INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Int. Agrophys., 2023, 37, 365-376
doi: 10.31545/intagr/163343

Effects of different management patterns on greenhouse gas emissions from single-season rice fields**

Wanling Hu[1,2], *Zhenzhong Bai*[3], *Ronggui Hu*[4], *Ying Diao*[1]*, *Xiangyu Xu*[5]*, *and Hongling Wang*[6]

[1]School of Life Science and Technology, Wuhan Polytechnic University, Wuhan 430023, China
[2]China Carbon Emissions Registration and Clearing CO., LTD, Wuhan 430070, China
[3]School of Economics, South-Central Minzu University, Wuhan 430074, China
[4]College of Resources and Environment, Huazhong Agricultural University, No.1 Shizishan Street, Hongshan District, Wuhan 430070, China
[5]Institute of Soil Fertilizer and Plant Protection, Hubei Academy of Agricultural Sciences, Wuhan 430064, China
[6]Hubei University Research Centre on China Agriculture Carbon Emission Reduction and Exchange, School of Business, Hubei University, Wuhan 430062, China

Received November 11, 2022; accepted April 17, 2023

Abstract. Different cultivation practices affect both rice yield and GHG emissions. In this study, GHG emissions, environmental factors, and soil factors on an annual scale for four common single-season rice-cultivation methods were monitored and the direct and indirect drivers of GHG emissions were analysed. The results showed that there were significant differences in the average soil temperature, water content and dissolved oxygen content for the different methods used, but not in terms of the NH_4^+-N and NO_3^--N content. The highest average methane flux was obtained using the waterlogging in the non-rice season with straw return mode method (4.20±0.16 mg m^{-2} h^{-1}), which was a significantly higher result than that produced by the other methods. The main factors influencing CH_4 emissions was atmospheric temperature for waterlogging in the non-rice season with straw return and crayfish farming, NO_3^--N for waterlogging in the non-rice season without straw return, NO_3^--N, and NH_4^+-N for waterlogging in the non-rice season with straw return, and NO_3^--N, NH_4^+-N, and soil water for non-rice season with straw return. The average fluxes of both CO_2 and N_2O were highest with the drainage in the non-rice season with straw return treatment, but the differences between the treatments were not significant. None of the factors that were determined had a significant direct effect on CO_2 emissions under either cropping system. The main factors affecting N_2O emission were NH_4^+-N and NO_3^--N in the WSC treatment, NH_4^+-N in the waterlogging in the non-rice season without straw return treatment, and NH_4^+-N, NO_3^--N, and dissolved oxygen content in the drainage in the non-rice season with straw return treatment. The results obtained have the potential to form an important basis for the establishment of agronomic measures to reduce and control GHG emissions from rice fields.

Keywords: greenhouse gas, single-season rice fields, cultivation practices, driving factors

INTRODUCTION

The greenhouse effect is considered to be the main cause of global warming. Nitrous oxide (N_2O) and methane (CH_4) are the main greenhouse gases, which are 265 times and 28 times more potent than CO_2 in terms of their warming potential in a 100-year period, respectively (IPCC, 2014). The process of N_2O production in the soil is determined by temperature, moisture, pH, nitrogen availability and other factors (Brown *et al.*, 2011), and that of CH_4 production is

---

*Corresponding author e-mail: xuxiangyu2004@sina.com

**This work was supported by the Major Programme of the National Social Science Foundation of China (19ZDA085, 2019-2024) and the National Natural Science Foundation of China (71871086 (2019-2022), 41301306 (2014-2016)), and also, the Scientific and Technological Achievements Cultivation Project of the Hubei Academy of Agricultural Sciences, China (2017CGPY01, 2017-2019).

mainly determined by oxygen content but also by soil temperature, pH, moisture and salinity (Serrano-Silva *et al.*, 2014). N_2O and CH_4 formation is also clearly affected by denitrification (or nitrification) and a methane-producing substrate, such as nitrate, ammonium, and acetate (Gao *et al.*, 2012). As multiple environmental factors affect both N_2O and CH_4 emissions, changes in either environmental factor can affect the production and emission rates of these gases (Mer and Roger, 2001). It may be observed that soil environmental factors have an impact on greenhouse gas emissions alone or through interaction, and that the impact of a single factor is limited by other factors. But no consistent conclusion may be arrived at concerning the direct or indirect impact of a certain factor on GHG emissions.

Rice fields are an important source of CH_4 and N_2O (Ma *et al.*, 2007), in which methane emissions account for 5~19% of the total global emissions (IPCC, 2007). The amount of greenhouse gas emissions from paddy fields is largely dependent on agricultural management measures. In order to improve the rice yield and maintain soil fertility, the application of chemical fertilizer and crop straw during rice cultivation is a conventional management measure, but these additions significantly increase the CH_4 and N_2O emissions from paddy fields, and the extent of the increase mainly depends on the water condition of the paddy fields (Lee *et al.*, 2010; Li *et al.*, 2014).

Integrated paddy farming is an efficient form of paddy ecosystem cultivation (Ruddle, 1982). At present, the global area of rice-fish co-cultivation is approximately 2.54 million ha, among which the rice-fish model has the largest area and the rice-crayfish model produces the greatest economic benefits. To date, research concerning greenhouse gas emissions has focused mainly on the rice-fish pattern, and few studies have addressed the rice-crayfish system. It is interesting to note that both positive and negative effects on paddy field CH_4 emissions have both been reported in integrated paddy farming. Thus, Datta *et al.* (2009), Frei *et al.* (2007a, b), and Bhattacharyya *et al.* (2013) believe that rice–fish farming significantly increases CH_4 emissions. But Yuan *et al.* (2009), Liu *et al.* (2006), and Zhan *et al.* (2008) found that it reduces CH_4 emissions. With reference to the rice-crayfish system, Xu *et al.* (2017) and Sun *et al.* (2019) found that it is capable of reducing CH_4 emissions. It may be observed that the GHG emission patterns are varied in terms of the different integrated paddy farming patterns (Ling *et al.*, 2021).

The area under rice cultivation in China is > 3×10^7 ha all year round (CAYEC, 2017), and the planting area of a single-season of rice in the southern rice-producing areas has risen to include approximately two-thirds of the total rice cultivation area (Liu *et al.*, 2013). Therefore, in this study, the different soil and environmental factors and the characteristics of greenhouse gas emissions in single-cropping rice fields under four management modes were simultaneously studied. In addition, the direct, indirect, and comprehensive effects of these factors on greenhouse gas emissions were assessed. The results provide basic data for the accurate evaluation of GHG emissions from rice fields in China. At the same time, they provide a guiding significance for clarifying the main determining factors of GHG emissions in various circumstances of rice paddy cultivation and for formulating emission reduction measures for different rice-cropping patterns.

MATERIALS AND METHODS

The experiment was carried out in Houhu Town, Qianjiang City, Hubei Province, China, which has a north subtropical monsoon-influenced humid climate, an annual average temperature of 16.1℃, a frost-free period of 246 days, and an annual average rainfall of 1 100 mm. The experimental site was in the low lake area of Jianghan Plain, with a static groundwater level of 40-60 cm in winter. The soil is classified as a tide rice soil which developed from lake sediment. At the time of our experiment the physical and chemical properties of the top soil (0-20 cm) were 26.43 g kg^{-1} organic matter, 0.21% total nitrogen, 129.50 mg kg^{-1} alkaline nitrogen, 9.13 mg kg^{-1} fast-acting phosphorus, 178.67 mg kg^{-1} fast-acting potassium, and the soil had a pH of 7.12.

