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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 CO_2 and CH_4 emissions, but reduced N_2O emissions during the growing period. The total cumulative CO_2 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. CH_4 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 N_2O during the different periods, respectively. The global warming potential (GWP) of CH_4 released by the SR-S, SR-A and CK treatments reached 26,055.37 kg CO_2 eq. ha^{-1}, 12,643.27 kg CO_2 eq. ha^{-1}, and 9,237.55 kg CO_2 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 CO_2 dan CH_4, tetapi pengurangan pelepasan N_2O dalam tempoh pertumbuhan. Jumlah keseluruhan pelepasan CO_2 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 CH_4 untuk semua tempoh pertumbuhan adalah seperti berikut SR-S > SR-A > CK. Perawatan CK dan SR-S mengeluarkan N_2O paling banyak dan paling sedikit dalam tempoh ini. Potensi pemanasan global (GWP) CH_4 yang dikeluarkan oleh SR-S, SR-A dan CK semasa rawatan mencapai 26,055.37 kg CO_2 eq. ha^{-1}, 12,643.27 kg CO_2 eq. ha^{-1} dan 9,237.55 kg CO_2 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 (CO_2), methane (CH_4) and nitrous oxide (N_2O) 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 CO_2 and CH_4 emissions have showed varying results, with most noting an increased CO_2 (Bhattacharyya et al. 2012; Chen et al. 2017b; Wang et al. 2018; Yoo et al. 2016) and CH_4 (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 CO_2 (Li et al. 2014) and CH_4 (Yeboah et al. 2016) emissions and others have noted no significant change in CO_2 (Cui et al. 2017) and CH_4 (Li et al. 2013). In addition, some previous studies showed that the practice increased N_2O 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 N_2O emissions, which contradicted the result of Zhou et al (2017). A few studies noted no notable impact of straw return on N_2O 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 m^2 (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 CO_2, CH_4 AND N_2O 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 CO_2, CH_4 and N_2O 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 CO_2, CH_4 and N_2O 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 (kg CO_2 eq. ha^{-1}) was calculated as follows:

$$GWP = F_{CO_2} + 25F_{CH_4} + 298F_{N_2O} \quad (1)$$

F_{CO_2}, F_{CH_4}, and F_{N_2O} 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 mg m^{-2} h^{-1}) > SR-A (1,139.26 mg m^{-2} h^{-1}) > CK (894.82 mg m^{-2} 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 mg m^{-2} h^{-1}-6.64 mg m^{-2} h^{-1}) and the grain-filling period (0.04 mg m^{-2} h^{-1}-12.58 mg m^{-2} 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 mg m^{-2} h^{-1}) was much higher than those that occurred later for CK (35.02 mg m^{-2} h^{-1}) and SR-A (42.96 mg m^{-2} h^{-1}).

