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Reducing greenhouse gas emission by alternating the upland crop rotation in the Mekong Delta, Vietnam

Van Dung Tran[1], Kim Thu Nguyen[2], Nguyen Hoang Phuc Ho[2], Nguyen Thanh Lich Duong[2], Ngoc Minh Tam Vu[2], Thi Phong Lan Nguyen[2], Long Vu Van[3], Ben MacDonald[4]*

[1]*Soil Science Department, College of Agriculture, Can Tho University, Can Tho, Vietnam*
[2]*Cuu Long Delta Rice Research Institute, Can Tho, Vietnam*
[3]*Faculty of Natural Resources-Environment, Kien Giang University, Kien Giang, Vietnam*
[4]*CSIRO Agriculture and Food, Black Mountain, Canberra, Australia*

**Corresponding author: vvlong@vnkgu.edu.vn*

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Abstract: Agricultural production is one of the main sources of anthropogenic greenhouse gas (GHG) emissions, contributing 50% and 60% of CH_4 and N_2O emissions, respectively. This study evaluated the rice yield and components, the CH_4 and N_2O emissions and the global warming potential between the triple rice (R-R-R) and sesame-rice rotation (S-R-R) systems in Can Tho city, Vietnam. The experiments were conducted in three cropping seasons: spring-summer 2016, summer-autumn 2016, and winter-spring 2016–2017. The results showed that there was no significant difference in the yield components and grain yield between the triple rice and sesame-rice rotation systems. The application of a sesame rotation in rice-based system could reduce the CH_4 and N_2O emission by 30.5% and 18.7%, respectively. The global warming potential in the S-R-R rotation was 9 860 kg CO_{2e}/ha, significantly lower than the R-R-R rotation (12 410 kg CO_{2e}/ha) by 20.6%. These results show that the S-R-R rotation has the potential to mitigate the GHG emissions, especially CH_4, which contributes a large amount of emissions in the rice cultivation.

Keywords: global warming potential; methane; nitrous oxide; *Oryza sativa* L.; rotation; triple rice

The concentration of greenhouse gases (GHGs) in the atmosphere has been increasing since the pre-industrial era (Islam et al. 2020). Methane (CH_4) and nitrous oxide (N_2O) are two important GHGs, which contribute to global warming (Kong et al. 2013). According to the Environmental Protection Agency (EPA 2019), CH_4 and N_2O have a global warming potential (GWP) of 25 and 298 times greater than CO_2 over a 100-year period, respectively. In addition, 40–65% of CH_4 and N_2O emissions to the atmosphere come from human activities, such as agriculture, energy, industry, and waste (EPA 2019).

Rice production is considered the most significant anthropogenic source of CH_4 and N_2O emissions (Datta et al. 2013; Xu et al. 2015; Islam et al. 2018). Globally, the paddy rice system contributes 1.5% of the total anthropogenic GHG emissions (FAOSTAT 2019). In the rice production system, irrigation water, soil preparation, crop management, and fertilisation practices affect these emission magnitudes (Sun et al. 2013; Islam et al. 2020). Continuous flooding is a common irrigation practice in the paddy field, producing a large amount of CH_4 in many countries, and Vietnam contributed 5.47% of the CH_4 emissions in 2019 (FAOSTAT 2019).

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In addition, N_2O emissions are also a major environmental problem in the paddy rice system (Adviento-Borbe et al. 2015; Ruser & Schulz 2015; Liu et al. 2016). The N_2O emissions in the paddy field depends on the soil Eh, waterlogging, and the amount of nitrogen (N) fertiliser in the soil profile (Adviento-Borbe et al. 2015; Bai et al. 2021). According to Barton et al. (2013), N fertilisers could increase the N_2O emissions via denitrification in the submerged soil. Urea fertiliser will be converted to nitrate (NO_3^-) in the thin aerobic soil layer in the paddy soil and NO_3^- is denitrified to form N_2O that diffuses in the anaerobic soil below (Weil & Brady 2017).

