 75% RG, 100% RG. Tillering stage represents cumulative CH_4 emissions from the start of experiment to rice tillering stage, filling stage represents cumulative CH_4 emissions from tillering stage to rice filling stage, first maturity represents cumulative CH_4 emissions from filling stage to first season rice maturity, second maturity represents cumulative CH_4 emissions from first season harvest to the second season maturity. Bars indicate the SE (standard error). The quadratic linear regression relationship between CH_4 cumulative emission and RG-urea substitution ratio was significant ($P < 0.01$).

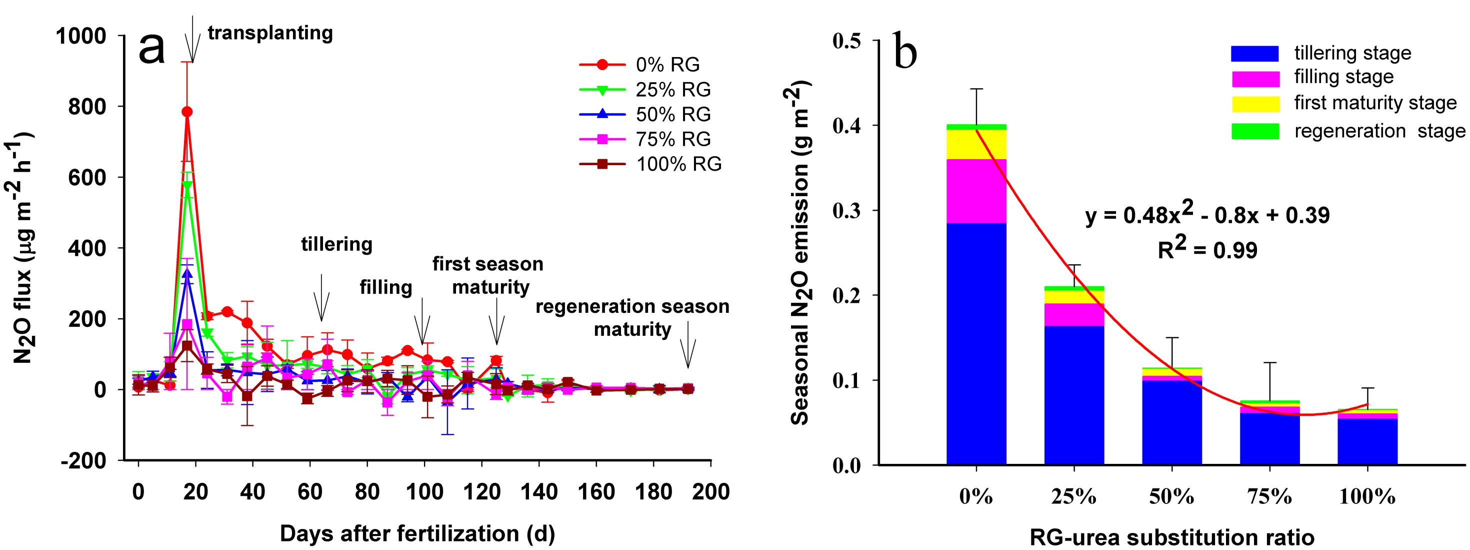

Figure 2

N_2O emission flux (a) and cumulative N_2O emissions (b) of different RG-urea substitution ratios: 0% RG, 25% RG, 50% RG, 75% RG, 100% RG. Tillering stage represents cumulative N_2O emissions from the start of experiment to rice tillering stage, filling stage represents cumulative N_2O emissions from tillering stage to rice filling stage, first maturity represents cumulative N_2O emissions from filling stage to first season rice maturity, second maturity represents cumulative N_2O emissions from first season harvest to the second season maturity. Bars indicate the SE (standard error). The quadratic linear regression relationship between N_2O cumulative emission and RG-urea substitution ratio was significant ($P < 0.01$).