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

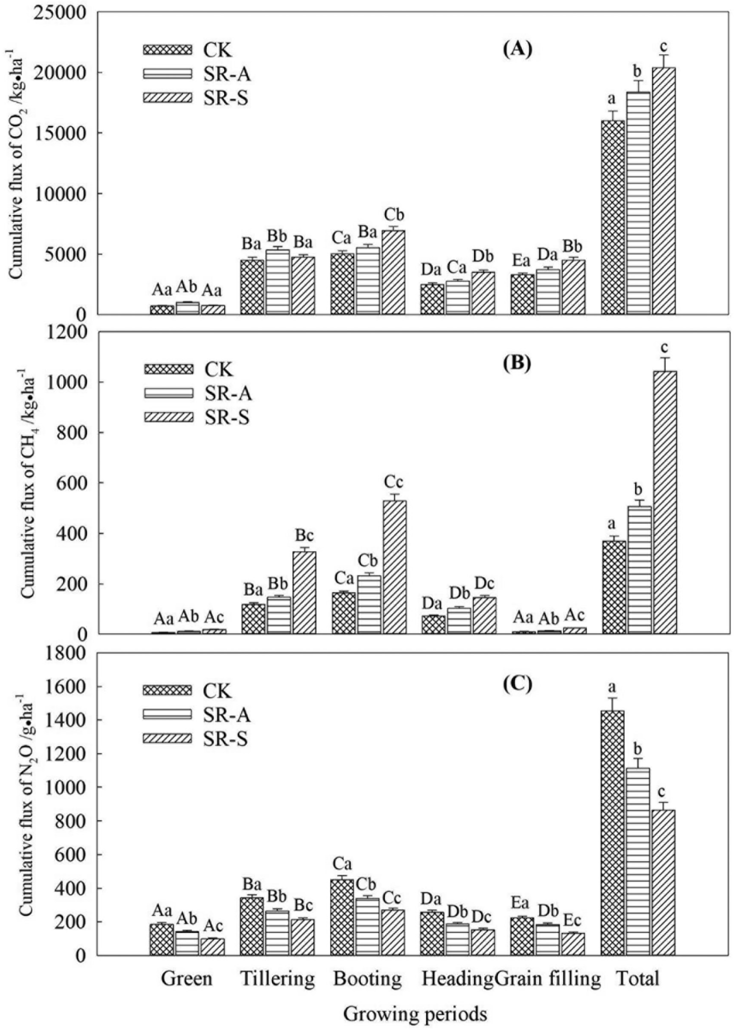

FIGURE 1. Measured mean flux of CO_2, CH_4, and N_2O in the three treatments. Note: CK treatment = no straw return, SR-A treatment = straw return in the autumn (5th October 2016) after harvest, and SR-S treatment = straw return in the spring (14th May 2017) before irrigation and rice transplanting

VARIATIONS IN MEAN CO_2, CH_4, AND N_2O FLUX DURING THE DIFFERENT PERIODS

Of the treatments, SR-A showed the highest mean fluxes of CO_2 during the green and tillering periods (Figure 2A). The highest and lowest mean fluxes of CO_2 during the booting to grain-filling periods were by the SR-S and CK treatments, respectively. The highest mean fluxes of CO_2 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 CH_4 flux during every growing period (Figure 2B). Relatively low mean CH_4 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 CH_4 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 N_2O fluxes of each period were found in the SR-S and CK treatments, respectively (Figure 2C). The mean N_2O fluxes during different periods of the three treatments followed the order of booting > tillering > heading > green > grain filling.

CUMULATIVE EMISSIONS OF CO_2, CH_4, AND N_2O

Of the treatments, SR-A emitted the most CO_2 during the green and tillering periods (Figure 3A). The highest cumulative CO_2 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 CO_2 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).

