

Effects of Drainage on Greenhouse Gas Emissions and Yields of Lowland Rice-Wheat Rotation System in East China

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Abstract

The subtropical region of East China is characterized by abundant water and temperature resources conducive to crop cultivation, and large areas of lowland have been widely used for agricultural planting. To explore the feasible methods of greenhouse gases (GHGs) reduction for rice-wheat rotation system, shallow ditch (SD) and deep ditch (DD) treatments in the wheat season were set up for drainage to control the water content in soil, with the conventional non-ditching treatment as the control group (CG). Results showed that methane (CH_4) emissions from paddy soil were in the majority in global warming potential (GWP) in rice-wheat rotation system. In the three years, compared with that of CG, the CH_4 cumulative emissions of SD and DD were reduced by 65.80% and 63.42% (rice season), and 101.37% and 77.28% (wheat season), respectively; the nitrous oxide (N_2O) cumulative emissions of SD and DD were reduced by 27.62% and 11.30% (rice season), and 1.53% and -37.40% (wheat season), respectively; the total GWP produced by SD and DD in the three years was reduced by 58.78% and 52.22%, respectively; GHG emission intensity (GHGI) of SD and DD declined by 60.67% and 53.85%, respectively; the CH_4 emission flux was significantly positively correlated with atmospheric temperature and 5 cm ground temperature, but negatively correlated with soil Eh; when the soil Eh value was lower than -150 mV, the CH_4 emission flux increased significantly, indicating that -150 mV was the key soil Eh value for CH_4 emissions in this area; in addition, both SD and DD led to markedly decrease in soil organic matter content and an increase in soil pH. The findings indicate that SD and DD not only ensure stably increasing production, but also effectively reduce GHG emissions.

1. Introduction

Methane (CH_4) and nitrous oxide (N_2O) are important greenhouse gases (GHGs), which contribute over 20% to the global increase in radiative forcing (Banger et al. 2012; Huang et al. 2018). Agricultural production has been recognized one of the dominant sources of CH_4 and N_2O emissions (Cheng et al. 2021; Wang et al. 2020), the characteristics of high humidity and high organic carbon of the paddy field soil determine that the paddy soil is the main source of CH_4 emissions (Haque and Biswas 2021; Pratibha et al. 2016). The annual total emissions of CH_4 in the global paddy fields account for approximately 5-19% of the total, while N_2O contributes up to 6-10% in global warming (Saarenheimo et al. 2015).

Rice-wheat rotation is a common planting system in East Asia and Southeast Asia. Winter wheat is planted during the slack winter season, so that the maximum benefits of winter farmland can be fully utilized through crop rotation. The areas of farmland under the rice-wheat rotation pattern account for more than half of the total rice areas in China (Zhao et al. 2009). This pattern includes irrigated paddy fields and dryland wheat fields, so it is difficult to count the GHG emissions in the entire rotation system (Montoya-González et al. 2009; Tellez-Rio et al. 2015). The yield of rice and wheat in eastern China contributes nearly 30% to China's grain production, making an important contribution to ensuring the safety of food production. With available water and temperature resources conducive to crop cultivation, rice-wheat rotation is an important planting system in fields along the middle and lower reaches of the Yangtze River among the main grain-producing areas in China (Hou et al. 2016; Xu et al. 2009), which to a certain extent also represents the watershed of China's humid and semi-humid regions. Chao Lake area is a typical polder area with a rice-wheat rotation pattern. A polder area refers to the low-lying drainage area formed by an embankment network of plain rivers and lakes along the rivers, which is comprised of a lower terrain, a shallow soil tillage layer, and high groundwater level. Large polder areas have been widely used for

agricultural planting, whose distribution is related to rivers and lakesides (Nillesen and Kok 2015). In the context of increasing demand for grain production, it is of great global significance to mitigate and adapt to climate change for researching and promoting the reduction of GHGs in rice-wheat rotation system.

CH₄ is an organic gas produced by methanogens decomposing organic matter in an extremely anaerobic environment. For the paddy fields, soil water control is a highly important factor affecting CH₄ and N₂O emissions, and the influences of water managements such as draining and alternate wetting and drying (AWD) on the CH₄ and N₂O emissions in farmlands have been well documented (Liang et al. 2017; Liang et al. 2016; Schimel et al. 2011). Related research has shown that the higher soil water content in winter will make the soil remain an extremely anaerobic state, thus promoting the emissions of CH₄ (Wu et al. 2018; Xu et al. 2003; Zhao et al. 2020). According to Kang et al. (2002) and Jain et al. (2014), water control in non-rice growing period is effective in controlling CH₄ emissions in China's rice growing period. Related scholars reported that drainage helps reduce CH₄ emissions by destroying the extreme anaerobic environment of methanogens, while flooded paddy soils are global sources of CH₄ due to the lack of oxygen (David et al. 2018; Liang et al. 2016). N₂O emissions from continuously flooded paddy fields are very low, and they are often ignored (Johnson-Beebout et al. 2009). However, water managements on farmlands usually produce large amount of N₂O emissions. Linquist et al. (2012) showed that the drainage in the wheat season leads to an increase in N₂O emissions from rice fields and a significant decrease in CH₄ emissions. Liu et al. (2019) showed through meta-analysis that draining in paddy fields is an effective way to mitigate GHG emissions in rice ecosystem, the global warming potential (GWP) of CH₄ and N₂O under mid-season drainage decreases significantly compared with that under continuous flooding. Furthermore, Hou et al. (2016) reported that water management has a significant impact on GHG emissions from rice-wheat rotation system, and long-term flooded rice fields have lower N₂O emissions. Another report pointed out that if a water control method is used in the flooded farmland in southwest China in winter, the total CH₄ emissions during the growth period of the next rice season will be effectively reduced by approximately 63–72% (Cai et al. 1998). Water control measures can inhibit CH₄ emissions, but it may increase N₂O emissions at the same time (Cai et al. 2000). However, it remains unclear whether the corresponding increase in N₂O emissions can partially offset or overcompensate the positive impact on CH₄ mitigation, leading to an increase or decrease in GWP (Khalid et al. 2019). Moreover, most studies on the impact of water management on N₂O and CH₄ emissions are restricted to the rice season. Relatively few studies have been devoted to the effects of water control during the wheat season on the GHG emissions of the entire annual rice-wheat rotation (Hou et al. 2016).