In the Vietnamese Mekong Delta (VMD) region, intensive double and triple rice are the dominant cropping systems (Wassmann et al. 2010). Recently, rice production in the VMD region has faced difficulties related to water scarcity and salinity intrusion due to climate change (Phuong et al. 2020). In response, farmers have converted dry season rice cropping to upland crop cultivation (Brown et al. 2018; Tran et al. 2019; Tan et al. 2020). Several studies demonstrated that the application of rice-crop rotation (wheat, soybean, rapeseed, maize, or aerobic rice) could reduce the flux of CH_4 and N_2O (Barton et al. 2013; Carvalho et al. 2014; Zhou et al. 2015, 2017; Weller et al. 2016). The results might be explained by the change in the soil oxidation-reduction conditions leading to an inhibition of CH_4 and N_2O emissions (Zhou et al. 2017), ashortened cropping season and an improved crop N use efficiency. The simultaneous quantification of CH_4 and N_2O emissions from rice-upland rotation systems relative to the triple rice system has not occurred in the VMD region. The objectives of this study were to (*i*) evaluate the change in the rice yield as affected by the sesame rotation in the rice-based paddy and (*ii*) determine the emissions of CH_4 and N_2O, and calculate the annual GWPs of CH_4 and N_2O under a diversified cropping system.

MATERIAL AND METHODS

Site description and soil properties. The experiment was conducted in the intensive rice (3 crops per year) area in Thoi Lai district, Can Tho city, which is located in the VMD region (10°03'44.4''N, 105°33'12.5''E). The three crops grown in this experimental site include the spring-summer (SS) season from 02/2016 to 06/2016, summer-autumn (SA) season from 06/2016 to 10/2016, and winter-spring (WS) season 2016–2017 from 11/2016 to 02/2017. The study area has a typical monsoon climate with a dry season (from November to April) and a wet season (from April to November). The average monthly precipitation and temperature in the study time are presented in Figure 1. The experimental soil was classified as Eutric Gleysols according to the International Union of Soil Sciences (IUSS) Working Group World Reference Base for Soil Resources (FAO 2014). At a 0–20 cm soil depth, the soil texture was classified as silty clay, slightly acidic (pH 4.98), with a total N content of approximately 0.11% N and organic carbon content of 1.76%, whose range is considered low for paddy rice (Metson 1961).

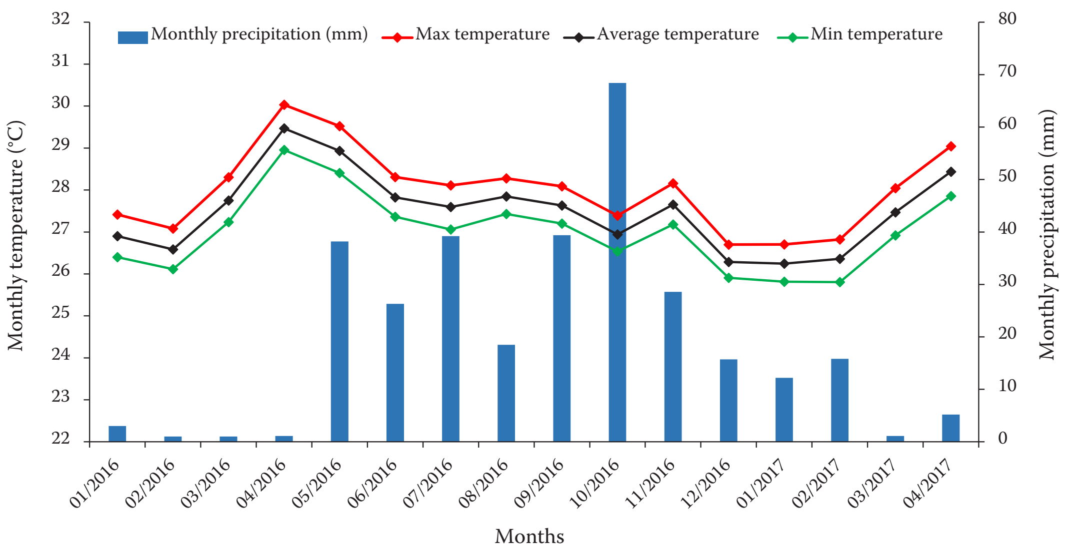

Figure 1. The average monthly precipitation and temperature of the study site from 01/2016 to 04/2017

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Experimental design and treatments. The field experiment was conducted during three consecutive crop seasons, SS 2016, SA 2016, and WS 2016–2017. The experiment was conducted in a randomised complete block design with three replicates. The experimental treatments included three cropping models: sesame-rice-rice (S-R-R) and rice-rice-rice (R-R-R) as the farmer's practice (control). The crop rotation treatment was conducted over two years, with the rotation consisting of sesame (SS 2016), rice (SA 2016), rice (WS 2016–2017).