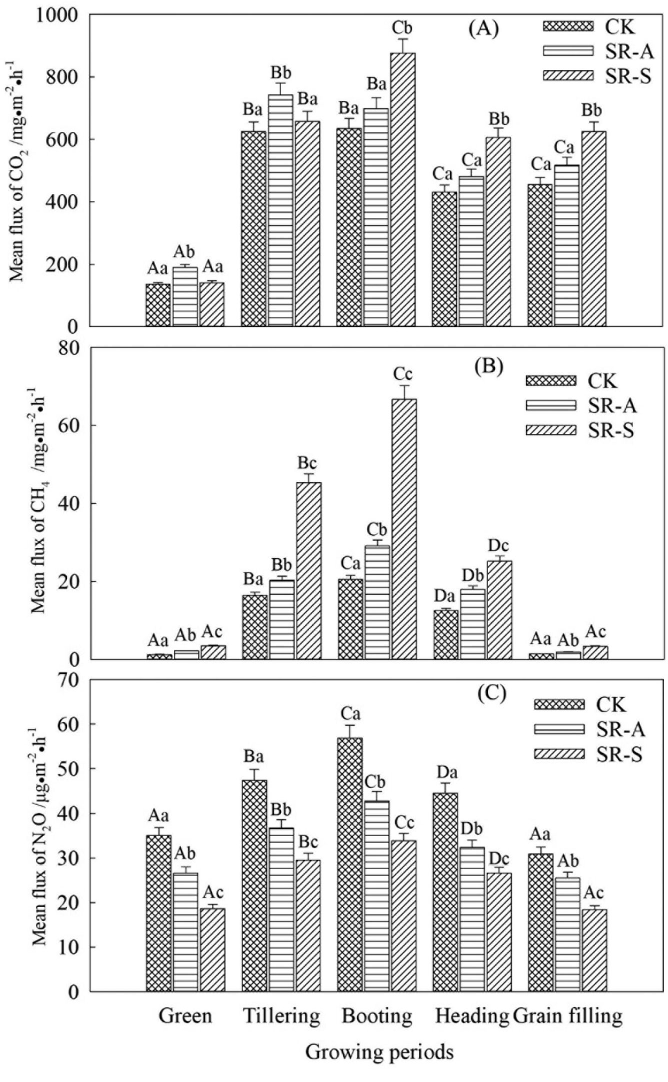

FIGURE 2. Mean flux of CO_2, CH_4, and N_2O during the different periods in the three treatments.

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 SR-S > SR-A > CK (Figure 3B). The maximum cumulative CH_4 emissions were observed during the booting period at 162.63 kg ha^{-1}, 230.87 kg ha^{-1} and 528.38 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 g h^{-1}, 1,113.30 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_{CH4} in the SR-S treatment reached 26,055.37 kg CO_2 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 kg CO_2 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

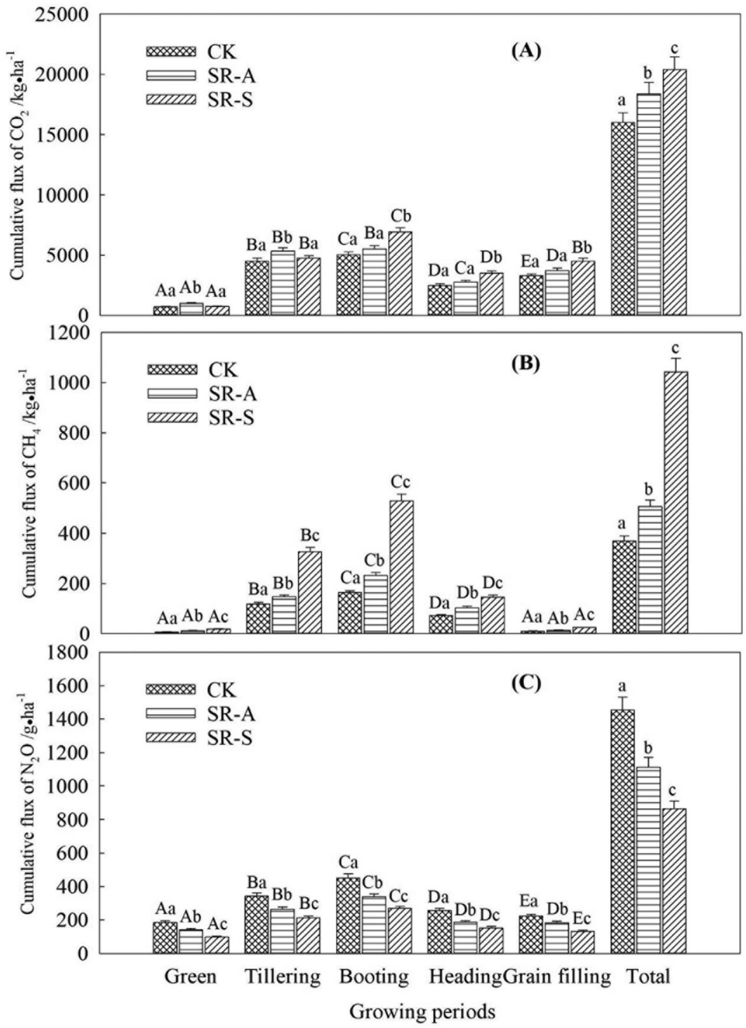

FIGURE 3. Cumulative emissions of CO_2, CH_4, and N_2O during the different periods in the three treatments