The experiment was conducted using four common management practices in one-season rice fields in the Hubei Province: (i) waterlogging in the non-rice season with straw return and crayfish farming (WSC), (ii) drainage in the non-rice season with straw return (DS), (iii) waterlogging in the non-rice season without straw return (W), and (iv) waterlogging in the non-rice season with straw return (WS). The experiment commenced in 2014, and GHG emission monitoring was conducted from 2015-2018. The rice variety planted was the single-season variety "Jianzhen2".

Flooding treatments: WSC, W, WS were conducted in the first year after the rice harvest. The field was flooded, and the water level gradually rose from approximately 20 cm to 50-55 cm. The fields were drained one week before transplanting (end of May) and dried for 5-7 days. Each treatment was repeated on three plots, and each plot had an area of 100 m². A 60 × 40 cm (width × height) ridge was created around the plots and wrapped with mulch to prevent any straining of water and crayfish. A crayfish trench (3.0-4.0 × 0.8-1.0 m (width × depth)) was dug on one side of the WSC plot, and an anti-escape net was set around the plots. Seed crayfish were released in October 2014 at a rate of 200 kg h m^{-1} (about 40 individuals kg^{-1}), and no additional crayfish were added in subsequent experiments, the experiment relied on the natural reproductive capacity of the initial crayfish. Crayfish feed was only provided from March to May each year, with 46.6, 11.0, and 10.5 g kg^{-1} of nitrogen, phosphorus, and potassium, respectively, as

Table 1. Rice cultivation and fertilization management practices (test period: June 2015-May 2018)

Treatment	Water management	Fertilization	Rice straw return	Crayfish breeding
Rice growing period – Mid-June to early-October				
W	Normal management in the rice season; waterlogging in the non-rice season with the average flooding depth is 33 cm	$N:P_2O_5:K_2O$= 180:90:144 kg h m^{-2}. Apply base fertilizer when transplanting seedlings, apply top-dressing fertilizer before heading, Phosphorus and potassium are all applied as base fertilizer, Nitrogen fertilizer is equally divided into base fertilizer and top dressing	–	–
WS			3 750 kg h m^{-2}	–
WSC				Feed the crayfish when they start to move in mid-to-late March. The feed input is 1 800 kg h m^{-2}. Fishing is carried out in the shrimp ditch. Fishing first occurs from mid-April to the beginning of June when the field is drained and dried. Fishing also occurs from August to September
DS	Normal management in the rice season; drainage in the non-rice season			–

the main components. The crayfish were harvested twice a year. The fertilization and field management measures for the different cultivation models are shown in Table 1.

Soil temperature data were recorded with a data logger (HOBO UTBI-001, Onset Computer Corporation, Bourne, MA, USA). In order to avoid any effects arising from the frequent collection of soil samples, the soil was collected from five sampling sites in each paddy field at a frequency of one soil sample for every two gas samples. The soil samples were collected at a depth of 0-20 cm and immediately preserved at 4°C. The soil water (SW) content was determined using the drying and weighing method (Bao, 2000). The concentrations of NH_4^+-N and NO_3^--N were analysed using an AA3 Auto Analyser (Bran+Luebbe GmbH, Norderstedt, Germany) according to classical colorimetric methods. The concentration of DOC was analysed using a TOC Analyser (vario TOC, Elementar Analysen systeme GmbH, Langenselbold, Germany) according to standard procedures.

The gas samples were analysed using stainless steel static-box sampling and indoor gas chromatography (Wu *et al.*, 2018). The static chamber was divided into three parts: base, middle chamber, and top chamber, with a small fan placed at the top, a small sampling hole was situated in the top panel of the top chamber, and a thermal insulation layer was wrapped around the chamber. Samples were taken every 7-10 days during the non-rice season, every 5-7 days during the rice-cultivation period, and twice a week after agricultural operations such as fertilization or drainage, the sampling time was 8:00-10:00 a.m. daily.

In the idle period and the early stages of rice growth (plant height > 50 cm), only the top chamber was used for collecting gas samples, and the middle chamber was added when the rice-plant height exceeded 50 cm. One gas sample was collected with a 30 mL medical syringe at 0, 5, 10, 15, and 20 min after the cover was removed. The samples were taken to the laboratory for analysis within 24 h. In order to avoid the frequent disturbance of the soil, the sampling base was fixed for the entire sampling period (except during field preparation). A probe-type electronic thermometer was used for detection and manual recording.

The gas flux was calculated as:

$$F = \rho \frac{V}{S}\frac{dC}{dt}\frac{273}{273+T},$$

where: F is the gas flux, *i.e.*, F_{CH4} (for CH_4, mg m^{-2} h^{-1}), F_{CO_2} (for CO_2, mg m^{-2} h^{-1}), and F_{N_2O} (for N_2O, mg m^{-2} h^{-1}), ρ is the density of the gas under standard conditions (kg m^{-3}), V is the effective volume of the confinement box (m^3), S is the base area (m^2), dC/dt represents the change in gas concentration in the confinement box per unit time, and T is the average temperature in the confinement box.

All data were processed using Excel software, and statistical analyses were performed using SPSS software (SPSS 20.0, SPSS Inc., Chicago, IL, USA) and R. The significance level for the statistical analysis was set at $p < 0.05$. The plots were created using Sigma plot, R, and AI software.

RESULTS

The SW content was 15.7-30.1 (W), 15.3-29.8 (DS), 21.9-31.0 (WS), and 21.9%-31.1% (WSC) during the rice-growing season, respectively. The soil temperature was

Table 2. Mean values of soil environmental factors during the observation period

Treatment	SW (%)	ST (°C)	DOC	NO_3^--N	NH_4^+-N
				(mg kg^{-1})	
W	35.74±0.07 a	26.44±0.18 b	19.57±0.57 a	1.71±0.41 a	5.35±0.12 a
WS	36.06±0.21 a	26.80±0.05 ab	17.58±2.01 a	1.90±0.16 a	4.77±0.13 a
WSC	35.90±0.25 a	26.77±0.17 ab	23.61±1.01 a	2.81±0.39 a	4.95±0.03 a
DS	35.28±0.12 a	27.16±0.04 a	22.21±1.47 a	2.22±0.25 a	4.80±0.25 a

Letters mean ± standard error.

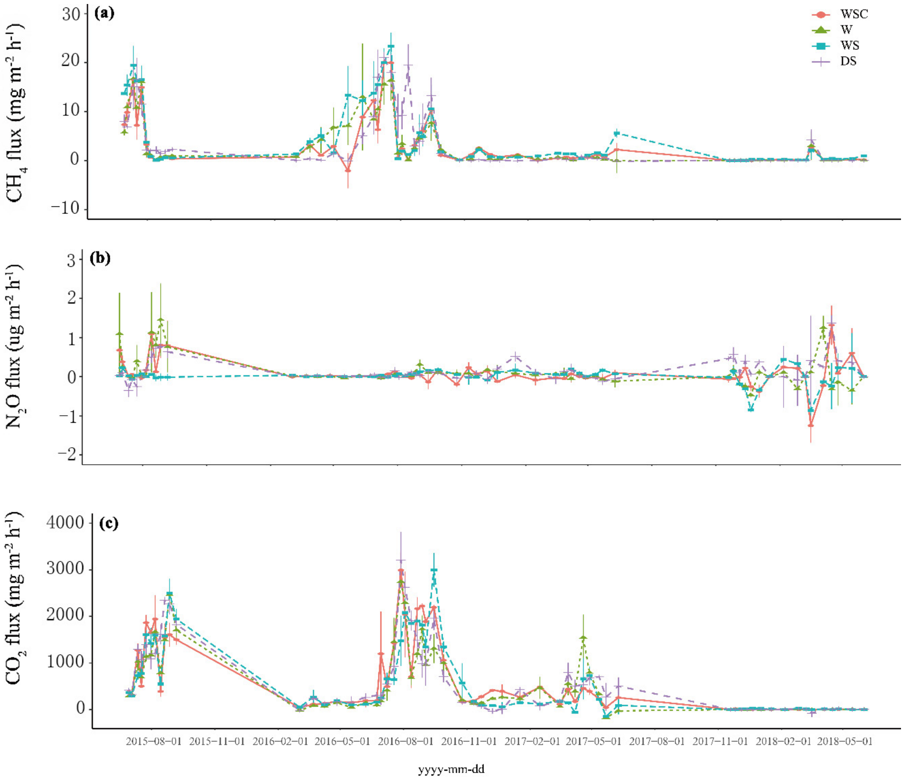

Fig. 1. Greenhouse gas emissions flux during the observation period: a – annual dynamics of the CH_4 flux, b – annual dynamics of the N_2O flux, c – annual dynamics of the CO_2 flux.

