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Different Responses of Greenhouse Gas Emissions to Straw Application at Different Seasons in Northeast China

(Tindak Balas Berbeza Pelepasan Gas Rumah Hijau untuk Penggunaan Jerami
pada Musim yang Berbeza di Timur Laut China)

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ABSTRACT

Although straw return plays a role in regulating greenhouse gas (GHG) emissions from rice paddy fields, little quantitative information is available on the extent at different periods. In this study, gas samples were collected during the rice growing period from an in-situ experiment comprising three treatments: no straw return (CK); straw return in the autumn (SR-A), and; straw return in the spring (SR-S). The results showed that SR-A and SR-S enhanced CO₂ and CH₄ emissions, but reduced N₂O emissions during the growing period. The total cumulative CO₂ emissions over the entire growing period in the SR-S treatment reached 20,383.72 kg ha⁻¹, significantly higher than those of the SR-A and CK treatments. CH₄ emissions for all the growing periods were in the order SR-S > SR-A > CK. The CK and SR-S treatments released the most and least N₂O during the different periods, respectively. The global warming potential (GWP) of CH₄ released by the SR-S, SR-A and CK treatments reached 26,055.37 kg CO₂ eq. ha⁻¹, 12,643.27 kg CO₂ eq. ha⁻¹, and 9,237.55 kg CO₂ eq. ha⁻¹, accounting for 55.80%, 40.35%, and 35.99% of the total GWP, respectively. These results can contribute to management of agricultural GHGs in this region.

Keywords: Greenhouse gas; growing period; paddy field; straw return

ABSTRAK

Hasil jerami telah memainkan peranan dalam mengawal selia pelepasan gas rumah hijau (GHG) daripada sawah padi, walau bagaimanapun, hanya sedikit maklumat kuantitatif boleh didapati untuk tempoh masa berlainan. Dalam kajian ini, sampel gas telah diambil dalam tempoh pertumbuhan semasa kajian in situ yang terdiri daripada tiga rawatan: tiada hasil jerami (CK); hasil jerami pada musim luruh (SR-A) dan hasil jerami pada musim bunga (SR-S). Hasil kajian menunjukkan bahawa SR-A dan SR-S meningkatkan pelepasan CO₂ dan CH₄, tetapi pengurangan pelepasan N₂O dalam tempoh pertumbuhan. Jumlah keseluruhan pelepasan CO₂ yang terkumpul sepanjang tempoh pertumbuhan keseluruhan dalam rawatan SR-S ialah 20,383.72 kg ha⁻¹, jauh lebih tinggi berbanding rawatan SR-A dan CK. Pelepasan CH₄ untuk semua tempoh pertumbuhan adalah seperti berikut SR-S > SR-A > CK. Perawatan CK dan SR-S mengeluarkan N₂O paling banyak dan paling sedikit dalam tempoh ini. Potensi pemanasan global (GWP) CH₄ yang dikeluarkan oleh SR-S, SR-A dan CK semasa rawatan mencapai 26,055.37 kg CO₂ eq. ha⁻¹, 12,643.27 kg CO₂ eq. ha⁻¹ dan 9,237.55 kg CO₂ eq. ha⁻¹ merangkumi 55.80%, 40.35% dan 35.99% jumlah GWP. Keputusan ini boleh menyumbang kepada pengurusan pertanian GHG di rantau ini.

Kata kunci: Gas rumah hijau; hasil jerami; sawah padi; tempoh pembesaran

INTRODUCTION

Increases in atmospheric concentrations of greenhouse gases (GHGs) such as carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) are responsible for current and predicted future global warming (Kong et al. 2013) and the associated environmental problems. Globally, agriculture is a major source of atmospheric GHGs (Ussiri et al. 2009), contributing approximately 10%-12% of the global total (Smith et al. 2014). Therefore, reducing agricultural GHGs is an essential component needed to alleviate the adverse impacts of climate warming.

Crop straw (i.e. rice straw), as an agricultural by-product, is an important source of organic C in

agro-ecosystems (Liu et al. 2014). Burning straw *in situ* after harvesting is a common practice resulting in smog pollution (Bossio 1999; Li et al. 2016) and GHG emissions (Crutzen et al. 1979) in China. As an alternative to burning, crop straw return to the soil has been widely recommended. Crop straw return into the soil has been reported to facilitate SOC sequestration (Lal & Bruce 1999), balance C loss (Chen et al. 2014) and enhance crop productivity (Liu et al. 2014). However, the practice also affects GHG emissions resulting from soil C and N cycles.