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

Treatments	GWP_{CO_2} / (kg CO_2 eq. ha^{-1})	GWP_{CH_4} / (kg CO_2 eq. ha^{-1})	GWP_{N_2O} / (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 CH_4 and N_2O to GWP in CO_2 eq. were GWP_{100} 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)

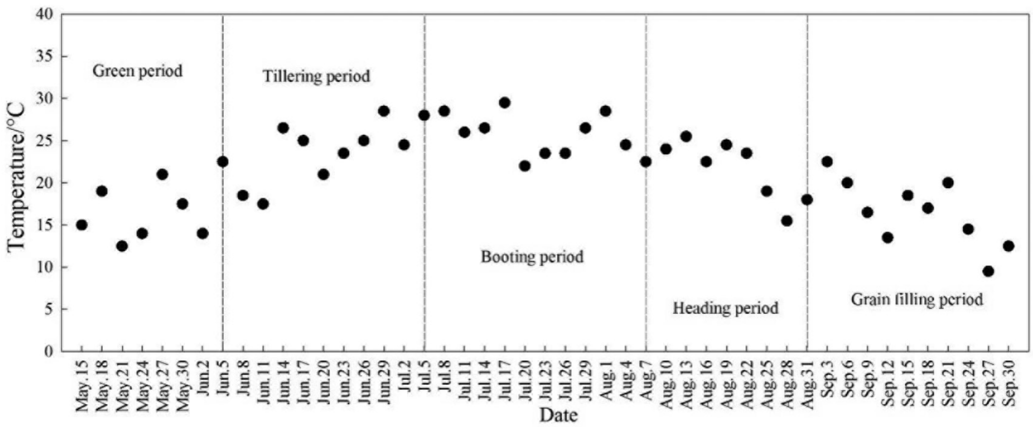

FIGURE 4. Recorded daily mean temperature during the entire growing period

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 CO_2 flux. However, the CO_2 flux reduced with decline in available substrate. Drainage implemented after the heading period resulted in anaerobic conditions, which further led to increased CO_2 emissions and the second peak in CO_2 flux in the three treatments. Decreasing temperature then resulted in reduced CO_2 flux.

Straw return enhanced CO_2 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 CO_2 emissions. Therefore, the SR-S and SR-A treatments emitted more CO_2 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 CO_2 flux and higher cumulative CO_2 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 CO_2 flux peak several days later (first peak), and in the SR-S treatment this led to greater CO_2 mean flux compared to the SR-A treatment in combination with higher cumulative CO_2 emissions during the booting to grain-filling periods. In addition, the total CO_2 emissions during the entire growing period in SR-S treatment were higher than that in the SR-A treatment.

CH_4 FLUX

Irrigation created a suitable environment for methanogens. Given the presence of temperature-sensitive methanogenic bacteria (Keppler et al. 2006), the CH_4 fluxes during the three treatments increased with increasing temperature during the green and tillering periods. The available methanogenic substrate was an important factor restricting CH_4 production. Therefore, peaks in CH_4 flux were observed in the three treatments.

Our results showed that CH_4 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 CH_4 production (Conrad & Klose 2006). In addition, straw decomposition acts as an electron donor, contributing to increased soil reduction, which is a favorable condition for CH_4 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 CH_4 formation by methanogenic bacteria (Hadi et al. 2010). Therefore, in our study, the SR-A and SR-S treatments produced more CH_4 across all the different periods than the CK treatment. The later CH_4 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 CH_4 production relative to straw added in autumn, which results in aerobic decomposition until irrigation. Therefore, the SR-S treatment emitted more CH_4 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 CH_4 flux during the grain-filling period.