In order to explore a feasible plan for reducing GWP under the rice-wheat rotation pattern, a three-year experiment was conducted, with the rice-wheat two-cropping farmland of Chao Lake polder area as the research object. Two water control treatments easy to be implemented and a control treatment were designed. In addition, the influencing factors for CH₄ emissions from paddy soils were analyzed, such as atmospheric temperature, 5 cm ground temperature and soil Eh. The results are applicable to the emission reduction and efficiency enhancement technology of subtropical rice-wheat rotation farmland cultivation in China.

2. Materials And Methods

2.1. Experiment site

The experiment was conducted at the Chao Lake Agricultural Environment Experimental Station of Anhui Agricultural University from 2013 to 2015. The monitoring site was located in Tangzui Village, Qi Town, Chaohu City ($117^{\circ}41'6''E$ and $31^{\circ}39'50''N$ with an elevation of 17 m), which belongs to the north subtropical monsoon climate zone. The annual average precipitation here is 1358.3 mm, the average temperature is $16.8^{\circ}C$, the annual frost-free period is 247 days, and the sunshine hours are 2106 h. According to the statistics in 2014, the grain crop planting area was around 49,800 ha in Chaohu City, with a total output of approximately 319,000 tons of crop, and rice production of about 256,000 tons.

This field was managed according to the traditional practices in the area, wherein the rice was flooded during the growing season, and the uncultivated fields were left after harvest until the next cultivation. The rice and winter wheat varieties used for the experiment were Huiliangyou 996 and Yangmai 16.

The soil type of this monitoring site in the Chao Lake lowland area is submerged paddy soil with a pH value (H_2O) of 6.19, organic carbon content of 23.71 g kg^{-1} , total nitrogen content of 1.29 g kg^{-1} , and physical clay content of 488 g kg^{-1} . The physical and chemical properties under different treatments from 0 cm to 20 cm soil are also shown in Table 1.

Table 1
Physical and chemical properties of 0 cm to 20 cm soil in each treatment

Treatments	Organic matter (g kg^{-1})	Total nitrogen (g kg^{-1})	Nitrate nitrogen (mg kg^{-1})	Ammonium nitrogen (mg kg^{-1})	Available nitrogen (mg kg^{-1})	pH
CG	22.38	1.29	9.62	0.71	81.58	6.24
SD	22.97	1.27	8.05	3.19	81.22	6.21
DD	22.46	1.33	4.97	1.55	82.63	6.18

2.2. Water control and fertilization measurements

In order to lower the groundwater level, ditches were set up for drainage during the wheat season. Two treatments and a control treatment were designed for the wheat season: Shallow ditch (SD): The depths of field ditch, row ditch and the ditch besides the field were 20, 25, and 35 cm, respectively. Deep ditch (DD): The depths of field ditch, row ditch and the ditch besides the field were 30, 40, and 45 cm, respectively; control group (CG): no ditch (schematic diagram of the field ditches is shown in Fig. 1). Each treatment was performed with 3 replicates. The designed depth of the ditch was determined based on actual situations. A large ditch outside the farmland was approximately 60-80 cm deep. The interval between the field drains was 3 m while ditches were interconnected.

The bund used to separate the experimental plots was made of cement. Each plot had water inlets and drains, and the drains were connected one another. Local routine management was adopted for the field management of each treated plot. The wheat season land was plowed before planting, and its depth was around 15 cm. Rice would be irrigated 4-5 times during the growth period and irrigated for 1-2 days before the three fertilizations, and the depth was approximately 6-7 cm at the end of the roasting field. Regular pest and disease control was performed during the growing period to ensure the normal growth state of the rice and wheat.

N fertilizer, P fertilizer, and K fertilizer were urea, superphosphate, and potassium chloride, respectively. The specific fertilization scheme and fertilization amount are shown in Table 2. The managements of wheat and rice fields in the three years are shown in Tables 3 and 4.