Recent studies on the effect of agricultural straw return on CO₂ and CH₄ emissions have showed varying

results, with most noting an increased CO₂ (Bhattacharyya et al. 2012; Chen et al. 2017b; Wang et al. 2018; Yoo et al. 2016) and CH₄ (Gaihre et al. 2013; Li et al. 2014; Liu et al. 2015; Naser et al. 2007; Zhang et al. 2017a;) emissions from agricultural fields, while few noted decreased CO₂ (Li et al. 2014) and CH₄ (Yeboah et al. 2016) emissions and others have noted no significant change in CO₂ (Cui et al. 2017) and CH₄ (Li et al. 2013). In addition, some previous studies showed that the practice increased N₂O emissions from agricultural fields (Malhi et al. 2006; Pathak et al. 2006; Shaaban et al. 2018) whereas others showed the opposite effect (Hu et al. 2013; Yao et al. 2017; Zhang et al. 2011). However, Chen et al. (2017b) showed that straw return resulted first in a decrease followed by an increase in N₂O emissions, which contradicted the result of Zhou et al (2017). A few studies noted no notable impact of straw return on N₂O emissions (Gaihre et al. 2013; Yao et al. 2009). Hence, there is not as yet a scientific consensus on the effects of straw return on GHG emissions. These varying results may in part be attributed to differences in management practices such as water regime, fertilization, cultivation system such as crop rotation and double cropping rice, and other variables such as climate and soil properties. Most of the above research used crop rotation or double rice cropping systems, and few studies in Northeast China used single rice cropping. Furthermore, most past studies applied straw return during the growing season, and few have considered the effects of straw return during the non-growing season on emissions during the growing season. Some studies showed that the soil aerobic condition before irrigation in the spring facilitates straw decomposition (Zhang et al. 2018) which may influence GHG emissions in the following growing season. Therefore, further knowledge of the response of growing season GHG emissions to straw return is essential to the assessment of greenhouse effects.

Rice production in China is the second largest globally (Frolking et al. 2002), with Western Jilin Province in Northeast China contributing a large rice yield. The growth period in this region is from mid-May (rice transplanting) to early October (harvesting). Large amounts of rice straw are retained in the soil after harvesting in October. Winter lasts approximately 6 months from the end of October to the end of April of the following year, during which there is no cultivation. Although much research has been conducted on GHG emissions from paddy soil in the area during the growing period, little is known regarding the effect of straw return during the non-growing period. The overall objectives of the current paper were to: determine the effect on the GHG emissions from straw return at different growth stages in Northeast China and quantify the resulting global warming potential (GWP). The results could provide a scientific basis for the accurate assessment of the effect of straw return on the greenhouse effect and guide field management in this area.

MATERIALS AND METHODS

SITE DESCRIPTION

The field experiment was conducted in Songyuan City of Western Jilin Province (123°091' E-124°221' E, 44°571' N-45°461' N), Northeast China. The entire growing season was divided into five periods: green; tillering; booting; heading; and grain filling. The experimental field has an area of 626.28 m² (20.4 m × 30.7 m). The main paddy soil properties (0 cm-20 cm) before straw return were pH of 7.4, moisture = 28.23%, soil organic carbon = 23.18 g kg⁻¹, total N = 2.14 g kg⁻¹ and hydrolyzable N = 236.75 mg kg⁻¹.

EXPERIMENTAL DESIGN

The experiment incorporated randomized 4 m × 4 m square plots and three replicates. The following three treatments were implemented: CK (no straw return); SR-A (straw return in the autumn after harvest, 5th October 2016), and; SR-S (straw return in the spring before irrigation and rice transplanting, 14th May 2017). Each plot was isolated using custom-built thin stainless-steel plate (25 cm × 400 cm × 400 cm) buried to a depth of 15 cm. All the surface litter and above-ground vegetation (including straw) in all the treatments were removed after the harvest. In the SR-A and SR-S treatments, each plot received 8 kg air-dried straw (equivalent to 5,000 kg ha⁻¹). Chemical fertilizer and farmyard manure were not applied during the growing season.