N_2O FLUX

In the present study, straw incorporation notably suppressed N_2O emissions, consistent with other research findings (Bhattacharyya et al. 2012; Wang et al. 2018; Zhang et al. 2017a). N_2O 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 (NH_4^+-N and NO_3^--N) for nitrification and denitrification, resulting in lower N_2O emissions (Liu et al. 2015; Millar & Baggs 2004). Straw application can result in a reductive soil environment (Liu et al. 2015) and increased soil Fe^{2+} content (Wang et al. 2011), favoring the reduction of N_2O to N_2, thus decreasing the N_2O/N_2 ratio and lessening N_2O 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 *nos*Z-population to facilitate N_2O 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 NO_3^--N as an electron acceptor during anaerobic conditions, thereby reducing it back to N_2 (Katayama et al. 1999), thus, decreasing N_2O emissions. This process explains why the CK treatment in our study maintained higher N_2O emissions than the SR-A and SR-S treatments. Compared to the SR-A treatment, the lower N_2O emissions observed in the SR-S treatment might be due to its restrictive reductive soil environment, which resulted in a stronger inhibitory effect on N_2O production.

CONCLUSION

The experimental paddy field was a source of CO_2, CH_4 and N_2O during the growing period. Rice straw incorporation elevated CO_2 and CH_4 emissions, but decreased N_2O emissions during growing period. Straw application in the spring emitted more CO_2 and CH_4 and less N_2O compared to application in autumn. CH_4 and N_2O emissions during the booting period contribute most to the GWP among different periods, respectively. Straw application in the spring resulted in CH_4 being the predominant GHG instead of CO_2. Straw incorporation, particularly, in spring, promoted the GWP of the paddy field during growing period.

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REFERENCES

Bhattacharyya, P., Roy, K.S., Neogi, S., Adhya, T.K., Rao, K.S. & Manna, M.C. 2012. Effects of rice straw and nitrogen fertilization on greenhouse gas emissions and carbon storage in tropical flooded soil planted with rice. *Soil & Tillage Research* 124: 119-130.

Bossio, D. 1999. Methane pool and flux dynamics in a rice field following straw incorporation. *Soil Biology & Biochemistry* 31: 1313-1322.

Chen, H., Zhao, Y., Feng, H., Liu, J., Si, B., Feng, H., Zhang, A., Chen, J., Cheng, G., Sun, B., Pi, X., Zhao, Y., Dyck, M., Si, B. & Zhao, Y. 2017. Effects of straw and plastic film mulching on greenhouse gas emissions in Loess Plateau, China: A field study of 2 consecutive wheat-maize rotation cycles. *Science of the Total Environment* 579: 814-824.

Chen, L., Zhang, J., Zhao, B., Yan, P., Zhou, G. & Xin, X. 2014. Effects of straw amendment and moisture on microbial communities in Chinese fluvo-aquic soil. *Journal of Soils & Sediments*14: 1829-1840.

Chen, Z., Wang, H., Liu, X., Zhao, X., Lu, D., Zhou, J. & Li, C. 2017a. Changes in soil microbial community and organic carbon fractions under short-term straw return in a rice-wheat cropping system. *Soil & Tillage Research* 165: 121-127.

Chen, Z., Hou, H., Zheng, Y., Qin, H., Zhu, Y., Wu, J. & Wei, W. 2012. Influence of fertilization regimes on a nosZ -containing denitrifying community in a rice paddy soil. *Journal of the Science of Food and Agriculture* 92: 1064-1072.

Conrad, R. & Klose, M. 2006. Dynamics of the methanogenic archaeal community in anoxic rice soil upon addition of straw. *European Journal of Soil Science* 57: 476-484.

Crutzen, P.J., Heidt, L.E., Krasnec, J.P., Pollock, W.H. & Seiler, W. 1979. Biomass burning as a source of atmospheric gases: CO, H_2, N_2O, NO, CH_3Cl and COS. *Nature* 282: 253-256.