Rice variety IR50404 from the International Rice Research Institute (IRRI) and the local sesame variety (black sesame), which have a growing time of approximately 90 and 65 days, respectively, were used in these experiments. The rice seeds were direct-seeded at seed rate of 192 kg/ha. The field experiments were conducted as the farmer's practice, the rice treatments were continuously flooded until two weeks before the harvest time. The irrigation water in all the sesame treatments were followed by the farmer's practice. The sesame crop was fertilised with 120 N-80 P_2O_5-30 K_2O (kg/ha), and the rice crops were fertilised with 100 N-60 P_2O_5-30 K_2O (kg/ha). A phosphorus fertiliser was applied before sowing in both the models. In the S-R-R rotation, urea and potassium fertiliser were topdressed at 12, 17, 25, 31, 41, and 48 days after sowing (DAS) while the fetilisation occurred at 8, 26, 38, and 54 DAS in the R-R-R rotation.

Soil analyses and plant sampling. Soil samples were taken at a 0–20 cm soil depth at the commencement of the experiment. The soil texture was analysed using the pipette method according to Kroetsch and Wang (2008). The soil pH was determined by extracting the soil with deionised water at a ratio of 1 : 2.5 (soil : water, *w* : *v*), measured using a pH meter. The soil organic carbon (% C) content was determined using the Walkley-Black method (Walkley & Black 1934), and the total N was analysed using the Kjeldahl method.

The yield components were taken in a frame of 0.25 m^2 for analysing the 1 000 grain weight, the number of panicles (No./m), and the total grains per panicle. The rice yield was determined by taking 5 m^2 plant samples at the centre of each treatment and calculated at a 14% moisture content.

Gas sampling and analysis. All the gas samples were collected at the same time in both the S-R-R and R-R-R models. Four gas samples were taken at 10 min intervals (0, 10, 20, and 30 min) for 30 min from 8:00 to 11:00 am, using a closed chamber according to Gaihre et al. (2013). Each closed chamber included one chamber base and a chamber cover (110 L). In each experimental treatment, one chamber-base was permanently inserted at a 10 cm soil depth and maintained in place over the entire crop rotation cycle. Each chamber was equipped with a circulating fan to keep the air inside the chamber mixing and a thermometer to measure the air temperature inside the chamber during the gas sampling. In the chamber wall, a rubber septum was fixed to collect the gas samples. CH_4 and N_2O gases were collected weekly, from the first week after sowing until a week before harvest. Gas samples were collected using a 60 mL polyvinylchlorid (PVC) syringe with a stainless steel needle and were transferred into 10-mL evacuated glass vials sealed with a butyl rubber stopper for laboratory analysis.

The CH_4 and N_2O concentrations were measured by gas chromatography equipped with a flame ionisation detector (Model SRI 8610C, Germany) at 300 °C and an electron capture detector (Model SRI 8610C, Germany) at 350 °C, respectively. The N_2O and CH_4 fluxes (mg/m^2/day) were calculated using the following equation (Gaihre et al. 2013):

$$CH_4 \text{ and } N_2O \text{ emissions} = \frac{\text{slope}(\text{ppm}/\text{min}) \times Vc \times \text{MW} \times 60 \times 24}{22.4 \times \left((273+T)/273\right) \times Ac \times 1000}$$

where:

*V*c – the volume of the gas chamber in litres (L);
MW – the molecular weight of the CH_4 or N_2O;
T – the temperature inside the chamber (°C);
*A*c – the area of chamber base in m^2;
1 000 – μg/mg;
60 – min/h;
24 – h/day;
22.4 – the volume of 1 mol of gas in L at a standard temperature and pressure;
273 – the standard temperature (°K).