SAMPLING AND MEASUREMENT OF CO₂, CH₄ AND N₂O FLUXES

Gas sampling was conducted from 15th May 2017 to 30 September 2017 using static chambers. Gas samples were collected every 3 days over the entire growing season between 9:00 am and 11:00 am. The hourly emission flux of the measured gas from 9:00 am to 11:00 am was converted into that for 24 h of one day using the calibration coefficient 1.24 by Tang et al. (2016) who studied the same region with this research. Every chamber consisted of two removable parts, namely a bottom collar (50 cm × 50 cm × 30 cm) with a seal groove and an upper compartment (50 cm × 50 cm × 100 cm). A circulating fan was attached to each upper compartment to ensure complete gas mixing. Four samples from a single plot were collected every 10 min over a 30 min duration. The static chambers were moved out of the plots after each sampling. Air temperature data were recorded at Songyuan weather station (Jilin Province, China).

Concentrations of CO₂, CH₄ and N₂O in the gas samples were analyzed by gas chromatography (GC, Agilent 7820A, Santa Clara, CA, USA) within 24 h of gas sampling. The analyses of concentration and of CO₂, CH₄ and N₂O fluxes were as described by Zhang et al. (2005). The calculation of mean and cumulative fluxes and GWP were as described by Zhang et al. (2017b). The GWP values

of CH_4 and N_2O were calculated over a time scale of 100 years. Statistical analyses were performed using SPSS 23.0 software (International Business Machines Corporation, State of New York, USA). All figures were drawn using Sigma plot 13.0 (Systat Software, Inc., State of Illinois, USA).

GWP ($\text{kg CO}_2 \text{ eq. ha}^{-1}$) was calculated as follows:

$$GWP = F_{\text{CO}_2} + 25F_{\text{CH}_4} + 298F_{\text{N}_2\text{O}} \quad (1)$$

F_{CO_2} , F_{CH_4} , and $F_{\text{N}_2\text{O}}$ are the cumulative flux of CO_2 , CH_4 , and N_2O across the entire growing period, respectively.

RESULTS

VARIATIONS IN CO_2 , CH_4 , AND N_2O FLUX

The CO_2 flux increased from the green period to the tillering period (Figure 1A). The first peaks in CO_2 emissions for the CK and SR-A treatments were on the 5th July, 2017,

respectively, whereas that of the SR-S treatment was on 17th July, 2017. The maximum peak values for the three treatments were of the order: SR-S ($1,152.65 \text{ mg m}^{-2} \text{ h}^{-1}$) > SR-A ($1,139.26 \text{ mg m}^{-2} \text{ h}^{-1}$) > CK ($894.82 \text{ mg m}^{-2} \text{ h}^{-1}$). The second peaks for the three treatments were observed on the same day during the grain-filling period.

CH_4 fluxes were relatively low during the green period ($0.75 \text{ mg m}^{-2} \text{ h}^{-1}$ – $6.64 \text{ mg m}^{-2} \text{ h}^{-1}$) and the grain-filling period ($0.04 \text{ mg m}^{-2} \text{ h}^{-1}$ – $12.58 \text{ mg m}^{-2} \text{ h}^{-1}$) (Figure 1B). The CH_4 fluxes increased during the tillering period in the three treatments. A notable single peak in CH_4 flux was observed during the booting period in each of the three treatments. The peak value for the SR-S treatment ($93.69 \text{ mg m}^{-2} \text{ h}^{-1}$) was much higher than those that occurred later for CK ($35.02 \text{ mg m}^{-2} \text{ h}^{-1}$) and SR-A ($42.96 \text{ mg m}^{-2} \text{ h}^{-1}$).

Extreme variability was evident in the daily N_2O fluxes in the CK treatment, alternating between a high of $105.45 \mu\text{g m}^{-2} \text{ h}^{-1}$ and low of $16.25 \mu\text{g m}^{-2} \text{ h}^{-1}$ (Figure 1C). Relatively less N_2O flux variability was evident in the SR-A and SR-S treatments, at $13.14 \mu\text{g m}^{-2} \text{ h}^{-1}$ – $72.31 \mu\text{g m}^{-2} \text{ h}^{-1}$ and $12.76 \mu\text{g m}^{-2} \text{ h}^{-1}$ – $48.23 \mu\text{g m}^{-2} \text{ h}^{-1}$, respectively.