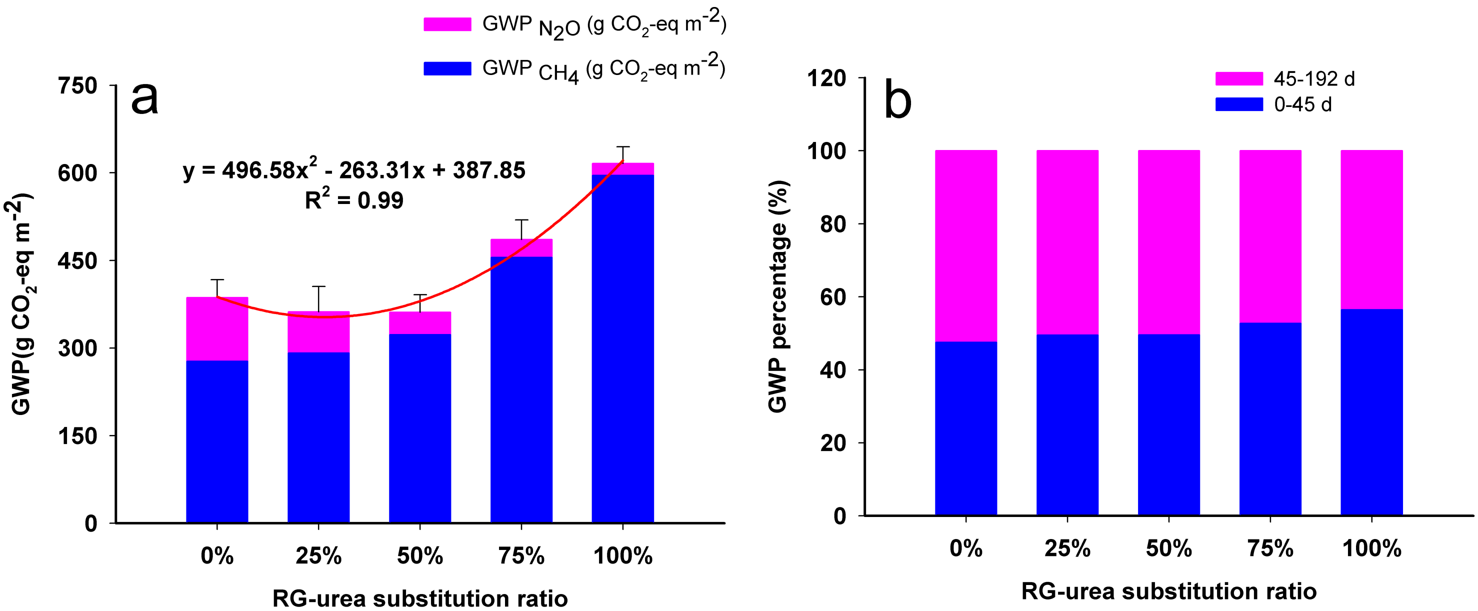

Figure 3

Global warming potential (GWP, a) of different RG-urea substitution ratios: 0% RG, 25% RG, 50% RG, 75% RG and 100% RG. GWP_{CH4} represents GWP caused by CH_4 emission, GWP_{N2O} represents GWP caused by N_2O emission. Bars indicate the SE (standard error). The quadratic linear regression relationship between GWP and RG-urea substitution ratio was significant ($P < 0.01$). Percentage of GWP (b) before and after major CH_4 peaks. 0-45d represents GWP calculated by cumulated CH_4 and N_2O emissions from the start of fertilization to 45 days, 45-192d represents GWP calculated by cumulated CH_4 and N_2O emissions from 45 days to 192 days.

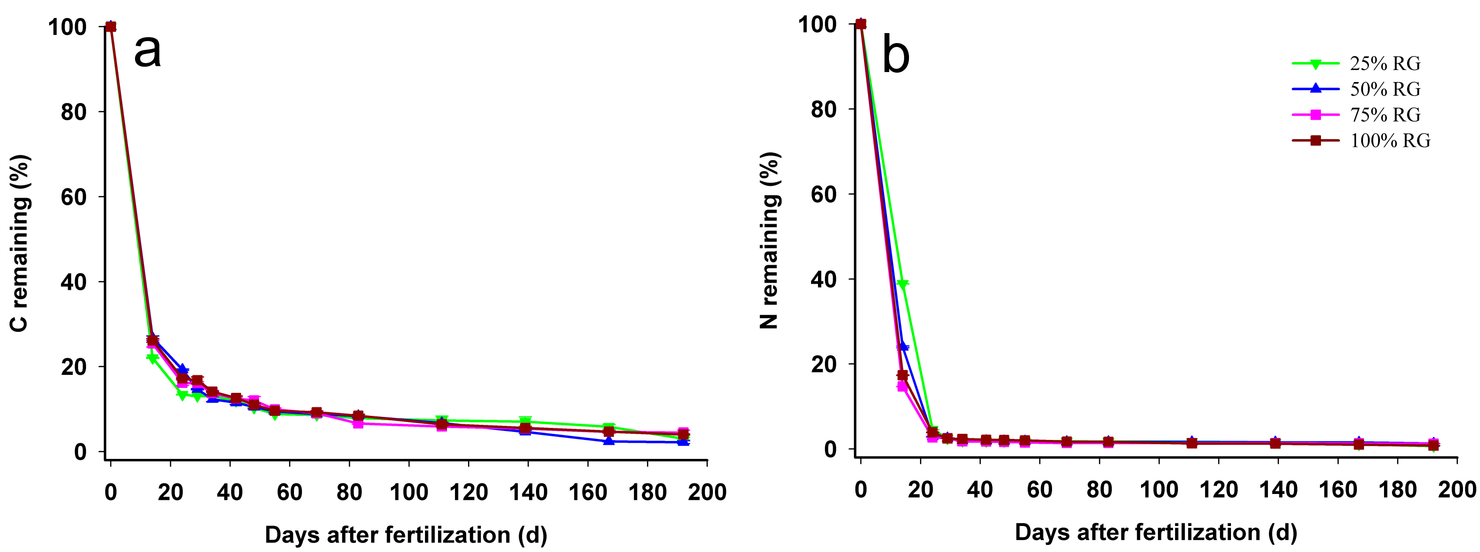

Figure 4

Percentage of C (a) and N (b) remaining in ryegrass residue during 192 days after fertilization under different RG-urea substitution ratios: 25% RG, 50% RG, 75% RG and 100% RG.