The total CH_4 and N_2O emissions of the rice (or sesame) each cropping season were calculated using the following equations:

TCH_4 = the average amount of CH_4 per day × 90 (or 65)

TN_2O = the average amount of N_2O per day × 90 (or 65)

The global warming potential was calculated using the following equation:

GWP (kg CO_2 equivalent/ha) = (TCH_4 × 25 + TN_2O × 298)

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where:

TCH_4 – the total amount of CH_4 flux (kg/ha);

TN_2O – the total amount of N_2O flux (kg/ha);

90, 65 – the days of rice and sesame growing, respectively;

25, 298 – the GWP values for CH_4 and N_2O, respectively, to convert them into CO_2 equivalents without including climate-carbon feedback over a 100-year time scale (Zhou et al. 2015).

Statistical analysis. The collected data were analysed using the STAR (Statistical Tool for Agricultural Research) software (Ver. 2.0.1, 2014) to determine if the crop rotation had a significant effect on the emission of CH_4, N_2O and rice yield. The means of the treatments were compared using the least significant difference test at a probability level of 5% or lower.

RESULTS

Rice yield components and grain yield

The results indicated that the yield components in the S-R-R and R-R-R systems did not differ significantly in both the SS 2016 and WS 2016–2017 cropping seasons, except the total number of grains per panicle (Table 1). It showed that the total number of grains per panicle in the rotation system varied at 50 grains per panicle, significantly lower than the triple rice system (55 grains per panicle) in the SS 2016 season. The rice yield ranged at 4.60, 5.31–5.33, 7.17–7.37 t/ha in the SS 2016, SA 2016, and WS 2016–2017 cropping seasons, respectively. Similarly, the application of the sesame crop in the rice-based system did not significantly affect the rice yield throughout the three consecutive cropping seasons (Table 1).

Crop rotation and CH_4 flux

Daily CH_4 flux. In the SS 2016 crop season, the average CH_4 emissions in the S-R-R rotation was 39.9 mg/m^2/day, lower than the R-R-R rotation (64.7 mg/m^2/day). (Figure 2A). In the SA 2016 season, the CH_4 emission rate in the sesame rotational system ranged at 73.9 mg/m^2/day lower than the triple rice system (126 mg/m^2/day) (Figure 2B). Similarly, the average rate of CH_4 emissions in the S-R-R rotation was 155 mg/m^2/day, which was a 8.9% reduction compared to the R-R-R rotation (170 mg/m^2/day) in the WS 2016–2017 season (Figure 2C). Generally, the CH_4 emission rates in both systems were high at the panicle initiation (34–41 DAS) and flowering (55–62 DAS) in all of the cropping seasons. In addition, the results also indicated that the CH_4 flux increased in the SA 2016 and WS 2016–2017 seasons than in the SS 2016 season in all the rotations.

Total CH_4 flux. The results show that the total CH_4 flux in the S-R-R rotation varied around 23.7 kg per ha, significantly lower than in the R-R-R rotation (47.3 kg/ha) in the SS 2016 season (Figure 3). The total CH_4 emissions of the two rotation models varied from 81.0–116 and 142–158 kg/ha in the SA 2016 and WS 2016–2017, respectively (Figure 3). The results indicate that the total CH_4 emissions in the S-R-R rotation were significantly lower than the R-R-R rotation in both SA 2016 and WS 2016–2017 crops.

Crop rotation and N_2O flux

Daily N_2O flux. In the SS 2016 season, the average of daily N_2O emissions in the S-R-R rotation was 9.15 mg/m^2/day which was lower than the R-R-R rotation of 9.56 mg/m^2/day (Figure 4A). The results show that daily N_2O flux was highly temporally variable,

Table 1. Rice yield components and grain yield under the crop rotation systems

Seasons	Models	1 000 grain weight (g)	Number of grains per panicle	Ratio of filled grain (%)	Rice yield (t/ha)
SS 2016	S-R-R	–	–	–	–
	R-R-R	24.1	68	72.4	4.60
SA 2016	S-R-R	25.9[a]	50[a]	78.8[a]	5.33[a]
	R-R-R	25.5[a]	55[b]	75.3[a]	5.31[a]
	F-test	ns	*	ns	ns
WS 2016–2017	S-R-R	24.4[a]	76[a]	84.0[a]	7.37[a]
	R-R-R	24.5[a]	78[a]	81.6[a]	7.17[a]
	F-test	ns	ns	ns	ns