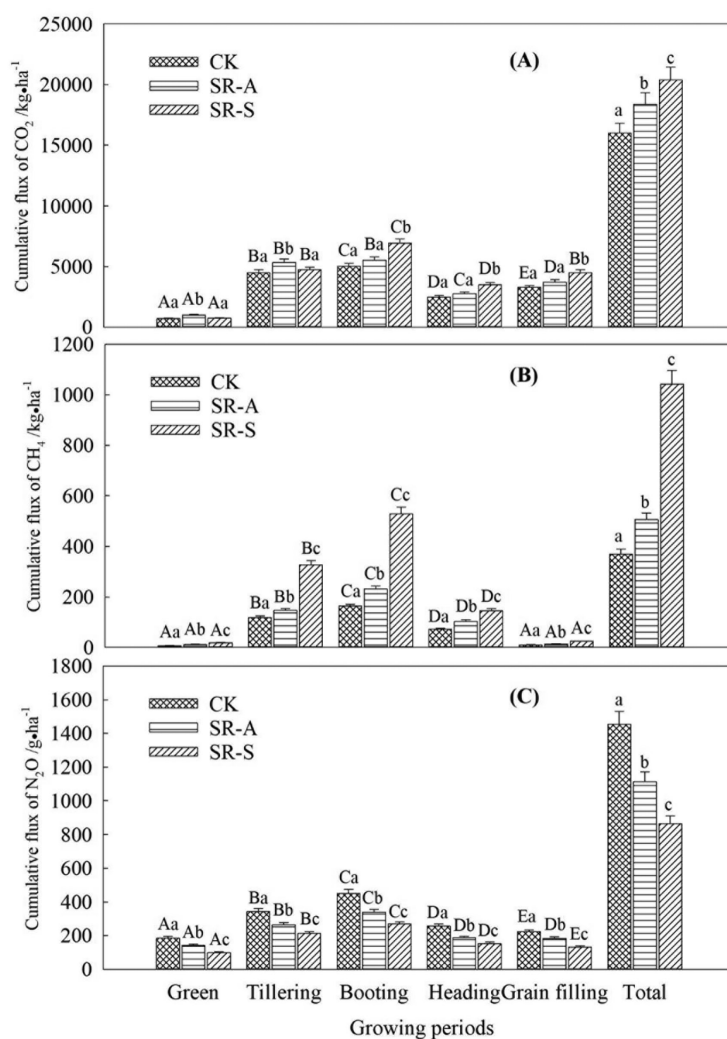


FIGURE 1. Measured mean flux of CO_2 , CH_4 , and N_2O in the three treatments. Note: CK treatment = no straw return in the autumn, SR-A treatment = straw return in the autumn (5th October 2016) after harvest, and SR-S treatment = straw return in the spring (14th May 2017) before irrigation and rice transplanting

VARIATIONS IN MEAN CO₂, CH₄, AND N₂O FLUX DURING THE DIFFERENT PERIODS

Of the treatments, SR-A showed the highest mean fluxes of CO₂ during the green and tillering periods (Figure 2A). The highest and lowest mean fluxes of CO₂ during the booting to grain-filling periods were by the SR-S and CK treatments, respectively. The highest mean fluxes of CO₂ in the CK, SR-A and SR-S treatments were observed in the booting, tillering and booting periods, respectively.

Of the treatments, SR-S had a significantly higher mean CH₄ flux during every growing period (Figure 2B). Relatively low mean CH₄ fluxes were observed during the green period (1.25 mg m⁻² h⁻¹–3.51 mg m⁻² h⁻¹) and the grain-filling period (1.40 mg m⁻² h⁻¹–3.33 mg m⁻² h⁻¹). Peaks in mean CH₄ flux of 20.53 mg m⁻² h⁻¹, 29.15 mg m⁻² h⁻¹ and 66.72 mg m⁻² h⁻¹ were observed during the booting period in the CK, SR-A, and SR-S treatments, respectively. The lowest and highest mean N₂O fluxes of each period

were found in the SR-S and CK treatments, respectively (Figure 2C). The mean N₂O fluxes during different periods of the three treatments followed the order of booting > tillering > heading > green > grain filling.