Table 2
Fertilization measures in 2013-2015 (kg/hm²)

Rice season	Base fertilizer			Tillering fertilizer		Panicle fertilizer		Total fertilizer		
	N	P ₂ O ₅	K ₂ O	N		N	K ₂ O	N	P ₂ O ₅	K ₂ O
	67.5	67.5	67.5	67.5		45	0	180	67.5	67.5
Wheat season	Base fertilizer			Winter fertilizer		Striking root fertilizer		Total fertilizer		
	N	P ₂ O ₅	K ₂ O	N		N	K ₂ O	N	P ₂ O ₅	K ₂ O
	72	72	72	69		69	0	210	72	72

Table 3
Field managements in the wheat season in 2012-2015

Wheat season	Sowing, applying base fertilizer	Applying winter fertilizer	Applying striking root fertilizer	Harvesting
2012-2013	2012.10.31	2013.1.17	2013.3.5	2013.6.1
2013-2014	2013.10.26	2014.1.9	2014.3.5	2014.5.26
2014-2015	2014.11.06	2015.1.28	2015.3.13	2015.6.6

Table 4
Field managements in the rice season in 2013-2015

Rice season	Transplanting seedlings, applying basal fertilizer	Applying tiller fertilizer	Field sunning	Irrigation and rehydration	Applying Panicle fertilizer	Harvesting
2012-2013	2013.6.13	2013.6.28	2013.7.11	2013.7.20	2013.7.27	2013.9.27
2013-2014	2014.6.21	2014.7.8	2014.7.17	2014.7.21	2014.8.20	2014.10.10
2014-2015	2015.6.19	2015.7.18	2015.8.6	2015.8.8	2015.8.20	2015.9.17

2.3. Collection and measurements of N₂O and CH₄ emissions

In this experiment, closed static boxes were used to monitor the sampling of farmland GHG under the rice-wheat rotation pattern in the Chao Lake lowland area. The boxes were made of 5 mm-thick transparent glass (50 × 50 × 60 cm and 50 × 50 × 120 cm). The former one had a top cover, whereas the latter did not have one. The box of the first specifications was used when the crop plant was less than 60 cm high. The two-layer box was used when the height of the crop plant exceeds 60 cm. Water was injected during the sampling process to keep the box sealed. Conventional gas sampling was carried out every day from 9:00 AM to 12:00 PM four times per day at an interval

of 10 minutes. 60 mL of gas was sampled each time. The data were recorded, and the Eh value of the soil was monitored.

The samples were taken in the wheat season once a week, and every 3 to 5 days in the rice season, which could be adjusted rationally according to weather conditions. In the periods of fertilization, topdressing, and roasting, the samples were taken every two days. The collected gas samples were measured for CH₄ and N₂O concentrations by gas chromatography (Brooker 450-GC) within 24 hours. And FID detector was used to detect CH₄. The detection conditions were as follows: column temperature: 50°C; detector temperature: 250°C; nitrogen flow, 10 mL/min; hydrogen: airflow 30 mL/min, 300 mL/min. N₂O was detected with the NI63ECD Detector under the following conditions: detector temperature of 300°C and nitrogen flow rate of 300 mL/min.

CH₄ and N₂O emission flux can be calculated by the following formula:

$$F = \rho \times V/A \times dc/dt \times 273/T, (1)$$

Where: F is the emission flux in units of mg m⁻² h⁻¹ (CH₄), µg m⁻² h⁻¹ (N₂O); ρ is the density of CH₄ or N₂O under standard conditions [0.714 kg m⁻³ (CH₄) and 1.25 kg m⁻³ (N₂O)]; V is the effective volume in the box (m³); A is the sampling box coverage area (m²); dc/dt is the changes of CH₄ or N₂O concentration in the sampling tank per unit time [µL L⁻¹ h⁻¹ (CH₄) and nL L⁻¹ h⁻¹ (N₂O)]; T is the temperature inside the box (K).

2.4. Calculation of yield, GWP and GHGI

To analyze the actual effect of the different water control methods on crop yield in the wheat season, production measurement was conducted after crop maturation and the average economic output of the three groups of repeated plots was taken.

GWP was calculated as CO₂ equivalents (CO₂-eq) over a 100-year time horizon using the radiative forcing potential of 298 for N₂O and 25 for CH₄ relative to CO₂ (IPCC, 2013):

$$GWP = \text{cumulative } CH_4 \text{ emission} \times 25 + \text{cumulative } N_2O \text{ emission} \times 298 \quad (2) \quad GHGI = GWP/Y, \quad (3)$$

In the formula: GHGI is the GHG emission intensity (t/hm², calculated as CO₂); Y represents the yield of rice and wheat (kg hm⁻²).

2.5. Soil properties

To clarify the mechanism of CH₄ production in rice fields, soil properties were analyzed during a complete wheat season. The HW type soil temperature automatic recorder was used to measure the 5 cm ground temperature. The soil Eh value was determined by *in-situ* measurement with an Eh meter. The model of the intelligent portable redox potential meter is QX6530, provided by the Nanjing Institute of Soil Science, Chinese Academy of Sciences. We used soil drills in the community to randomly sample fresh soil samples of 0-20 cm from 3 locations. The Eh electrode was inserted 3-5 cm below the soil surface. After each removal, we quickly inserted the electrode into the soil sample to a depth of about 2 cm, the Eh value was recorded after the reading became stable.

In each study area, a soil drill was used to take field soil samples from 5 points 0-20 cm soil layer using the "Z" method. The soil pH was measured by the potentiometric method (water-soil ratio: 2.5:1), and soil organic matter

was determined by the potassium dichromate volumetric method with oil bath heating.

2.6. Statistical analysis

Microsoft Excel 2010 was used to calculate the data on CH₄ and N₂O emissions. Figures were plotted by Origin 8.5. The correlation of CH₄ emission flux was subjected to Pearson correlation analysis.