Cui, Y.F., Meng, J., Wang, Q.X., Zhang, W.M., Cheng, X.Y. & Chen, W.F. 2017. Effects of straw and biochar addition on soil nitrogen, carbon, and super rice yield in cold waterlogged paddy soils of North China. *Journal of Integrative Agriculture* 16: 1064-1074

Frolking, S., Qiu, J., Boles, S., Xiao, X., Liu, J., Zhuang, Y., Li, C. & Qin, X. 2002. Combining remote sensing and ground census data to develop new maps of the distribution of rice agriculture in China. *Global Biogeochemical Cycles* 16(4): 38-1-38-10.

Gaihre, Y.K., Wassmann, R. & Villegas-Pangga, G. 2013. Impact of elevated temperatures on greenhouse gas emissions in rice systems: Interaction with straw incorporation studied in a growth chamber experiment. *Plant & Soil* 373: 857-875.

Hadi, A., Inubushi, K. & Yagi, K. 2010. Effect of water management on greenhouse gas emissions and microbial properties of paddy soils in Japan and Indonesia. *Paddy & Water Environment* 8: 319-324.

Hu, X.K., Su, F., Ju, X.T., Gao, B., Oenema, O., Christie, P., Huang, B.X., Jiang, R.F. & Zhang, F.S. 2013. Greenhouse gas emissions from a wheat-maize double cropping system with different nitrogen fertilization regimes. *Environmental Pollution* 176: 198-207.

Jensen, E.S. 1997. Nitrogen immobilization and mineralization during initial decomposition of ^{15}N-labelled pea and barley residues. *Biology & Fertility of Soils* 24: 39-44.

Katayama, S., Okabe, A., Sun, Y., Taniguchi, Y., Fujinaga, K., Matsushita, O. & Minami, J. 1999. Analysis of genes involved in nitrate reduction in *Clostridium perfringens*. *Microbiology* 145: 3377-3387.

Keppler, F., Hamilton, J.T., Brass, M. & Rockmann, T. 2006. Methane emissions from terrestrial plants under aerobic conditions. *Nature* 439: 187-191.

Khalil, M.I., Boeckx, P., Rosenani, A.B. & Van Cleemput, O. 2001. Nitrogen transformations and emission of greenhouse gases from three acid soils of humid tropics amended with n sources and moisture regime. II. Nitrous oxide and methane fluxes. *Communications in Soil Science & Plant Analysis* 32: 2909-2924.

Kong, Y., Nagano, H., Kátai, J., Vágó, I., Oláh, Á.Z., Yashima, M. & Inubushi, K. 2013. CO_2, N_2O and CH_4 production/consumption potentials of soils under different land-use types in central Japan and eastern Hungary. *Soil Science and Plant Nutrition* 59: 455-462.

Lal, R. & Bruce, J.P. 1999. The potential of world cropland soils to sequester C and mitigate the greenhouse effect. *Environmental Science & Policy* 2: 177-185.

Lee, C.H., Park, K.D., Jung, K.Y., Ali, M.A., Lee, D., Gutierrez, J. & Kim, P.J. 2010. Effect of Chinese milk vetch (*Astragalus sinicus* L.) as a green manure on rice productivity and methane emission in paddy soil. *Agriculture, Ecosystems & Environment* 138: 343-347.

Li, F., Cao, X., Zhao, L., Yang, F., Wang, J. & Wang, S. 2013. Short-term effects of raw rice straw and its derived biochar on greenhouse gas emission in five typical soils in China. *Soil Science and Plant Nutrition* 59: 800-811.

Li, H.J., Yan, J.X., Yue, X.F. & Wang, M.B. 2008. Significance of soil temperature and moisture for soil respiration in a Chinese mountain area. *Agricultural & Forest Meteorology* 148: 490-503.

Li, S., Li, Y., Li, X., Tian, X., Zhao, A., Wang, S., Wang, S. & Shi, J. 2016. Effect of straw management on carbon sequestration and grain production in a maize-wheat cropping system in Anthrosol of the Guanzhong Plain. *Soil & Tillage Research* 157: 43-51.