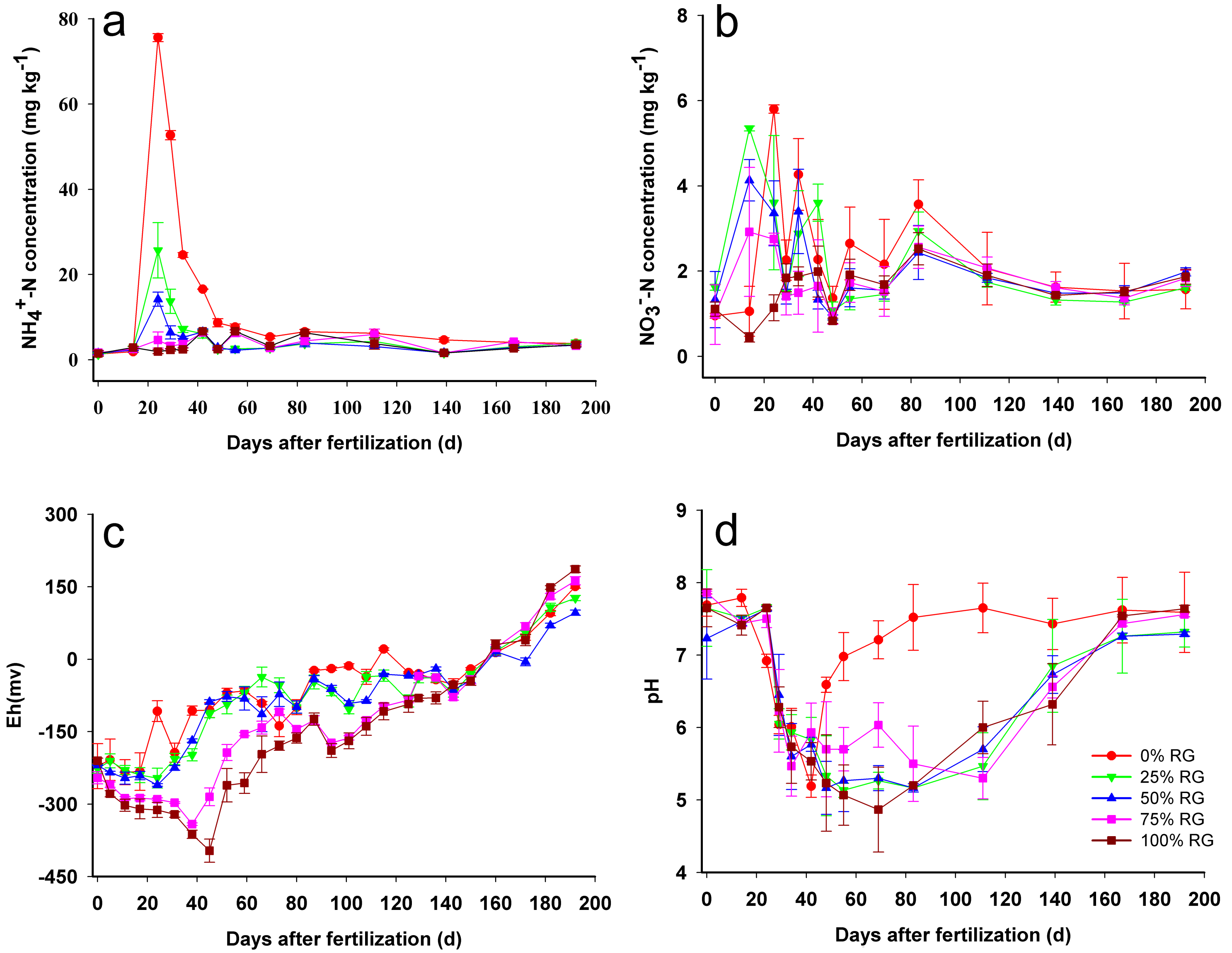

Figure 5

Soil NH_4^+-N (a), NO_3^--N (b), Eh (c) and pH (d) changes of different RG-urea substitution ratios: 0% RG, 25% RG, 50% RG, 75% RG and 100% RG. Bars indicate the SE (standard error).

Figure 6

Distance-based redundancy analysis (dbRDA) of composition of CH_4 (a), N_2O (c) and soil properties. Variance decomposition, with the percentages of CH_4 (b) and N_2O (d) variance explained by soil properties. Soil properties include NH_4^+-N, NO_3^--N, Eh, pH, C and N remaining in ryegrass residue.