3. Results

3.1. CH₄ emissions

CH₄ emissions from rice-wheat rotation system were mainly in the rice season, while drainage during the wheat season effectively reduced the CH₄ emissions in the middle and late stages in the rice season (Fig. 2 and Table 5). CH₄ emission flux from rice fields of CG showed many peaks after applying fertilization (Table 4), while the CH₄ emission flux of SD and DD generally had single peaks during the rice season.

In the rice season, compared with that of CG, the cumulative CH₄ emissions of SD and DD were reduced by 56.36% and 53.88% in 2013, 74.95% and 72.03% in 2014, and 73.19% and 70.97% in 2015, respectively. The results showed that the CH₄ emissions of paddy fields of SD and DD were significantly less than those of CG ($P<0.05$, Table 5), while there was no significant difference between SD and DD ($P>0.05$). In addition, CH₄ emissions from rice seasons in the last two years declined significantly, and the cumulative CH₄ emissions in 2014 and 2015 were reduced by 56.24% and 50.64% (average value for each treatment), respectively, compared with 2013. Relatively speaking, the CH₄ emission reduction effect of SD in the rice season was slightly better than that of DD. Although the CH₄ emissions in the wheat season were low, they still existed, while drainage also significantly reduced CH₄ emissions during the wheat season. The total CH₄ emissions of SD and DD were significantly reduced by 139.66% and 59.48% in 2013, 93.11% and 94.09% in 2014, and 82.59% and 74.34% in 2015, respectively ($P<0.05$).

Table 5
Cumulative CH₄ emissions in each treatment during the rice-wheat season (kg/hm²)

Treatments	2013		2014		2015	
	Rice season	Wheat season	Rice season	Wheat season	Rice season	Wheat season
CG	330.44±11.32 ^a	2.32±1.02 ^a	180.08±27.22 ^a	3.05±1.27 ^a	198.64±14.06 ^a	3.39±1.34 ^a
SD	144.22±14.22 ^b	-0.92±0.12 ^c	45.03 ±7.01 ^b	0.21±0.05 ^b	53.25±3.24 ^b	0.59±0.13 ^b
DD	152.43±18.10 ^b	0.94±0.32 ^b	49.29±13.90 ^b	0.18±0.07 ^b	57.67±3.52 ^b	0.87±0.12 ^b

Note: Lowercase letters indicate significant differences between treatments ($P<0.05$); ± means the standard errors ($n=3$) of the replicates. The same as below.

3.2. N₂O emissions

The seasonal variation of N₂O flux of SD and DD were approximately the same as that of CG (Fig. 3). In the wheat season, SD and DD treatments led to no significant emission reduction compared with CG. In some periods, the N₂O flux of SD and DD was significantly higher than that of CG. In contrast, during the rice season, both SD and DD effectively reduced N₂O emissions, and the cumulative N₂O emissions of SD and DD were reduced by 35.71% and 53.57% in 2013, 20.51% and 6.41% in 2014, and 43.64% and 3.64% in 2015, respectively, with the decrease of SD reaching a significant level in the three years ($P<0.05$).

Over the entire rice-wheat rotation system, the cumulative N₂O emissions in the three years were DD > CG > SD (Table 6). Compared with CG, the cumulative N₂O emissions of SD declined by 8.50%, while DD increased by 24.38%. Although water management in the wheat season effectively reduced the total CH₄ emissions in the rice season, the N₂O emissions in the wheat season were not lower than those under the conventional treatment, and the cumulative N₂O emissions even exceeded those under the conventional treatment in some stages.

Table 6
Cumulative N₂O emissions in each treatment during the rice-wheat season (kg/hm²)

Treatments	2013		2014		2015	
	Rice season	Wheat season	Rice season	Wheat season	Rice season	Wheat season
CG	0.28±0.16 ^a	1.36±0.46 ^c	1.56±0.52 ^a	1.19±0.54 ^a	0.55±0.20 ^a	4.00±1.76 ^a
SD	0.18±0.11 ^b	2.35±1.87 ^b	1.24±0.46 ^c	0.82±0.26 ^b	0.31±0.10 ^b	3.28±0.81 ^b
DD	0.13±0.09 ^c	3.53±1.21 ^a	1.46±0.33 ^b	0.95±0.44 ^b	0.53±0.23 ^a	4.52±1.62 ^a

3.3. GWP, yield, and GHGI

The cumulative CH₄ emissions during the rice season was the main contributor to GWP of rice-wheat rotation system, and the GWP produced by CH₄ in the rice season accounted for 86.01%, 71.35%, and 65.85%, respectively, among the total processed by CG, SD and DD (Tables 7 and 8). The GWP calculated with the CH₄ and N₂O emissions after the SD and DD treatments in 2013 was about half that after the CG treatment, with more than 98% caused by CH₄. In 2014, the GWP generated by CH₄ and N₂O after the SD and DD treatments were about one-third that after the CG treatment, and the GWP of all the treatments was reduced to different extents compared with that in 2013. Compared with the other two years, the GWP generated by CH₄ in the rice season in 2014 accounted for a relatively small proportion of the total GWP, especially in the SD and DD treatments wherein the percentage was approximately 75%, and SD treatment achieved the best emission reduction effect.