CUMULATIVE EMISSIONS OF CO₂, CH₄, AND N₂O

Of the treatments, SR-A emitted the most CO₂ during the green and tillering periods (Figure 3A). The highest cumulative CO₂ emissions for all three treatments were during booting period. The SR-S treatment released 6,939.601 kg ha⁻¹ during the booting treatment, 1,410.55 kg ha⁻¹ and 1,914.04 kg ha⁻¹ higher than those of SR-A and CK, respectively. The total cumulative CO₂ emissions over the entire growing period in the SR-S treatment reached 20,383.72 kg ha⁻¹, significantly higher than those of the SR-A and CK treatments by 2,023.99 kg ha⁻¹ and 4,390.32 kg ha⁻¹, respectively (Figure 3A).

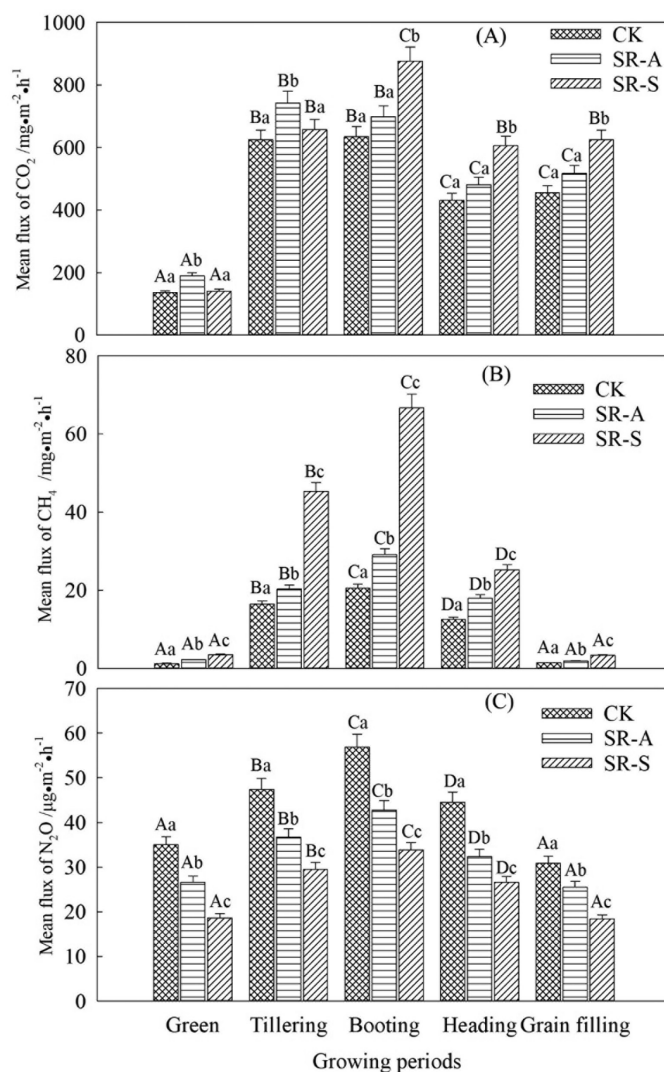


FIGURE 2. Mean flux of CO₂, CH₄, and N₂O during the different periods in the three treatments.

Note: different uppercase letters A, B, C, and D indicate significant differences between different periods in the same treatment, while different lowercase letters a, b, and c indicate significant differences among treatments in the same period. The same below.

The order of treatments releasing the most CH_4 in each growing period was $\text{SR-S} > \text{SR-A} > \text{CK}$ (Figure 3B). The maximum cumulative CH_4 emissions were observed during the booting period at $162.63 \text{ kg ha}^{-1}$, $230.87 \text{ kg ha}^{-1}$ and $528.38 \text{ kg ha}^{-1}$ for the CK, SR-A and SR-S treatments, respectively, contributing 44.01%, 45.65% and 50.70% of the total emissions during the entire growing period, respectively.

Of the treatments, CK and SR-S released the most and least N_2O during the different periods, respectively (Figure 3C). The booting period showed the highest maximum cumulative N_2O emissions. The CK, SR-A and SR-S treatments contributed $1,455.50 \text{ g h}^{-1}$, $1,113.30 \text{ g h}^{-1}$ and 864.06 g h^{-1} of total N_2O , respectively, 30.96%, 30.40% and 31.00% of which originated from booting period, respectively.