SS – spring-summer; SA– summer-autumn; WS – winter-spring; means in a column followed by the same letter are not significantly different; ns – not significantly different ($P > 0.05$); *significantly different ($P \leq 0.05$)

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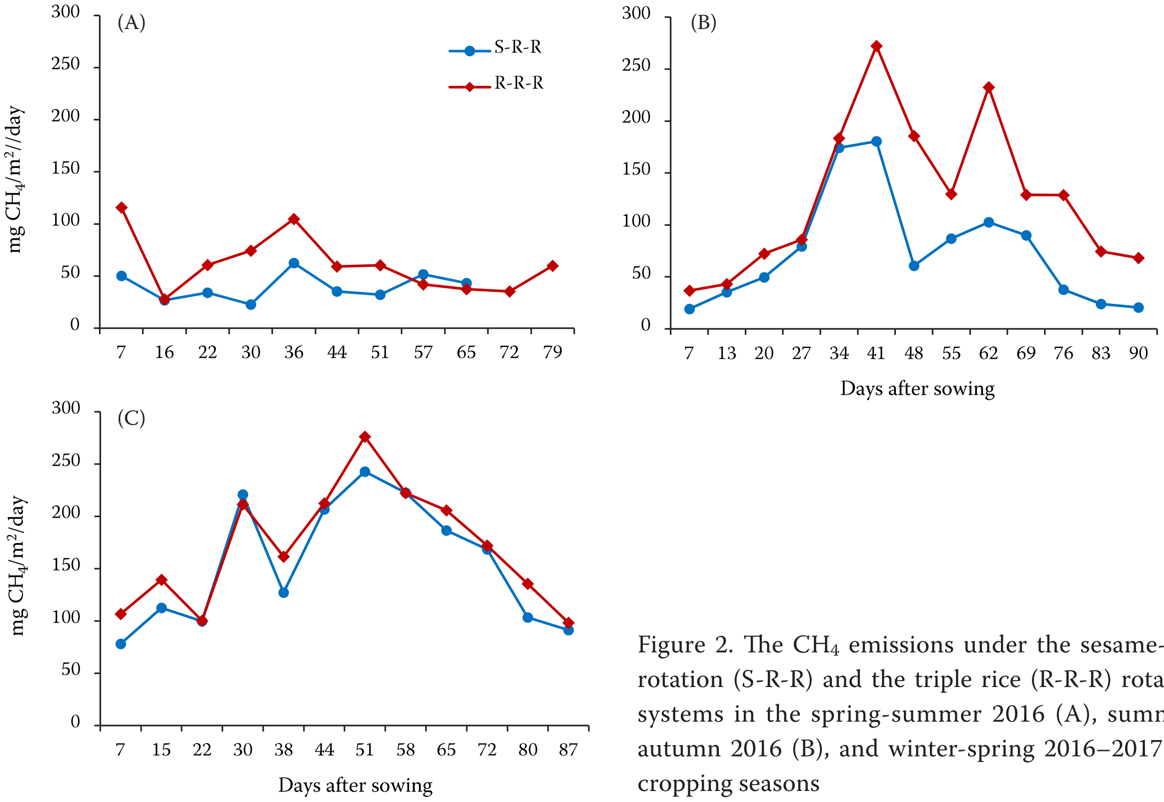

Figure 2. The CH_4 emissions under the sesame-rice rotation (S-R-R) and the triple rice (R-R-R) rotation systems in the spring-summer 2016 (A), summer-autumn 2016 (B), and winter-spring 2016–2017 (C) cropping seasons

with the greatest flux occurring at 30 DAS in the S-R-R rotation and 51 DAS in the R-R-R rotation. After the sesame crop rotation, the results show that the average daily N_2O flux was lower than the triple rice cropping model in both of SA 2016 and WS 2016–2017 seasons (Figure 4B, C). In contrast, the daily N_2O emissions in the SS 2016 crop was higher than the SA 2016 and WS 2016–2017 crops compared to the CH_4 flux.