Li, X., Ma, J., Yao, Y., Liang, S., Zhang, G., Xu, H. & Yagi, K. 2014. Methane and nitrous oxide emissions from irrigated lowland rice paddies after wheat straw application and midseason aeration. *Nutrient Cycling in Agroecosystems* 100: 65-76.

Li, X., Yuan, W., Xu, H., Cai, Z. & Yagi, K. 2011. Effect of timing and duration of midseason aeration on CH4 and N2O emissions from irrigated lowland rice paddies in China. *Nutrient Cycling in Agroecosystems* 91: 293-305.

Liu, C., Lu, M., Cui, J., Li, B. & Fang, C.M. 2014. Effects of straw carbon input on carbon dynamics in agricultural soils: A meta-analysis. *Global Change Biology* 20: 1366-1381.

Liu, G., Yu, H., Ma, J., Xu, H., Wu, Q., Yang, J. & Zhuang, Y. 2015. Effects of straw incorporation along with microbial inoculant on methane and nitrous oxide emissions from rice fields. *Science of the Total Environment* 518-519: 209-216.

Loya, W.M., Johnson, L.C. & Nadelhoffer, K.J. 2004. Seasonal dynamics of leaf- and root-derived C in arctic tundra mesocosms. *Soil Biology & Biochemistry* 36: 655-666.

Malhi, S.S., Lemke, R., Wang, Z.H. & Chhabra, B.S. 2006. Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality, and greenhouse gas emissions. *Soil & Tillage Research* 90: 171-183.

Mathieu, O., leveque, J., Henault, C., Milloux, M., Bizouard, F. & Andreux, F. 2006. Emissions and spatial variability of N_2O, N_2 and nitrous oxide mole fraction at the field scale, revealed with ^{15}N isotopic techniques. *Soil Biology & Biochemistry* 38: 941-951.

Millar, N. & Baggs, E.M. 2004. Chemical composition, or quality, of agroforestry residues influences N2O emissions after their addition to soil. *Soil Biology & Biochemistry* 36: 935-943.

Minamikawa, K. & Sakai, N. 2006. The practical use of water management based on soil redox potential for decreasing methane emission from a paddy field in Japan. *Agriculture, Ecosystems & Environment* 116: 181-188.

Naser, H.M., Nagata, O., Tamura, S. & Hatano, R. 2007. Methane emissions from five paddy fields with different amounts of rice straw application in central Hokkaido, Japan. *Soil Science and Plant Nutrition* 53: 95-101.

Pathak, H., Singh, R., Bhatia, A. & Jain, N. 2006. Recycling of rice straw to improve wheat yield and soil fertility and reduce atmospheric pollution. *Paddy & Water Environment* 4: 111-117.

Senbayram, M., Chen, R., Budai, A., Bakken, L., Dittert, K., Zavattaro, L. & Rochette, P. 2012. N_2O emission and the $N_2O/(N_2O + N_2)$ product ratio of denitrification as controlled by available carbon substrates and nitrate concentrations. *Agriculture, Ecosystems & Environment* 147: 4-12.

Shaaban, M., Wu, Y., Peng, Q., Wu, L., Van Zwieten, L., Khalid, M.S., Younas, A., Lin, S., Zhao, J., Bashir, S., Zafar-ul-hye, M., Abid, M. & Hu, R. 2018. The interactive effects of dolomite application and straw incorporation on soil N_2O emissions. *European Journal of Soil Science* 69: 502-511.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F. & Tubiello, F. 2014. Forestry and other land use (AFOLU). In *Climate Change 2014: Mitigation of Climate Change. In: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T. & Minx, J.C. UK and New York: Cambridge University Press Cambridge. pp. 811-922.

Spormann, A.M. & Widdel, F. 2000. Metabolism of alkylbenzenes, alkanes, and other hydrocarbons in anaerobic bacteria. *Biodegradation* 11: 85-105.