GLOBAL WARMING POTENTIAL (GWP)

The GWP of different GHGs are presented in Table 1. CO_2 was the predominant GHG for the CK (62.32%) and SR-A (58.59%) treatments, followed by CH_4 (35.99% and

40.35%, respectively) (Table 1). In contrast, CH_4 (55.80%) was the predominant GHG for the SR-S treatment, followed by CO_2 (43.63%). GWP_{CH_4} in the SR-S treatment reached $26,055.37 \text{ kg CO}_2 \text{ eq. ha}^{-1}$, factors of 2.06 and 2.82 those in the SR-A and CK treatments, respectively. N_2O contributed 1.69%, 1.06% and 0.55% to the total GWP in the CK, SR-A and SR-S treatments, respectively. The total SR-S GWP was $46,696.57 \text{ kg CO}_2 \text{ eq. ha}^{-1}$, factors of 1.49 and 1.82 those in the SR-A and CK treatments, respectively.

DISCUSSION

CO_2 FLUX

Temperature is one of the key factors affecting microbial activities and CO_2 emissions (Li et al. 2008). Rising temperatures (as observed in our study; Figure 4) have been shown to facilitate microbial respiration (Zhang et al. 2017b) during the green and tillering periods, resulting in enhanced CO_2 flux. In our research, the first peak in CO_2 flux in the three treatments resulted from sufficient

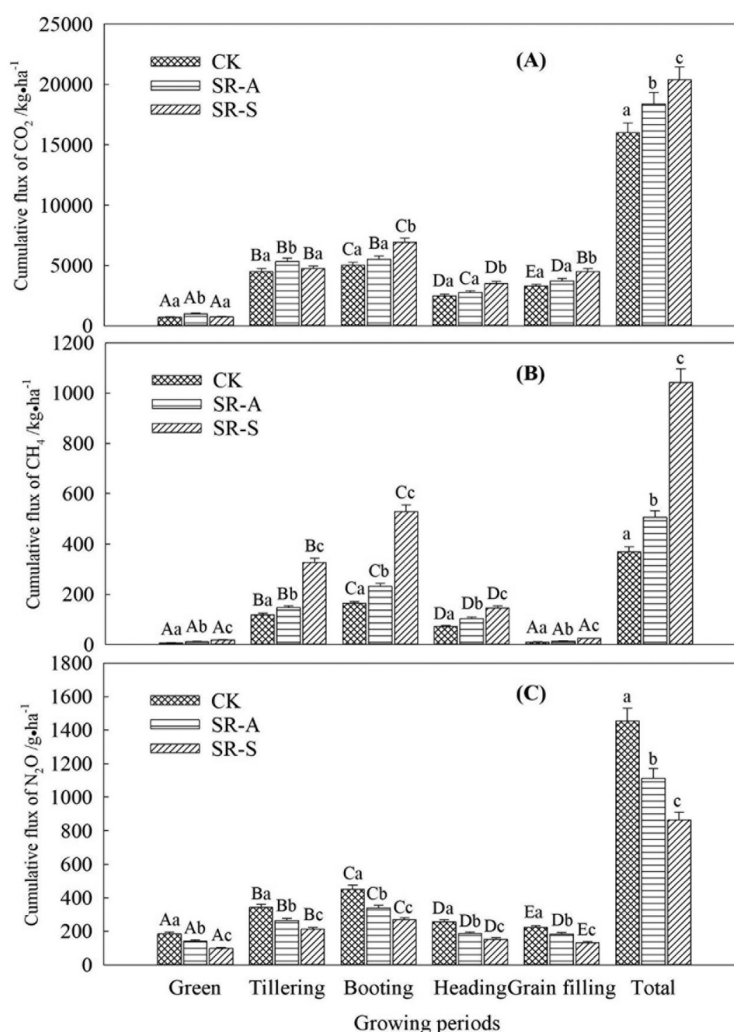


FIGURE 3. Cumulative emissions of CO_2 , CH_4 , and N_2O during the different periods in the three treatments