15.7-30.1 (W), 15.3-29.8°C (DS), 16.6-31.0°C (WS), and 21.9°C-31.1°C (WSC). The soil DOC content was 0-107.34 (W), 0-126.19 (DS), 0-88.26 (WS), and 1.25-100.26 mg kg^{-1} (WS). The soil NO_3^--N concentrations were 0-13.32 (W), 0-9.76 (DS), 0.14-9.76 (WS), and 0.14-11.27 mg kg^{-1} (WSC), respectively. The soil NH_4^+-N concentrations were 0.21-11.55 (W), 0.16-27.75 (DS), 0.18-28.7 (WS), and 0.18-33.44 mg kg^{-1} (WSC), respectively.

The average SW content ($p = 0.072$), the average temperature ($p = 0.027$), and the DOC content ($p = 0.063$) showed significant differences among the four modes, but the NO_3^--N concentration ($p = 0.3$) and the NH_4^+-N concentration ($p = 0.15$) did not (Table 2).

The CH_4 fluxes showed similar trends with different treatments (Fig. 1a). The CH_4 emissions increased with increasing temperature before transplanting, they peaked at the end of July during rice cultivation, and then decreased, with a second peak emission period in September and then a decrease until the rice harvest and idle period. Emissions were lower during the flooding period from November of the first year until March of the second year after that they continued to increase with increasing temperatures. The average gaseous CH_4 fluxes at different stages were highest with treatment WS, which were significantly higher than those for the other treatments during the flooding stage (stage A) and the rice-planting stage (stage B). In the idle stage (stage C), CH_4 flux was highest with treatment WSC, which was significantly higher than that under treatments W and DS. The mean flux throughout the monitoring cycle was highest with treatment WS, which was significantly higher than that with WSC ($p < 0.0005$), W ($p < 0.0005$), or DS ($p < 0.0005$) (Table 3, Fig. 2b).

Table 3. Mean values of the greenhouse gas emissions flux

Greenhouse gas (mg m^{-2} h^{-1})	Treatment	Observation period			
		A	B	C	Average
CO_2	W	173.3±22.5 a	1023.3±19.6 b	173.1±9.5 a	337.8±17.2 a
	WS	100.9±21.5 a	1266.1±29.9 a	308.1±147.5 a	335.8±16.4 a
	WSC	167.1±12.2 a	1207.6±74.5 ab	222.3±4.2 a	370.9±16.1 a
	DS	171.9±12.9 a	1231.2±24.7 a	135.3±22.2 a	375.2±14.3 a
CH_4	W	1.30±0.03 B	6.84±0.55 b	0.74±0.09 B	2.35±0.23 B
	WS	2.80±0.10 A	10.46±0.78 a	1.01±0.10 AB	4.20±0.16 A
	WSC	1.00±0.08 B	7.77±0.51 ab	1.25±0.05 A	2.33±0.11 B
	DS	0.29±0.08 C	9.77±0.79 ab	0.03±0.01 C	2.00±0.18 B
N_2O	W	0.13±0.03 a	0.05±0.01 a	0.07±0.03 a	0.17±0.06 a
	WS	0.40±0.14 a	0.04±0.01 a	0.01±0.01 a	0.31±0.11 a
	WSC	0.25±0.15 a	0.02±0.01 a	0.12±0.03 a	0.20±0.11 a
	DS	0.45±0.03 a	0.04±0.01 a	0.06±0.12 a	0.36±0.02 a

A, B, and C represent the different stages of flooding, rice planting, and post-harvest to pre-flood. Other explanations as in Table 2.

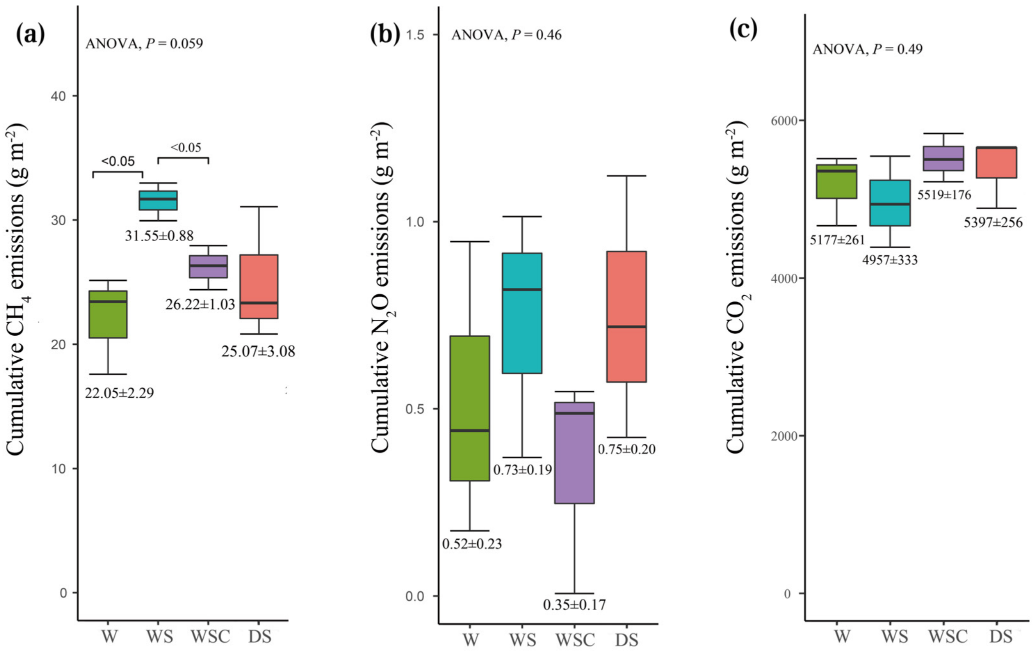

Fig. 2. Annual cumulative emissions of greenhouse gases: a – CO_2, b – CH_4, c – N_2O.

The flux dynamics of the CO_2 emissions were consistent among the various treatments (Fig. 1c). Emissions were very low in the flooding stage and increased gradually after transplanting, reaching a peak at the end of July, and then decreased until the rice harvest and idle period. The average CO_2 flux did not differ among treatments at the flooding stage (stage A), but was highest in treatment W and lowest in WS. At the rice-planting stage (stage B), the average CO_2 flux was lowest in treatment W, which was significantly lower than that in WS and DS, but not significantly different from that in the WSC treatment. At the idle stage (stage C), emissions were highest with treatment WSC, but did not differ significantly between treatments. Throughout the monitoring period, the average CO_2 fluxes were higher for the WSC and DS treatments and lowest in the WS treatment, but the differences were not significant (Table 3, Fig. 2a).