The drainage experiment improved the economic yields of both rice and wheat fields. The yields increased by 3.28% (SD) and 2.88% (DD) in the rice season, and increased by 7.64% (SD) and 4.71% (DD) in the wheat season, respectively. In addition, the GHGI can reflect the comprehensive impact of different treatments on crop yields and GHG emissions. In the rice season, the GHGI of SD and DD declined by 65.46% and 62.49%, respectively (three-year total) ($P<0.05$). Moreover, the GHGI of SD declined by 18.75% and GHGI of DD rose by 25.00% in the wheat season ($P<0.05$).

Table 7
Integrated greenhouse effect in the rice and wheat seasons in each treatment in the three years

Treatments		CO ₂ -e (CH ₄)	Percentage %	CO ₂ -e (N ₂ O)	Percentage %	Total CO ₂ -e	Percentage reduction %
2013	CG	8319.12	94.45	488.72	5.55	8807.72	
	SD	3582.52	82.61	753.94	17.39	4336.44	50.77
	DD	3834.25	77.85	1090.68	22.15	4924.93	44.08
2014	CG	4578.25	84.82	819.52	15.18	5397.75	
	SD	1131.23	64.82	613.88	35.18	1744.88	67.67
	DD	1236.75	63.26	718.18	36.74	1954.93	63.78
2015	CG	5050.75	78.84	1355.92	21.16	6406.65	
	SD	1346.32	55.72	1069.82	44.28	2415.82	62.29
	DD	1463.51	49.30	1504.91	50.70	2968.4	53.67

Table 8
Average yield (kg hm⁻²) and yield-scaled GWP (kg CO₂-Eq kg⁻¹) in the rice-wheat seasons in each treatment

	Treatments	CO ₂ -e (CH ₄)	CO ₂ -e (N ₂ O)	GWP	Yield	GHGI
Rice season	CG	5909.67 ^a	237.40 ^a	6147.07 ^a	8104.42 ^a	0.76 ^a
	SD	2020.87 ^b	171.83 ^c	2192.71 ^b	8370.12 ^a	0.26 ^b
	DD	2161.63 ^b	210.57 ^b	2372.20 ^b	8337.74 ^a	0.28 ^b
Wheat season	CG	73.03 ^a	650.63 ^c	723.67 ^b	4433.31 ^a	0.16 ^b
	SD	-0.97 ^c	640.70 ^b	639.73 ^c	4772.22 ^a	0.13 ^c
	DD	16.60 ^b	894.00 ^a	910.60 ^a	4642.24 ^a	0.20 ^a

3.4. Main factors affecting CH₄ emission

3.4.1. Atmospheric temperature and 5 cm ground temperature

The seasonal variation of CH₄ flux was significantly correlated with the average atmospheric temperature in the whole growth period of rice ($r=0.62$, $df=35$, $P<0.05$). The CH₄ emission flux of the paddy field was mostly at a low level when the temperature was lower than 26°C, while it showed a significant upward trend when the ambient temperature exceeded 30°C.

In the early stage of rice growth (0-28 days before rice field sunning), the trend of the 5 cm ground temperature and CH₄ flux in the paddy soil was approximately the same (Fig. 4). The soil drying period in the field was

between 29th and 34th days after transplanting. During this period, the paddy field surface water was evaporated, wherein the soil permeability and the oxygen content in the soil void increased, and then the soil environment changed from anaerobic to aerobic state, inhibiting the activity of methanogens, and finally reducing the CH₄ emissions. Accordingly, no significant correlation existed between the CH₄ emissions and 5 cm ground temperature. Generally, during the whole growth period of rice, the CH₄ emissions of paddy soil were significantly correlated with the 5 cm ground temperature.

As shown in Fig. 5, the correlation between the change in CH₄ emission flux and the 5 cm ground temperature was significant ($P<0.01$). As the 5 cm ground temperature increased, CH₄ emissions also increased gradually. According to the comparison of the R² value between the 5 cm ground temperature and the CH₄ flux in the water-controlled farmland, the fitting degree of each treatment was higher (0.7 or higher), indicating that the 5 cm ground temperature plays an important role in the change in CH₄ flux.

Figure 5. Relationship between the CH₄ emission flux and 5 cm ground temperature in each treatment.

3.4.2 Soil properties

The corresponding Eh values were mostly between -150 and -300 mV when the CH₄ emission flux was higher; when the soil Eh value was lower than -150 mV, the CH₄ emission flux increased significantly with the decrease of Eh; whereas the corresponding CH₄ emission flux was close to zero when the Eh value was higher than -100 mV (Fig. 6-a, b, c).

In the wheat season, the changes in soil organic matter (28.20-26.59 g/Kg) and soil pH (5.79-6.12) of CG were relatively more stable. In contrast, the soil organic carbon content of both SD and DD showed declining trends, among which the soil organic matter of SD dropped from 29.6 g/Kg to 14.75 g/Kg while that of DD dropped from 28.62 g/Kg to 16.68 g/Kg. The lowland soil in Chao Lake area was an acidic soil type, and it was observed that the drainage would raise the soil pH: The soil pH of SD increased from 5.29 to 6.67 while that of DD increased from 5.15 to 6.41 (Fig. 7-a, b).