TABLE 1. The global warming potential (GWP) of greenhouse gases in the three treatments

| Treatments | GWP _{CO₂} / (kg CO ₂ eq. ha ⁻¹) | GWP _{CH₄} / (kg CO ₂ eq. ha ⁻¹) | GWP _{N₂O} / (kg CO ₂ eq. ha ⁻¹) | Total GWP / (kg CO ₂ eq. ha ⁻¹) |
|------------|---|---|---|---|
| CK | 15993.39 a | 9237.55 a | 433.74 a | 25664.68 a |
| SR-A | 18359.72 b | 12643.27 b | 331.76 b | 31334.75 b |
| SR-S | 20383.72 c | 26055.37 c | 257.49 c | 46696.57 c |

Conversions of CH₄ and N₂O to GWP in CO₂ eq. were GWP₁₀₀ of 25 and 298, respectively. Values of GWP_{CO₂}, GWP_{CH₄}, GWP_{N₂O} and total GWP followed by a different letter differ significantly among themselves ($p < 0.05$)

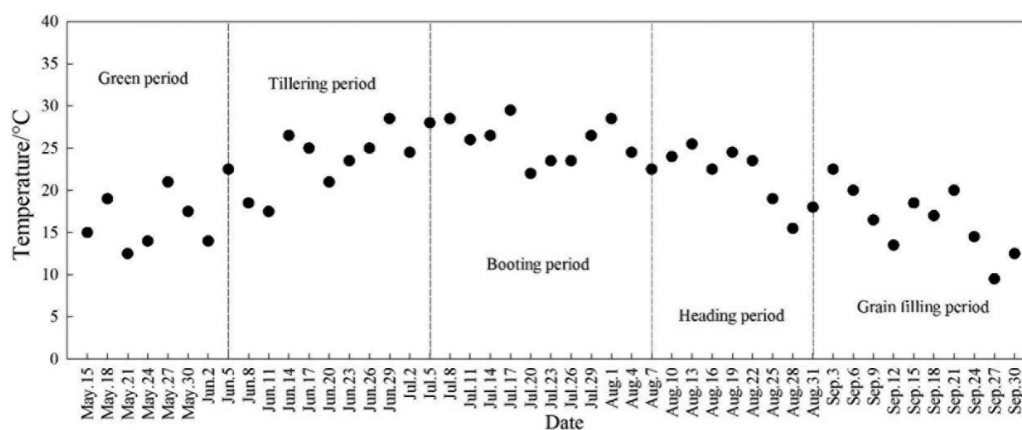


FIGURE 4. Recorded daily mean temperature during the entire growing period

substrate (including straw, residual root and other organic matter in the soil) being available for facilitating increase in microbial respiration. Furthermore, with the rapid growth in the rice plants, the plants' respiration contributed to CO₂ flux. However, the CO₂ flux reduced with decline in available substrate. Drainage implemented after the heading period resulted in anaerobic conditions, which further led to increased CO₂ emissions and the second peak in CO₂ flux in the three treatments. Decreasing temperature then resulted in reduced CO₂ flux.

Straw return enhanced CO₂ emissions during the growing period, in accordance with results reported by Bhattacharyya et al. (2012) and Wang et al. (2018). Straw amendment resulted in increased substrate availability for microorganisms (Zheng et al. 2015) and suitable conditions for microbial C-turnover (Chen et al. 2017a), thus resulting in increased soil CO₂ emissions. Therefore, the SR-S and SR-A treatments emitted more CO₂ than the CK treatment during all the periods.

Straw incorporation during autumn in the SR-A treatment resulted in prolonged aerobic decomposition (Zhang et al. 2018) due to drainage implemented after the heading period. Consequently, soil organic carbon input increased (Loya et al. 2004), resulting in increased available substrate during the green and tillering periods, which further led to higher mean CO₂ flux and higher cumulative CO₂ emission than those from the SR-S treatment. However, the anaerobic conditions (Spormann & Widdel 2000) present after irrigation and the high carbon/nitrogen ratio (Khalil et al. 2001) retarded straw decomposition for the entire growing period during spring

in the SR-S treatment. Abundant substrate was thereby made available for a longer period, leading to a CO₂ flux peak several days later (first peak), and in the SR-S treatment this led to greater CO₂ mean flux compared to the SR-A treatment in combination with higher cumulative CO₂ emissions during the booting to grain-filling periods. In addition, the total CO₂ emissions during the entire growing period in SR-S treatment were higher than that in the SR-A treatment.