The dynamics of the N_2O emission fluxes were complex (Fig. 2b). N_2O flux was low in the non-rice flooding phase which lasted from February to the end of May in 2016, but varied more from November to the end of May in both 2016-2017 and 2017-2018. While the degree of variation was high in 2015 during rice cultivation, it was low

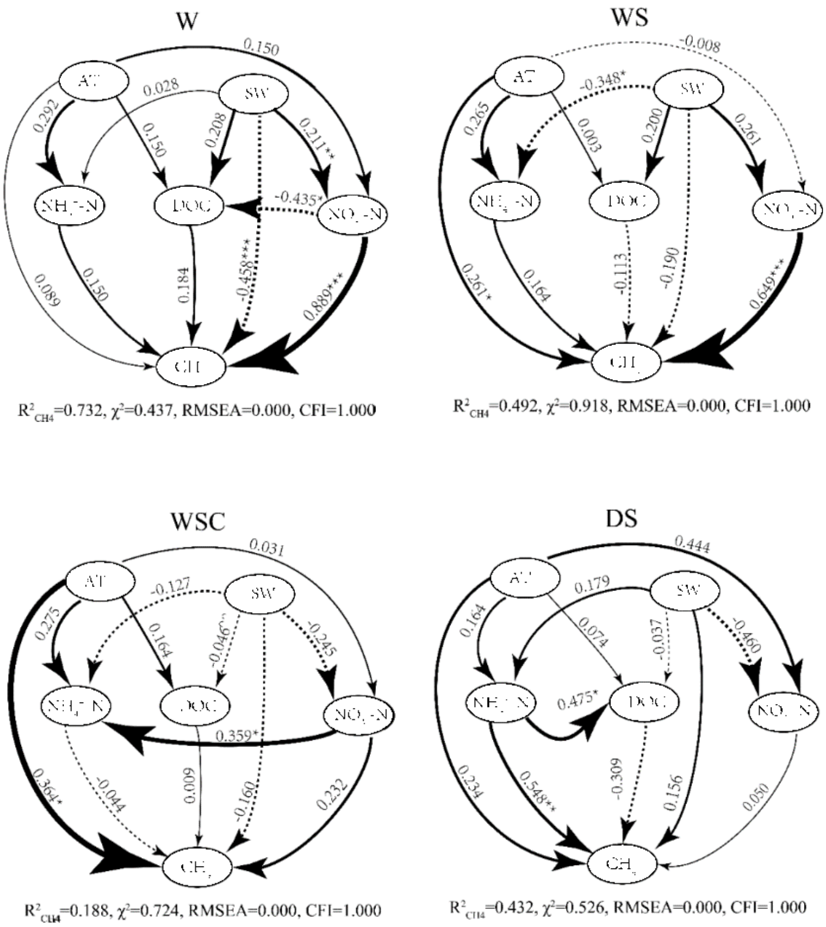

Fig. 3. SEMs of soil factors and environmental factors as predictors of CH_4 flux.

in 2016 and high during the non-rice, non-flooding phase. The greatest variability in emissions flux was observed in the rice-cultivation phase in 2015 and the flooding phase in 2018. The average N_2O emissions at different stages showed no significant differences among the various treatments at any stage. The mean N_2O emissions flux was highest in DS and lowest in W throughout the monitoring period, but the differences were not significant (Table 3, Fig. 2c).

The influence of various soil factors (NO_3^--N, NH_4^+-N, DOC) and environmental factors (atmospheric temperature (AT), SW) on CH_4 emission fluxes during the rice-cropping season were analysed using structural equation modelling (Fig. 3). The model explained 43.2% of the variation in CH_4 emission fluxes in a conventional cropping system (DS), and NH_4^+-N had a direct and significantly positive effect on CH_4 flux, with a path coefficient of 0.548 ($p < 0.001$). The whole model explained 73.2% of the variation in CH_4 emissions flux under treatment W, in which NO_3^--N had a significant direct positive effect on CH_4 flux, with a path coefficient of 0.899 ($p < 0.001$), and also SW had a significant direct negative effect on CH_4 flux, with a path coefficient of -0.458 ($p < 0.001$).

In treatment WS (straw return and flooding), the whole model explained 49.2% of the variance in CH_4 flux, and also NO_3^--N and AT had significant direct positive effects, with path coefficients of 0.649 ($p < 0.001$) and 0.261 ($p < 0.05$). The whole model explained 19.0% of the variation in CH_4 flux in treatment WSC, and also AT had a significant direct positive effect, with a path coefficient of 0.364 ($p < 0.05$). Overall, SW had a positive effect on DS, which became negative when the field was flooded in the non-rice season. The effect of AT on the CH_4 emissions flux gradually increased after flooding as elements such as straw return and crayfish farming influenced the system, while the effects of SW and NO_3^--N on CH_4 gradually decreased.

These results showed that the drivers of CH_4 fluxes differed among the cultivation systems tested. The multiple stepwise regression and quadratic regression results (Table 4) showed that the R^2 of all of the treatments decreased after the optimized regression, which indicates that the explanatory power became lower as the number of factors decreased, while the significance increased. For the optimized model, the dominant factors were AT for WSC,

Table 4. Relationships between soil CH_4 fluxes and environmental factors during the observation period were determined by multiple linear regression analyses and the optimization of the regression

Model of fit	Treatment	Regression	R^2	p	n
Quadratic regression	WSC	$0.2779AT^2-0.3658AT + 0.2697$	0.1793	0.0468*	34
Multiple linear Stepwise regression	W	$0.601NO_3^-$	0.3615	0.0002***	33
	WS	$0.765NO_3^- + 0.369NH_4^+ - 0.445SW$	0.5928	0.0002***	25
	DS	$0.45NO_3^- + 0.43NH_4^+$	0.3296	0.0123*	35

*$p \leq 0.05$, ***$p \leq 0.001$

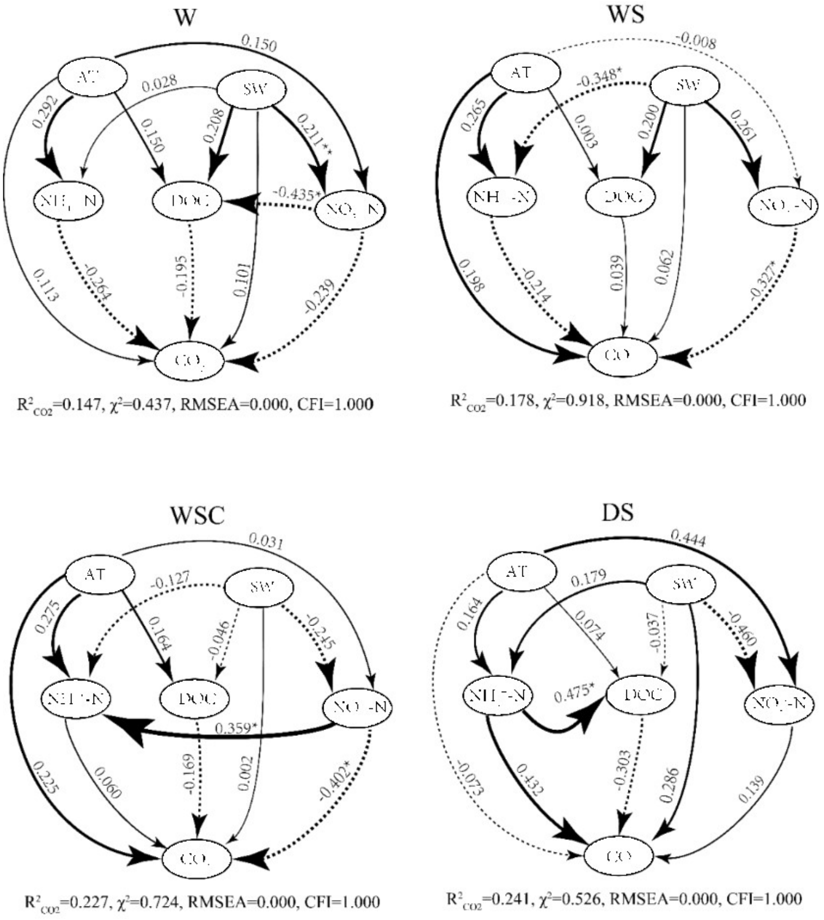

Fig. 4. SEMs of soil factors and environmental factors as predictors of CO_2 flux.