4. Discussion

4.1. CH₄ emissions

In this study, the annual emissions of CH₄ were lower than those in the study from the subtropical permanently flooded rice paddy fields of China (Zhou et al. 2018). Compared with CG, the cumulative CH₄ emissions from the rotation system in the rice season were reduced by 56.36%, 74.99% and 73.19% (SD), and 53.87%, 72.63% and 70.97% (DD) in 2012-2013, 2013-2014 and 2014-2015, respectively ($P<0.01$). It can be concluded that SD and DD are very stable in reducing CH₄ emissions, so they can be regarded as effective measures for CH₄ emission reduction of rice-wheat rotation system.

The cumulative CH₄ emissions in the first year were notably too high in this study (Table 5), which could be attributed to the fact that the drainage released the CH₄ originally stored in the soil and improved the aerobic state of the soil, not only inhibiting the production of CH₄, but also increasing the activity of methane oxidizing bacteria.

The existence of a large number of anaerobic zones in the soil structure during the initial drainage stage is suitable for the production of CH₄ (Yuan et al. 2016). Furthermore, through the comparison of the CH₄ emissions in the three years, it was found that multiple peaks often existed in the early and late stages of rice growth (Fig. 3), and they all appeared after applying fertilization (Tables 2 and 3 and 4), suggesting that the application of fertilizer provided an excessive carbon source to the soil in a short time, thus promoting the emissions of CH₄, consistent with the finding of previous research (Fan et al. 2016; Masuda et al. 2018). Over the entire rice-wheat rotation system, it can be seen that the peaks of N₂O flux in the rice season roughly coincided with the low value of CH₄ flux, all in the period of rice field sunning. CH₄ tends to be generated under anaerobic conditions (Cai et al. 1997). During the period of rice field sunning, the CH₄ emissions are very low due to the soil aeration enhanced by rice field sunning, which destroy the extreme anaerobic environment of methanogens (Nayak et al. 2015). Therefore, rice field sunning can be regarded as an effective measure for CH₄ emission reduction in paddy fields.

Temperature mainly controls CH₄ emissions and absorption by affecting the activity against methanogens and methane oxidizing bacteria (Green et al. 2018). The soil Eh is a characterization of the soil moisture status of the soil oxygen availability. Gas exchange is reduced between the atmosphere and the soil when the soil is flooded (Nobrega et al. 2016). Accordingly, the soil is in an extremely anaerobic environment, wherein the soil Eh decreases rapidly and the production activity of CH₄ bacteria is enhanced. Under flooding conditions, polysaccharides in the paddy fields produce a large amount of acetic acid, H₂, and CO₂ during the decomposition process, which offer abundant basic substances to the production of CH₄ bacteria, thereby significantly increasing the CH₄ emission flux of the rice fields (Nobrega et al. 2016). The corresponding Eh values were mostly between -150 and -300 mV when the CH₄ emission flux was high in this study, indicating that -150 mV may be the critical value affecting the CH₄ emission flux in lowland paddy soils. However, due to the complicated field conditions, the relationship between CH₄ emissions and soil Eh has not been definitely clarified. Szafranek-Nakonieczna and Stępniewska (2015) reported that when the soil Eh value is less than 240 mV, the CH₄ production and emission will be concentrated, inconsistent with the results of this study. The discrepancy among these results may be due to differences in soil texture.

Ferrari Machado et al. (2021) and Quang et al. (2019) reported that soil environmental factors are the main factors affecting the GWP of the rice-wheat rotation system. Methanogens and methane oxidizing bacteria are ubiquitous in paddy soils where they are affected by the physical and chemical properties of the soil. Under flooding conditions, a series of simple organic compounds are produced by the ferment of soil organic matters. These simple compounds prone to mineralization are the carbon source and energy source for CH₄ production. CH₄ in rice fields is mainly produced by the decomposition of soil organic matter in those soils by methanogens in the soil under anaerobic conditions (Takakai et al. 2019; Yuan et al. 2018). Both SD and DD reduce soil organic matter content, and low organic matter content may inhibit the activities of methanogens. Related research has revealed a significant positive correlation between CH₄ emission flux and soil organic matter content (Pramanik et al. 2014). The results of this study indicated that the reduction of organic matter caused by drainage may be the dominant reason for CH₄ emissions. The possible reason is that after soil flooding, anaerobic decomposition of organic matter is dominated, and microorganisms deprive the organic matter of oxygen in the soil to form various reducing substances, resulting in a rapid decline of soil Eh. The faster the Eh value declines, the more the reducing substances will be produced (Verdi et al. 2018).

Moreover, soil pH significantly influences the activities and growth of methanogens and methane oxidizing bacteria that control CH₄ production and oxidation, respectively. Some studies have demonstrated that methanogens have the ability to adapt to acidic environments (Lin et al. 2017; Wu et al. 2018). In this study, drainage in the wheat season led to an increase in soil pH, and lower CH₄ emissions were observed in the rice season, consistent with the findings by Jeffery et al. (2016) that the increase in soil pH is conducive to the survival of methane oxidizing bacteria, thus reducing the CH₄ emissions. However, another study reported that an increase in soil pH will promote the activity of methanogens (Liu et al. 2011). There are also reports that the production of CH₄ is affected by a combination of various soil properties (Shen et al. 2021). Therefore, effects of other soil properties should be considered when the effects of organic matters on CH₄ emissions are assessed.