Total N_2O flux. The total N_2O emissions in the S-R-R rotation was 5.86 kg/ha/crop, which was significantly lower than the R-R-R rotation (7.19 kg/ha/crop) in the SS 2016 crop (Figure 5). However, the total N_2O flux in the S-R-R rotation (4.03 kg/ha/ crop) did not differ significantly compared to the R-R-R rotation (4.37 kg per ha/crop) in the SA 2016 season ($P > 0.05$). In the WS 2016–2017 season, the total N_2O emissions in the S-R-R rotation ranged at 2.49 kg/ha/crop, which was

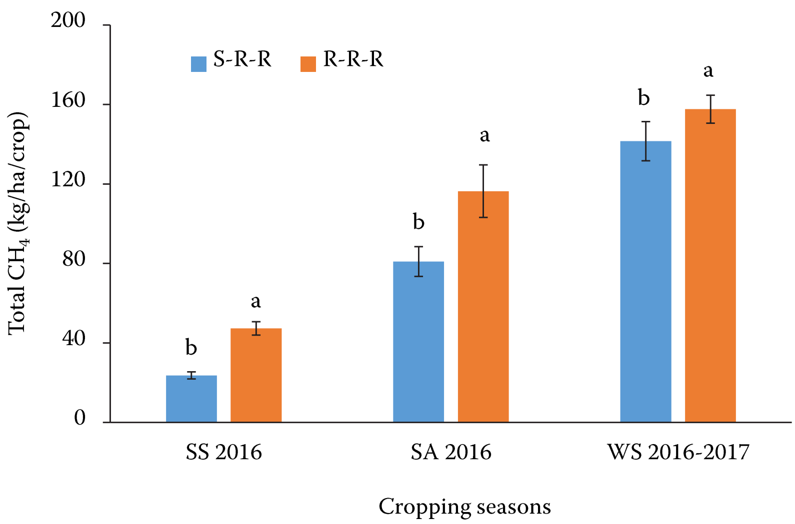

Figure 3. The total CH_4 flux under two cropping models

SS – spring-summer; SA– summer-autumn; WS – winter-spring; S-R-R – sesame-rice rotation; R-R-R– the triple rice rotation systems; vertical bars are the standard deviations of the means; columns with different letters (a, b) are significantly different at $P \leq 0.05$

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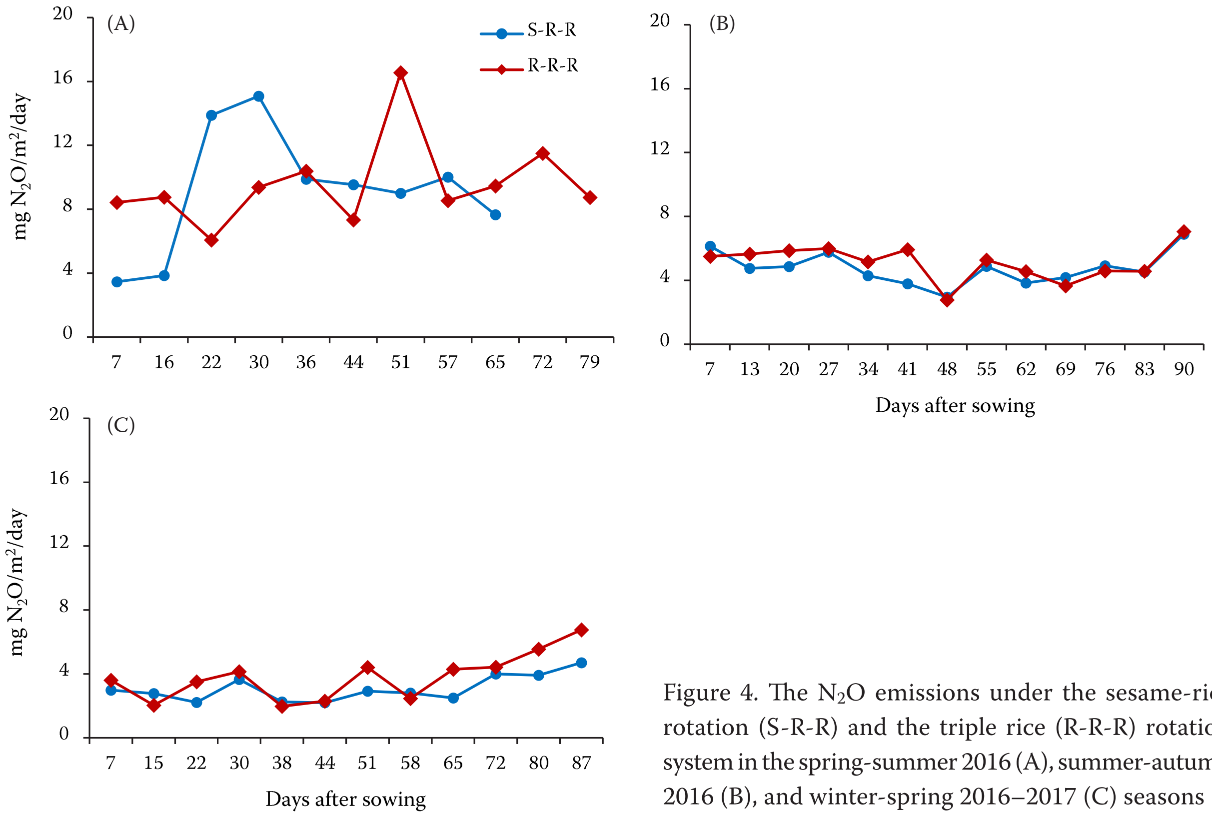