NO_3^--N for W, NO_3^--N, and NH_4^+-N for WS, and NO_3^--N, NH_4^+-N, and SW for DS, which is consistent with the structural equation model results.

The model explained 24.1 and 14.7% of the variation in CO_2 emission fluxes for DS and W (Fig. 4). No factors had a significant direct effect under either cropping system. The whole model explained 17.8 and 22.7% of the variance for WS and WSC, respectively, and NO_3^--N had a significant direct negative effect on CO_2 emission fluxes, with path coefficients of −0.327 ($p<0.05$) and −0.402 ($p<0.05$), respectively. There was no significant direct effect due to other factors. Overall, temperature had a negative effect in treatment DS, but when flooding occurred in the non-rice season (W, WS, WSC), temperature had a positive effect on the CO_2 flux. As elements such as straw and cultured crayfish gradually entered the system, the effects of NO_3^--N and AT on the CO_2 emission fluxes gradually increased, while the effects of NH_4^+-N on CO_2 production gradually decreased.

After all of the factors were taken into consideration, the model only had a limited explanatory power. After excluding the less influential factors using a multiple stepwise regression method, the results showed that CO_2 emission fluxes were mainly influenced by AT, DOC, and NO_3^--N in

Table 5. Relationships between soil CO_2 fluxes and environmental factors during the observation period determined by multiple linear regression analysis and optimization of regression

Model of fit	Treatment	Regression	R^2	p	n
Multiple linear Stepwise regression	WSC	$0.585AT - 0.318DOC - 0.358NO_3^-$	0.4772	0.0002****	34
	W	$0.489AT - 0.274NH_4^+ - 0.313NO_3^-$	0.3639	0.0040**	33
	WS	$0.356AT - 0.287NO_3^- - 0.457NH_4^+ - 0.299DOC$	0.3184	0.0955	25
	DS	$0.299AT + 0.435NH_4^+ - 0.373DOC$	0.2209	0.1472	35

**$p \leq 0.01$, **** $p \leq 0.0001$.

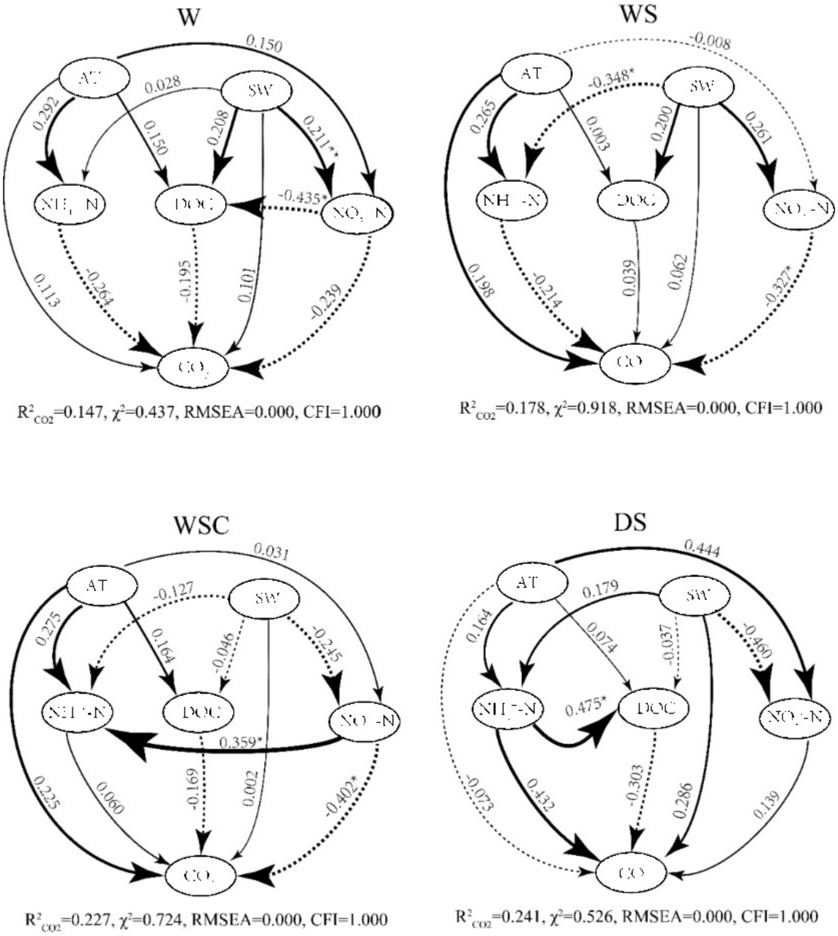

Fig. 5. SEMs of soil factors and environment factors as predictors of N_2O flux.

the WSC treatment, and by AT, NH_4^+-N, and NO_3^--N in the WS treatment (Table 5). The stepwise regression models for W and DS were not significant, thereby indicating that important factors were omitted in these two systems.

The effects of environmental factors on N_2O emission fluxes are shown in Fig. 5. The results showed that the model explained 47.8% of the variance for the DS treatment, where NO_3^--N and AT had significant direct effects on N_2O emission fluxes, with path coefficients of 0.612 ($p < 0.01$) and -0.452 ($p < 0.05$), respectively, while the other factors had no significant effects. The model explained 45.9% of the variation for treatment W, with significant effects occurring on N_2O flux due to NO_3^--N and NH_4^+-N, with path coefficients of -0.480 ($p < 0.01$) and −0.360 ($p < 0.05$), respectively, and no significant effects observed for other factors. The model explained 17.5% of the variation in the N_2O flux after straw was returned to the field (WS). NH_4^+-N had a significant direct negative effect on the N_2O flux, with a path coefficient of -0.355 ($p < 0.05$), while other factors had no significant effect. The model explained

Table 6. Relationships between soil N_2O fluxes and environmental factors during the observation period were determined by multiple linear regression analyses and the optimization of regression

Model of fit	Treatment	Regression	R^2	p	n
Multiple linear Stepwise regression	WSC	$-0.397NO_3^- + 0.366NH_4^+$	0.1800	0.0418*	34
	W	$-0.276NH_4^+$	0.0760	0.1145	21
	WS	$-0.018NO_3^- - 0.021NH_4^+ - 0.001DOC$	0.3706	0.0125*	34
	DS	$0.481NO_3^- - 0.317NH_4^+ + 313DOC$	0.4074	0.0275*	21

* $p \leq 0.05$.

21.0% of the variation in the N_2O flux with the WSC treatment, and NH_4^+-N and NO_3^--N had significant direct effects on the N_2O flux, with path coefficients of 0.416 ($p < 0.05$) and -0.389 ($p < 0.05$). Overall, NO_3^--N had a positive effect on the N_2O flux in the DS treatment, while NH_4^+-N had a negative effect on the N_2O flux in non-crayfish systems, but a positive effect in the WSC treatment.