4.2. N₂O emissions

Soil moisture regimes are important for the activities of nitrifying and denitrifying bacterial enzymes, major drivers of N₂O emissions (Cai et al. 1997; Lan et al. 2013). Notably, since flooding conditions will stimulate the denitrification process of soil nitrate nitrogen, the N₂O emissions of each treatment increase to varying degrees. Drainage in the wheat season has a certain inhibitory effect on CH₄ emissions, but the content of N₂O is increased compared with that under the conventional treatment, because water management affects the content of O₂ in the soil, weakening anaerobic condition of soil gradually and promoting nitrification (Zhang et al. 2021). When the soil is in an alternating aerobic and anaerobic condition, its moderate O₂ concentration is conducive to the production of N₂O in the nitrification and denitrification processes, which leads to massive N₂O production and emissions (Song et al. 2020; Vilarrasa-Nogue et al. 2020; Wang et al. 2017). Therefore, the dry and wet alternation of the soil caused by drainage satisfies both the above conditions and greatly promotes the emission of N₂O, and wheat field soils have the largest amount of emissions (Liao et al. 2020; Xu et al. 2013). In the wheat season, the peak of N₂O emissions of each treatment emerged after fertilization. Abalos et al. (2016) and Wang et al. (2021) reported that applying fertilization will produce a large amount of nitrogen to the soil, which provide a reaction substrate for nitrifying and denitrifying bacteria. Affected by the typhoon bringing frequent rainfall in 2015, the soil was in aerobic and anaerobic alternation, which promoted the process of nitrification and denitrification, so the N₂O emissions greatly increased and fluctuated (Gao et al. 2018; Hou et al. 2016), directly leading to a significant increase in N₂O emissions of rice-wheat rotation system in 2015 (Table 7). In order to further clarify the mechanism of N₂O emissions, it is necessary to study the impact of rainfall pattern on N₂O emissions.

Dryland soil has great porosity, making the oxygen easily get in, so the extreme anaerobic environment required for the survival of methanogens is blocked, while the activity of methanotrophic bacteria is preserved (Hofmann et al. 2016). Liu et al. (2015) reported that winter-wheat fields are often regarded as the sink of CH₄. In this experiment, CH₄ emissions in the wheat season were very low but should not be ignored (Table 5). It is worth noting that the CH₄ emissions of rice-wheat rotation farmland in this study were too high, while the N₂O emissions were considerably low. Wen et al. (2017) reported that the substantial reduction of N₂O to N₂ under anaerobic condition may lead to lower N₂O emissions. The lowland polder areas along the middle and lower reaches of the Yangtze River are mostly derived from the development of water, and the groundwater level is strongly affected by the nearby main waters (Huang et al. 2016). It has been reported that groundwater level fluctuation is a key predictor for CH₄ and N₂O emissions from cultivated lowland (Wen et al. 2020). Evans et al.

(2021) observed that the high groundwater level in lowland areas usually leads to CH₄ increase and N₂O decrease, which is a scientific issue that cannot be ignored in global climate change. Therefore, in arable lands with different groundwater levels, the effect of water control treatments on the total greenhouse effect caused by CH₄ and N₂O needs to be further assessed. For the further exploration of the GHG emission reduction technologies applicable to lowland polder areas, it is suggested that long-term observations be conducted on soil water content and groundwater levels in the future to study the specific mechanisms of water control and emissions reduction.

4.3. Yield, GWP, and GHGI

The previous studies mainly focused on the cumulative emission and integrative GWP of CH₄ and N₂O from the paddy fields. Although there are related reports on the assessment of GHG in the entire rice-wheat rotation system, that in the lowland polder area remains unclear (Li et al. 2021). China's subtropical regions are widely planted with rice, but it has always been a difficult point in related research to ensure stable crop production or even production increase when reducing GHG emissions from rice paddy soils.

Among the total GWP treated by CG, SD, and DD, the contribution rate of CH₄ was 86.01%, 71.35%, and 65.85%, respectively, in this study. Therefore, the most effective way to reduce the total amount of GHG in rice fields is usually to reduce CH₄ emissions (Lagomarsino et al. 2016). Jiang et al. (2019) pointed out that compared with continuous submerged irrigation, non-continuous submerged irrigation effectively reduces the GWP of rice fields by 44%. In south China, after adopting mid-term drainage in the double-cropping rice planting area, the GWP in the early and late rice seasons are reduced by 22% and 41%, respectively (Liang et al. 2017). Drainage in the wheat season significantly reduces the GWP of the entire rice-wheat rotation system, even with increased N₂O emissions in some years, and the net GWP of the entire system has dramatically declined because of significantly reduced CH₄ emissions. In this study, it was found that the yield of rice increased, because drainage can improve the soil permeability of the paddy field, and the oxygen supply is sufficient, creating good growth conditions for the rice, so the GHGI of the entire rice-wheat rotation system was significantly reduced. In general, based on the current situation that a large amount of fertilizers are used to increase production and environmental protection is neglected, the drainage is a planting technique worth promoting.