Figure 4. The N_2O emissions under the sesame-rice rotation (S-R-R) and the triple rice (R-R-R) rotation system in the spring-summer 2016 (A), summer-autumn 2016 (B), and winter-spring 2016–2017 (C) seasons

significantly lower than the R-R-R rotation (3.13 kg per ha/crop). After three consecutive crops, the result showed that the total N_2O emissions in the application of the sesame rotation in the paddy rice-based varied around 12.4 kg/ha, which was significantly lower than the triple rice cropping system (14.7 kg per ha). This study demonstrated that the S-R-R rotation system could reduce 18.7% of the total N_2O emissions compared to the triple rice cultivation system in the VMD region (Figure 5).

Global warming potential

The S-R-R rotation compared to the R-R-R rotation had a significant effect on the total CO_2 equivalent (CO_{2eq}) emission in all the SS 2016, SA 2016, and WS 2016–2017 cropping seasons (Table 2). The total CO_{2eq} ranged from 2 339 to 4 279 kg/ha in the S-R-R system and from 3 325 to 4 875 kg/ha in R-R-R system. The GWP value in the S-R-R rotation was 9 860 kg CO_{2eq}/ha, significantly lower than the R-R-R rotation (12 410 kg CO_{2eq}/ha). This study indi-

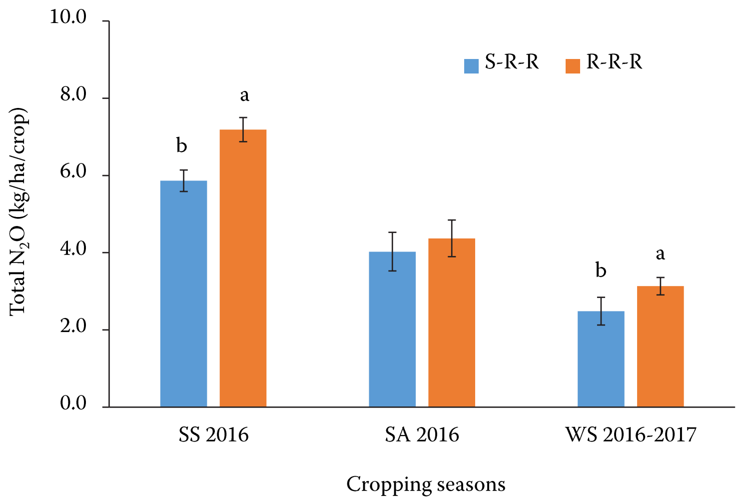

Figure 5. Effects of the sesame rotation on the total N_2O emissions in the spring-summer (SS) 2016, summer-autumn (SA) 2016, and winter-spring (WS) 2016–2017 cropping seasons
S-R-R – sesame-rice rotation; R-R-R– the triple rice rotation systems; vertical bars are the standard deviations of the means; columns with different letters (a, b) are significantly different at $P \leq 0.05$

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Table 2. The global warming potential under the crop rotation system

Cropping season	Models	SS 2016	SA 2016	WS 2016–2017	GWP for three cropping seasons (kg CO_{2e}/ha)
GWP (kg CO_{2eq}/ha)	S-R-R	2 339^{b}	3 224^{b}	4 279^{b}	9 860^{b}
	R-R-R	3 325^{a}	4 214^{a}	4 875^{a}	12 410^{a}
	F-test	***	***	***	***

SS – spring-summer; SA– summer-autumn; WS – winter-spring; GWP – global warming potential; ***significantly different at $P \leq 0.001$

cated that the sesame rotation could reduce the GWP by 20.6% compared to the triple rice cropping system.