After excluding the less influential factors using multiple stepwise regression, the results (Table 6) showed that the R^2 value decreased for all treatments, and the ability of the model to explain the variance in the N_2O flux decreased, but the overall significance of the retained factors increased. Stepwise regressions also showed that the main influences on the N_2O flux were NH_4^+-N and NO_3^--N in the WSC treatment, NH_4^+-N in the W treatment, and NH_4^+-N, NO_3^--N, and DOC in the DS treatment.

DISCUSSION

Flooding and straw return, alone or in combination, can significantly increase the average CH_4 emissions flux in rice or non-rice seasons by creating an anaerobic environment and providing a substrate (Conrad, 2007; Jiang *et al.*, 2019; Li *et al.*, 2007; Xu *et al.*, 2017; Zhang *et al.*, 2009). The results showed that the average flux of CH_4 was highest in the WS treatment with both straw return and flooding measures, but applying the WS treatment together with crayfish farming (WSC) can reduce CH_4 emissions, which is consistent with previous studies (Li *et al.*, 2007). Although the large amount of rice straw entering the system as feed increases carbon input, the digging behaviour of crayfish greatly increases the water-soil contact area, and the diurnal foraging behaviour of crayfish and night-time fishing behaviour of farmers may increase the level of dissolved oxygen in the water column. These factors could lead to a change in the carbon-to-nitrogen ratio, and also to an increase in the overall level of dissolved oxygen due to an expansion of the soil and water interface, and to an increase in the redox potential leading to the oxidation of CH_4, resulting in lower CH_4 emissions (Abutoama and Abdulhalim, 2017; Bodelier, 2011).

The effect of water management on the CO_2 emissions from farm systems is complex. The respiration of paddy systems depends mainly on soil microorganisms (Raich and Potter, 1995), and moisture severely affects microbial respiration (Keith *et al.*, 1997; Orchard and Cook, 1983; Turcu *et al.*, 2005). For example, soil CO_2 emissions from flooded farmland are much lower than those from alternating wet and dry conditions (Kuzyakov and Siniakina, 2001), and paddy drying can promote soil CO_2 emissions (Nishimura *et al.*, 2008; Palmer *et al.*, 2014). In addition, water-layer thickness also affects CO_2 transport and emissions (Wu *et al.*, 2009). Returning rice straw to paddy fields is common, and studies have shown that returning straw during non-rice-season drainage enhances soil microbial populations and stimulates soil CO_2 emissions in rice fields (Yin *et al.*, 2008). Returning straw to rice fields under continuous flooding throughout the rice season increases CO_2 emissions (Shen *et al.*, 2014).

In this study, we found that straw return did not increase CO_2 emissions under flooding conditions in the non-rice season while the rice season was managed normally, this suggests that the synergistic scientific management of paddy moisture and straw can effectively control CO_2 emissions. The direct positive effects of NH_4^+-N and NO_3^--N on CO_2 fluxes were significantly reduced or changed to negative effects, and the direct positive effect of AT was strengthened by flooding in the non-rice season under straw return conditions. The relationship between the effects of SW and AT on NO_3^--N changed (from positive to negative or from negative to positive), and these shifts in mutual effects may influence CO_2 emissions.

Crayfish activity in rice-crayfish systems disturb the soil much more than in rice-duck or rice-fish systems (Brown *et al.*, 2004; Fanjul *et al.*, 2011; Musgrove and Geddes, 1995; Sarr *et al.*, 2001; Stieglitz *et al.*, 2000; Wang *et al.*, 2010), this results in a substantial increase in the aerobic and anaerobic soil interface (Fanjul *et al.*, 2007), which could theoretically lead to a decrease in CH_4 emissions and an increase in CO_2 emissions. Our study confirmed that crayfish farming with flooding and straw return increases CO_2 emissions, but not significantly. The direct effects of AT, DOC, and NO_3^--N on CO_2 fluxes were significantly enhanced by crayfish farming, most likely due to the increase in DOC with increases in temperature and crayfish activity, as well as to the interrelationship among these three factors.

In this study, the DS fields were drained in the non-rice season, *i.e.*, the soil surface became more oxidized, whereas other treatments were flooded in the non-rice season (stage C took place in the non-rice season but remained for a short time and could be classified as the rice season). In the rice season, all treatments had the same water management regime. A comparison of DS and WS showed that the overall N_2O emissions were slightly reduced by flooding after straw return, mainly in stage A. WS fields were always anaerobic, and denitrification caused a further reduction of N_2O to N_2 as an electron acceptor (Chapuis-Lardy *et al.*, 2007; Ryden, 1983), resulting in lower N_2O emissions. The DS fields were aerobic for the most part with occasional anaerobic conditions and alternated between nitrification and denitrification, resulting in higher N_2O emissions. The NO_3^--N content was the main factor influencing N_2O emissions from DS fields. Many studies have shown that N_2O emissions in paddy farming systems are regulated by the Eh value which is related to the amount of dissolved oxygen in a system (Bhattacharyya *et al.*, 2013; Li *et al.*, 2007; Liu *et al.*, 2016; Yuan *et al.*, 2009; Zhan *et al.*, 2008), mainly because of the influence of redox conditions on nitrification and denitrification. In this study, N_2O emissions were lower in the WSC treatment, mainly because the NO_3^--N content had a significant negative effect on N_2O emissions, and the NO_3^--N content was significantly higher in the WSC treatment than that in the WS treatment (Table 4). In crayfish farming, aquatic grass planting and crayfish hole-digging behaviour may lead to a significant expansion of the water-soil interface and the total aerobic surface area (Kristensen *et al.*, 2012). In this case, NO_3^--N is not completely reduced but rather, NO_2^- may be accumulated which is toxic to microorganisms and may reduce the production efficiency of microbial N_2O. The application of quicklime for disinfection at this stage can increase the pH value, which is significantly and negatively correlated with N_2O emissions (Datta *et al.*, 2009). This result explains, to some extent, the reduction in N_2O emissions in the WSC treatment.

CONCLUSIONS

1. Both straw return and flooding significantly increased CH_4 emissions, but crayfish farming suppressed the increase in CH_4 emissions to a significant extent due to straw return.

2. Inorganic nitrogen (mainly NO_3^--N) in the three treatments of (waterlogging in the non-rice season without straw return, waterlogging in the non-rice season with straw return mode, drainage in the non-rice season with straw return) without crayfish significantly affected CH_4 emissions, while temperature was the main factor affecting CH_4 emissions in the crayfish culture system.

3. The highest total CO_2 emissions were found in cultured crayfish (waterlogging in the non-rice season with straw return and crayfish farming) and non-rice-season drainage (drainage in the non-rice season with straw return) with straw return. The lowest total CO_2 emissions were found in non-rice-season flooding (waterlogging in the non-rice season without straw return) without straw return. Both temperature and NO_3^--N had a negative effect on CO_2 emission fluxes in all non-rice-season flooding systems (waterlogging in the non-rice season without straw return, waterlogging in the non-rice season with straw return mode, drainage in the non-rice season with straw return) and a positive effect in drainage in the non-rice season with straw return.

4. The highest N_2O emissions were found in drainage in the non-rice season with straw return and the lowest in waterlogging in the non-rice season without straw return. Straw return under flooded conditions promoted N_2O emissions, and crayfish farming (waterlogging in the non-rice season with straw return and crayfish farming) significantly reduced them. Soil NO_3^--N content had a significant positive effect on N_2O emissions in drainage in the non-rice season with straw return and a significant negative effect in waterlogging in the non-rice season with straw return mode and waterlogging in the non-rice season with straw return and crayfish farming, the increase in NO_3^--N content may have been the main factor regulating N_2O emissions in waterlogging in the non-rice season with straw return and crayfish farming.