CH₄ FLUX

Irrigation created a suitable environment for methanogens. Given the presence of temperature-sensitive methanogenic bacteria (Keppler et al. 2006), the CH₄ fluxes during the three treatments increased with increasing temperature during the green and tillering periods. The available methanogenic substrate was an important factor restricting CH₄ production. Therefore, peaks in CH₄ flux were observed in the three treatments.

Our results showed that CH₄ emissions were greatly enhanced by straw incorporation into the soil, consistent with the findings of Gaihre et al. (2013), Liu et al. (2015) and Naser et al. (2007). Straw in the field is a source of methanogenic substrates (Li et al. 2014) and it selectively favors the growth of methanogenic populations, thereby accelerating CH₄ production (Conrad & Klose 2006). In addition, straw decomposition acts as an electron donor, contributing to increased soil reduction, which is a favorable condition for CH₄ production (Lee et al. 2010; Minamikawa & Sakai 2006). Straw incorporation into

the soil can also result in lower soil redox potential (Li et al. 2014; Liu et al. 2015), which favors CH₄ formation by methanogenic bacteria (Hadi et al. 2010). Therefore, in our study, the SR-A and SR-S treatments produced more CH₄ across all the different periods than the CK treatment. The later CH₄ flux peak observed in the SR-S treatment is possibly linked to the straw being able to host sufficient available methanogenic substrate for a longer time period. Freshly-added straw before irrigation could possibly donate more electrons and provide a more suitable reductive condition for CH₄ production relative to straw added in autumn, which results in aerobic decomposition until irrigation. Therefore, the SR-S treatment emitted more CH₄ than the SR-A treatment.

Methanogens are strict anaerobes (Li et al. 2011); therefore, the aerobic condition resulting from drainage after the heading period and decreasing temperature greatly restrained the activity of methanogenic bacteria resulting in a falling CH₄ flux during the grain-filling period.

N₂O FLUX

In the present study, straw incorporation notably suppressed N₂O emissions, consistent with other research findings (Bhattacharyya et al. 2012; Wang et al. 2018; Zhang et al. 2017a). N₂O emissions are influenced by denitrification and nitrification. Straw application with a high C:N ratio can result in increased net N immobilization (Jensen 1997) and lower N mineralization and a relatively lower abundance of nitrogen. This further leads to lower quantities of available N (NH₄⁺-N and NO₃⁻-N) for nitrification and denitrification, resulting in lower N₂O emissions (Liu et al. 2015; Millar & Baggs 2004). Straw application can result in a reductive soil environment (Liu et al. 2015) and increased soil Fe²⁺ content (Wang et al. 2011), favoring the reduction of N₂O to N₂, thus decreasing the N₂O/N₂ ratio and lessening N₂O emissions (Mathieu et al. 2006; Senbayram et al. 2012). Previous investigations have shown that rice straw incorporation can significantly change the soil microbial community structure, thereby increasing the relative abundance of the *nosZ*-population to facilitate N₂O reduction (Chen et al. 2012). Straw addition has been shown to result in an increased relative abundance of *Clostridium* (Wang et al. 2018), which is able to employ NO₃⁻-N as an electron acceptor during anaerobic conditions, thereby reducing it back to N₂ (Katayama et al. 1999), thus, decreasing N₂O emissions. This process explains why the CK treatment in our study maintained higher N₂O emissions than the SR-A and SR-S treatments. Compared to the SR-A treatment, the lower N₂O emissions observed in the SR-S treatment might be due to its restrictive reductive soil environment, which resulted in a stronger inhibitory effect on N₂O production.

CONCLUSION

The experimental paddy field was a source of CO₂, CH₄ and N₂O during the growing period. Rice straw incorporation

elevated CO₂ and CH₄ emissions, but decreased N₂O emissions during growing period. Straw application in the spring emitted more CO₂ and CH₄ and less N₂O compared to application in autumn. CH₄ and N₂O emissions during the booting period contribute most to the GWP among different periods, respectively. Straw application in the spring resulted in CH₄ being the predominant GHG instead of CO₂. Straw incorporation, particularly, in spring, promoted the GWP of the paddy field during growing period.

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