DISCUSSION

Dynamics of CH_4 and N_2O fluxes. The CH_4 emission increases with the time of rice growth until the flowering stage and declines sharply thereafter until the harvest time, as previous studies have shown (Gaihre et al. 2014; Islam et al. 2020). The lower emission rates were found in the SS 2016 season compared to the SA 2016 and WS 2016–2017 cropping seasons. After three cropping seasons, the application of the sesame rotation in the rice-based system significantly ($P \leq 0.05$) reduced the CH_4 emissions by 30.5% compared to the triple rice cultivation system. These results are lower than the previous findings (Adhya et al. 2000; Cha-un et al. 2017). The study of Cha-un et al. (2017) in Thailand reported that the CH_4 emissions from the rotation of upland crops (corn, sorghum) in the rice-based system ranged from 166 to 199 kg/ha/year, which was significantly lower than the double rice system (893 kg/ha/year) by 78–84%. According to Xu et al. (2015), the CH_4 emissions depend on many factors, such as the water irrigation, soil characteristics, and other cultivation managements. Cai et al. (2016) stated that improved soil aeration resulted in an unfavourable conditions for the anaerobic reduction of organic matter and the production of CH_4 by methanogen. The oxidation of CH_4 by methanotrophic bacteria was promoted in the oxidised soil conditions (Weil & Brady 2017). The change in the water management was the direct cause of the lower dry season CH_4 emissions in the S-R-R rotation than the R-R-R rotation during the SS 2016 season.

During the dry season in the S-R-R rotation, there was potentially less denitrification because the soil was drier, and as a result, the N_2O emissions are lower than the triple rice system. Besides, the N_2O flux is always low in the other growing seasons compared to the R-R-R rotation (Figure 5). Denitrification is an anaerobic process, Khalil et al. (2004) reported that the N_2O emissions from the soil undergoing rice monoculture (R-R-R) was higher compared to an upland crop rotation system (S-R-R).

In contrast, Janz et al. (2019) studied the effects of the crop rotation (rice-aerobic rice or rice-maize) with the same N fertiliser (130 kg N/ha) and reported that diversifying the rice cropping system significantly increased the N_2O emissions as compared to a double-rice cropping system. Nitrogen losses in the N_2O, NO, and N_2 forms can increase after the dry soil is flooded again (Boyer & Groffman 1996; Weil & Brady 2017).

Global warming potential under a crop rotation system. The GWP – the total CH_4 and N_2O emissions – was closely related to the different water management practiced during the dry-season crops (SS). Previous studies have reported that the CH_4 flux dominate the GWP of the flooded rice system, contributing over 80% (Shang et al. 2011; Weller et al. 2016; Janz et al. 2019). In this study, the annual N_2O emissions decreased in the diversified systems combined to the strong reduction in CH_4 which led to a significantly lower annual GWP (illustrated in CO_{2eq}) compared to the traditional triple rice cropping system. The reduction in the CH_4 flux has dramatic implications for reducing greenhouse gas emissions from rice fields under the current climate change conditions. Greenhouse gas emissions can also be reduced by replacing triple rice with rice-upland crop rotation, such as legumes, reducing the dependence on fertilisers and other inputs (Izaurralde et al. 2001; West & Post 2002).

CONCLUSION

Applying sesame rotation in a rice-based system reduced the CH_4 emissions by 30.5% and the N_2O emissions by 18.7% compared to the triple rice cul-

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tivation system. The S-R-R rotation system showed a lower annual GWP (CH_4 + N_2O) than the R-R-R rotation. The global warming potential from the rotation system with sesame is lower than the triple rice system by 20.6% without compromising the yield components and rice yield. Therefore, the fundamental recommendation is to promote a rotational rice-upland crop system to improve the environment by reducing the GHG emissions and optimising the rice yield.

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