Many factors and agronomic measures affect CH_4 and N_2O emissions in paddy fields, but there are still certain patterns among similar types of agronomic parameters. Although these findings cannot be generalized to include all soils (and zones) as variations in soil type and temperature will produce some different effects, this study provides a basis for the selection of agronomic measures for the targeted reduction and control of GHG emissions for rice cultivation.

Author contribution statement: Wanling Hu: methodology, writing-original draft preparation, data curation. Zhenzhong Bai: investigation, visualization. Ronggui Hu: conceptualization, writing-reviewing and editing. Ying Diao, Xiangyu Xu and Hongling Wang: Methodology, writing-reviewing and editing, supervision.

Conflict of interest: The authors declare no conflict of interest.

REFERENCES

Abutoama M., and Abdulhalim I., 2017. Angular and intensity modes self-referenced refractive index sensor based on thin dielectric grating combined with thin metal film. IEEE J. Sel. Top. Quant., 23, 72-80. https://doi.org/10.1109/jstqe.2016.2520878.

Bao S.D., 2000. Agricultural Chemical Analysis of Soil, Chinese Agricultural Press, Beijing.

Bhattacharyya P., Sinhababu D.P., Roy K.S., Dash P.K., Sahu P.K., Dandapat R., Neogi S., and Mohanty S., 2013. Effect of fish species on methane and nitrous oxide emission in relation to soil C, N pools and enzymatic activities in rainfed shallow lowland rice-fish farming system. Agr. Ecosyst. Environ., 176, 53-62. https://doi.org/10.1016/j.agee.2013.05.015.

Bodelier P.L.E., 2011. Interactions between nitrogenous fertilizers and methane cycling in wetland and upland soils. Curr. Opin. Env. Sust., 3, 379-388. https://doi.org/10.1016/j.cosust.2011.06.002.

Brown G.G., Edwards C.A., and Brussaard L., 2004. How Earthworms Affect Plant Growth: Burrowing into the Mechanisms. CRC Press, Boca Raton, FL, USA.

Brown J.R., Blankinship J.C., Niboyet A., van Groenigen K.J., Dijkstra P., Le Roux X., Leadley P.W., and Hungate B.A., 2011. Effects of multiple global change treatments on soil N_2O fluxes. Biogeochemistry, 109, 85-100. https://doi.org/10.1007/s10533-011-9655-2.

CAYEC, 2017. China Agricultural Yearbook, China Agricultural Press, Beijing, China.

Chapuis-Lardy L., Wrage N., Metay A., Chotte J.L., and Bernoux M., 2007. Soils, a sink for N_2O? A review. Global Change Biol., 13, 1-17. https://doi.org/10.1111/j.1365-2486.2006.01280.x.

Conrad R., 2007. Microbial ecology of methanogens and methanotrophs. Adv. Agron., 96, 1-63. https://doi.org/10.1016/s0065-2113(07)96005-8.

Datta A., Nayak D.R., Sinhababu D.P., and Adhya T.K., 2009. Methane and nitrous oxide emissions from an integrated rainfed rice-fish farming system of Eastern India. Agr. Ecosyst. Environ., 129, 228-237. https://doi.org/10.1016/j.agee.2008.09.003.

Fanjul E., Bazterrica M.C., Escapa M., Grela M.A., and Iribarne O., 2011. Impact of crab bioturbation on benthic flux and nitrogen dynamics of Southwest Atlantic intertidal marshes and mudflats. Estuar. Coast. Shelf Sci., 92, 629-638. https://doi.org/10.1016/j.ecss.2011.03.002.

Fanjul E., Grela M.A., and Iribarne O., 2007. Effects of the dominant SW Atlantic intertidal burrowing crab *Chasmagnathus granulatus* on sediment chemistry and nutrient distribution. Mar. Ecol. Prog. Ser., 341, 177-190. https://doi.org/10.3354/meps341177.

Frei M., Khan M.A. M., Razzak M.A., Hossain M.M., Dewan S., and Becker K., 2007a. Effects of a mixed culture of common carp, *Cyprinus carpio* L., and Nile tilapia, *Oreochromis niloticus* L., on terrestrial arthropod population, benthic fauna, and weed biomass in rice fields in Bangladesh. Biological Control., 41, 207-213. https://doi.org/10.1016/j.biocontrol.2007.02.001.

Frei M., Razzak M.A., Hossain M.M., Oehme M., Dewan S., and Becker K., 2007b. Methane emissions and related physicochemical soil and water parameters in rice-fish systems in Bangladesh. Agr. Ecosyst. Environ., 120, 391-398. https://doi.org/10.1016/j.agee.2006.10.013.

Gao F., Zhang H., Yang F., Qiang H., and Zhang G., 2012. The contrast study of anammox-denitrifying system in two non-woven fixed-bed bioreactors (NFBR) treating different low C/N ratio sewage. Bioresource Technol., 114, 54-61. https://doi.org/10.1016/j.biortech.2012.02.113.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC, Cambridge University Press, New York, USA.

IPCC, 2014. Climate Change 2013-The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, USA.

Jiang Y., Qian H.Y., Huang S., Zhang X.Y., Wang L., Zhang L., Shen M.X., Xiao X.P., Chen F., Zhang H.L., Lu C.Y., Li C., Zhang J., Deng A.X., van Groenigen K.J., and Zhang W.J., 2019. Acclimation of methane emissions from rice paddy fields to straw addition. Sci. Adv., 5, eaau9038. https://doi.org/10.1126/sciadv.aau9038.

Keith H., Jacobsen K.L., and Raison R.J., 1997. Effects of soil phosphorus availability, temperature and moisture on soil respiration in *Eucalyptus pauciflora* forest. Plant Soil, 190, 127-141. https://doi.org/10.1023/A:1004279300622.

Kristensen E., Penha-Lopes G., Delefosse M., Valdemarsen T., Quintana C.O., and Banta G.T., 2012. What is bioturbation? The need for a precise definition for fauna in aquatic sciences. Mar. Ecol. Prog. Ser., 446, 285-302. https://doi.org/10.3354/meps09506.

Kuzyakov Y., and Siniakina S.V., 2001. A novel method for separating root-derived organic compounds from root respiration in non-sterilized soils. J. Plant Nutr. Soil Sc., 164, 511-517. https://doi.org/10.1002/1522-2624(200110)164:5<511::AID-JPLN511>3.0.CO;2-T.

Lee C.H., Park K.D., Jung K.Y., Ali M.A., Lee D., Gutierrez J., and 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. Agr. Ecosyst. Environ., 138, 343-347. https://doi.org/10.1016/j.agee.2010.05.011.

Li X.L., Ma J., Yao Y.J., Liang S.L., Zhang G.B., Xu H., and Yagi K., 2014. Methane and nitrous oxide emissions from irrigated lowland rice paddies after wheat straw application and midseason aeration. Nutr. Cycl. Agroecosyst., 100, 65-76. https://doi.org/10.1007/s10705-014-9627-8.

Li X.L., Xu H., Cao J.L., Cai Z.C., and Yagi K., 2007. Effect of water management on CH_4 emission during rice-growing season. Soils, 39, 238-242.

Ling L., Shuai Y.J., Xu Y., Zhang Z.S., Wang B., Liangzhi Y., Sun Z.C., Zhang H.R., Zhan M., Li C.F., Wang J.P., Jiang Y., Ayitula M., and Cao C.G., 2021. Comparing rice production systems in China: Economic output and carbon footprint. Sci. Total Environ., 791, 147890. https://doi.org/10.1016/j.scitotenv.2021.147890.