Tang, J., Liang, S., Li, Z., Zhang, H., Wang, S. & Zhang, N. 2016. Emission laws and influence factors of greenhouse gases in saline-alkali paddy fields. *Sustainability* 8(2): 163.

Ussiri, D.A.N., Lal, R. & Jarecki, M.K. 2009. Nitrous oxide and methane emissions from long-term tillage under a continuous corn cropping system in Ohio. *Soil & Tillage Research* 104(2): 247-255.

Wang, J.Y., Jia, J.X., Xiong, Z.Q., Khalil, M.A.K. & Xing, G.X. 2011. Water regime-nitrogen fertilizer-straw incorporation interaction: Field study on nitrous oxide emissions from a rice agroecosystem in Nanjing, China. *Agriculture, Ecosystems & Environment* 141: 437-446.

Wang, N., Yu, J.G., Zhao, Y.H., Chang, Z.Z., Shi, X.X., Ma, L.Q. & Li, H.B. 2018. Straw enhanced $CO_2$and CH_4 but decreased N_2O emissions from flooded paddy soils: Changes in microbial community compositions. *Atmospheric Environment* 174: 171-179.

Yao, Z., Yan, G., Zheng, X., Wang, R., Liu, C. & Butterbach-Bahl, K. 2017. Straw return reduces yield-scaled N_2O plus NO emissions from annual winter wheat-based cropping systems in the North China Plain. *Science of the Total Environment* 590-591: 174-185.

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

Yeboah, S., Zhang, R., Cai, L., Song, M., Li, L.L., Xie, J., Luo, Z., Wu, J. & Zhang, J. 2016. Greenhouse gas emissions in a spring wheat-field pea sequence under different tillage practices in semi-arid Northwest China. *Nutrient Cycling in Agroecosystems* 106: 77-91.

Yoo, G., Kim, Y.J., Lee, Y.O. & Ding, W. 2016. Investigation of greenhouse gas emissions from the soil amended with rice straw biochar. *KSCE Journal of Civil Engineering* 20: 2197-2207.

Zhang, H., Tang, J., Liang, S., Li, Z., Wang, J. & Wang, S. 2018. Early thawing after snow removal and no straw mulching accelerates organic carbon cycling in a paddy soil in Northeast China. *Journal of Environmental Management* 209: 336-345.

Zhang, J., Hang, X., Lamine, S.M., Jiang, Y., Afreh, D., Qian, H., Feng, X., Zheng, C., Deng, A., Song, Z. & Zhang, W. 2017a. Interactive effects of straw incorporation and tillage on crop yield and greenhouse gas emissions in double rice cropping system. *Agriculture, Ecosystems & Environment* 250: 37-43.

Zhang, H., Tang, J., Liang, S., Li, Z., Yang, P., Wang, J. & Wang, S. 2017b. The emissions of carbon dioxide, methane, and nitrous oxide during winter without cultivation in local saline-alkali rice and maize fields in Northeast China. *Sustainability* 9: 1916.

Zhang, J.B., Song, C.C. & Yang, W.Y. 2005. Cold season CH_4, CO_2 and N_2O fluxes from freshwater marshes in northeast China. *Chemosphere* 59: 1703-1705.

Zhang, Y., Liu, J., Mu, Y., Pei, S., Lun, X. & Chai, F. 2011. Emissions of nitrous oxide, nitrogen oxides and ammonia from a maize field in the North China Plain. *Atmospheric Environment* 45: 2956-2961.

Zheng, L., Wu, W., Wei, Y. & Hu, K. 2015. Effects of straw return and regional factors on spatio-temporal variability of soil organic matter in a high-yielding area of northern China. *Soil & Tillage Research* 145: 78-86.

Zhou, Y., Zhang, Y., Tian, D. & Mu, Y. 2017. The influence of straw returning on N_2O emissions from a maize-wheat field in the North China Plain. *Science of the Total Environment* 584-585: 935-941.

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