Liu S.W., Hu Z.Q., Wu S., Li S.Q., Li Z.F., and Zou J.W., 2016. Methane and nitrous oxide emissions reduced following conversion of rice paddies to inland crab-fish aquaculture in Southeast China. Environ. Sci. Technol., 50, 633-642. https://doi.org/10.1021/acs.est.5b04343.

Liu X.Y., Huang H., Yang Z.P., Yu J. B., Dai Z.Y., Wang D.J., and Tan S.Q., 2006. Methane emission from rice-duck-fish complex ecosystem. Ecol. Env., 15, 265-269.

Liu Z.H., Li Z.G., Tang P.Q., Li Z.P., Wu W.B., Yang P., You L.Z., and Tang H.J., 2013. Spatial-temporal changes of rice area and production in China during 1980-2010. Acta Geogr. Sin., 68, 680-693.

Ma J., Li X.L., Xu H., Han Y., Cai Z.C., and Yagi K., 2007. Effects of nitrogen fertiliser and wheat straw application on CH_4 and N_2O emissions from a paddy rice field. Aust. J. Soil Res., 45, 359-367. https://doi.org/10.1071/sr07039.

Mer J.L., and Roger P., 2001. Production, oxidation, emission and consumption of methane by soils: A review. Eur. J. Soil Biol., 37, 25-50. https://doi.org/10.1016/S1164-5563(01)01067-6.

Musgrove R.J.B., and Geddes M.C., 1995. Tissue accumulation and the moult cycle in juveniles of the Australian freshwater crayfish *Cherax destructor*. Freshwater Biol., 34, 541-588. https://doi.org/10.1111/j.1365-2427.1995.tb00912.x.

Nishimura S., Yonemura S., Sawamoto T., Shirato Y., Akiyama H., Sudo S., and Yagi K., 2008. Effect of land use change from paddy rice cultivation to upland crop cultivation on soil carbon budget of a cropland in Japan. Agr. Ecosyst. Environ., 125, 9-20. https://doi.org/10.1016/j.agee.2007.11.003.

Orchard V.A., and Cook F.J., 1983. Relationship between soil respiration and soil moisture. Soil Biol. Biochem., 15, 447-453. https://doi.org/10.1016/0038-0717(83)90010-X.

Palmer M.M., Forrester J.A., Rothstein D.E., and Mladenoff D.J., 2014. Establishment phase greenhouse gas emissions in short rotation woody biomass plantations in the Northern Lake States, USA. Biomass. Bioenerg., 62, 26-36. https://doi.org/10.1016/j.biombioe.2014.01.021.

Raich J.W., and Potter C.S., 1995. Global patterns of carbon dioxide emissions from soils. Global Biogeochem. Cycles, 9, 23-36. https://doi.org/10.1029/94gb02723.

Ruddle K., 1982. Traditional integrated farming systems and rural development: The example of rice field fisheries in Southeast Asia. Agric. Administration, 10, 1-11. https://doi.org/10.1016/0309-586X(82)90036-X.

Ryden J.C., 1983. Denitrification loss from a grassland soil in the field receiving different rates of nitrogen as ammonium nitrate. J. Soil Sci., 34, 355-356. https://doi.org/10.1111/j.1365-2389.1983.tb01041.x.

Sarr M., Agbogba C., Smith A.R., and Masse D., 2001. Effects of soil faunal activity and woody shrubs on water infiltration rates in a semi-arid fallow of Senegal. Appl. Soil Ecol., 16, 283-290. https://doi.org/10.1016/S0929-1393(00)00126-8.

Serrano-Silva N., Sarria-Guzman Y., Dendooven L., and Luna-Guido M., 2014. Methanogenesis and Methanotrophy in Soil: A Review. Pedosphere, 24, 291-307. https://doi.org/10.1016/S1002-0160(14)60016-3.

Shen J.L., Tang H., Liu J.Y., Wang C., Li Y., Ge T.D., Jones D.L., and Wu J.S., 2014. Contrasting effects of straw and straw-derived biochar amendments on greenhouse gas emissions within double rice cropping systems. Agr. Ecosyst. Environ., 188, 264-274. https://doi.org/10.1016/j.agee.2014.03.002.

Stieglitz T., Ridd P., and Müller P., 2000. Passive irrigation and functional morphology of crustacean burrows in a tropical mangrove swamp. Hydrobiologia, 421, 69-76. https://doi.org/10.1023/A:1003925502665.

Sun Z., Guo Y., Li C., Cao C., Yuan P., Zou F., Wang J., Jia P., and Wang J., 2019. Effects of straw returning and feeding on greenhouse gas emissions from integrated rice-crayfish farming in Jianghan Plain, China. Environ. Sci. Pollut. Res. Int., 26, 11710-11718. https://doi.org/10.1007/s11356-019-04572-w.

Turcu V.E., Jones S.B., and Or D., 2005. Continuous soil carbon dioxide and oxygen measurements and estimation of gradient-based gaseous flux. Vadose Zone J., 4, 1161-1169. https://doi.org/10.2136/vzj2004.0164.

Wang J.Q., Zhang X.D., Jiang L.F., Bertness M.D., Fang C.M., Chen J.K., Hara T., and Li B., 2010. Bioturbation of burrowing crabs promotes sediment turnover and carbon and nitrogen movements in an estuarine salt marsh. Ecosystems, 13, 586-599. https://doi.org/10.1007/s10021-010-9342-5.

Wu H.B., Guo Z.T., Gao Q., and Peng C.H., 2009. Distribution of soil inorganic carbon storage and its changes due to agricultural land use activity in China. Agr. Ecosyst. Environ., 129, 413-421. https://doi.org/10.1016/j.agee.2008.10.020.

Wu L., Wu X., Lin S., Wu Y.P., Tang S.R., Zhou M.H., Shaaban M., Zhao J.S., Hu R.G., Kuzyakov Y., and Wu J.S., 2018. Carbon budget and greenhouse gas balance during the initial years after rice paddy conversion to vegetable cultivation. Sci. Total. Environ., 627, 46-56. https://doi.org/10.1016/j.scitotenv.2018.01.207.

Xu X.Y., Zhang M.M., Peng C.L., Si G.H., Zhou J.X., Xie Y.Y., and Yuan J.F., 2017. Effect of rice-crayfish co-culture on greenhouse gases emission in straw-puddled paddy fields. Chin. J. Eco-Agric., 25, 1591-1603.

Yin C.M., Xie X.L., and Wang K.R., 2008. Effects of straw mulching on CO_2 flux in wintry fallow paddy field. Chin. J. Appl. Ecol., 19, 115-119.

Yuan W.L., Cao C.G., Li C.F., Zhan M., Cai M.L., and Wang J.P., 2009. Methane and nitrous oxide emissions from rice-fish and rice-duck complex ecosystems and the evaluation of their economic significance. Sci. Agr. Sin., 42, 2052-2060. https://doi.org/10.3864/j.issn.0578-1752.2009.06.022.

Zhan M., Cao C.G., Wang J.P., Yuan W.L., Wang Y., and Gao D.W., 2008. Effects of rice-duck farming on paddy field's methane emission. Chin. J. Appl. Ecol., 19, 2666-2672. https://doi.org/10.13287/j.1001-9332.2008.0053.

Zhang G.B., Ma E.D., Zhang X.Y., Ma J., Xu H., and Cai Z.C., 2009. Effects of rice straw incorporation and land management in winter on methane emission during rice-growing season. J. Agro-Env. S., 28, 2501-2505.