5. Conclusion

The CH₄ emissions in the rice season were the main contributor to GWP of the rice-wheat rotation cropping system. The CH₄ and N₂O emissions of the rice-wheat rotation system were obviously affected by drainage. Compared with those of CG, the CH₄ cumulative emissions of SD and DD were reduced by 65.80% and 63.42% (rice season), and 101.37% and 77.28% (wheat season), respectively, while the N₂O emissions increased in some years. Drainage led to an increase in the yields of both rice and wheat. In the rice season, the GHGI of SD and DD reduced by 65.46% and 62.49%, respectively (three-year total) ($P<0.05$). The GHGI of SD declined by 18.75% and GHGI of DD rose by 25.00% in the wheat season. It can be inferred that SD and DD ensure stably increasing production and effectively reduce GHG emissions. The CH₄ emission flux was significantly positively correlated with air temperature and 5 cm ground temperature, but negatively correlated with soil Eh. When the soil Eh value was lower than -150 mV, the CH₄ emission flux increased markedly with the decrease of Eh. In addition, both SD and DD led to marked decrease in soil organic matter content and an increase in soil pH, which may be the reason for decreased CH₄ emissions.

Declarations

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Declaration of Interest Statement

The authors declare that they have no known competing financial interests that could have appeared to influence the work reported in this paper.

Data availability

All data analyzed during the study are included in this article.

Credit Author Statement

Hao He: Sampling, Measuring, Data curation, Writing - original draft, Writing - review & editing.

Dandan Li, Ze Wu, Tiancheng Zhang, Feifan Pan, Fengwen Wang: Sampling, Measuring, Formal analysis.

Shuyun Yang, Youhua Ma : Methodology, Supervision, Writing- review and Editing.

Ethics declarations

Consent to participate

All authors voluntarily participate in this research study.

Consent to publish

All authors consent to the publication of the manuscript.

Conflict of interest

The authors declare no competing interests.

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Figures

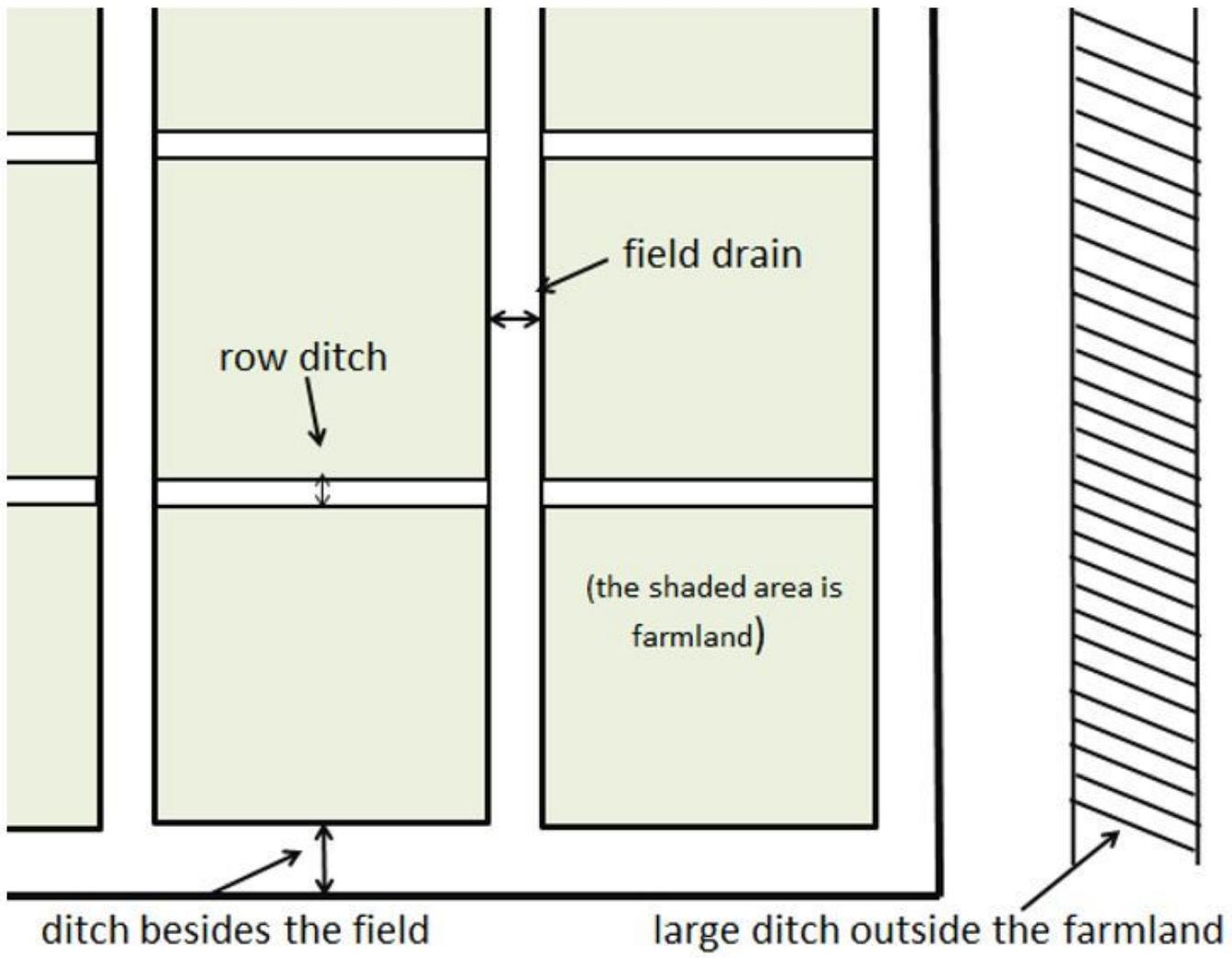


Figure 1

Schematic diagram of the field ditches.

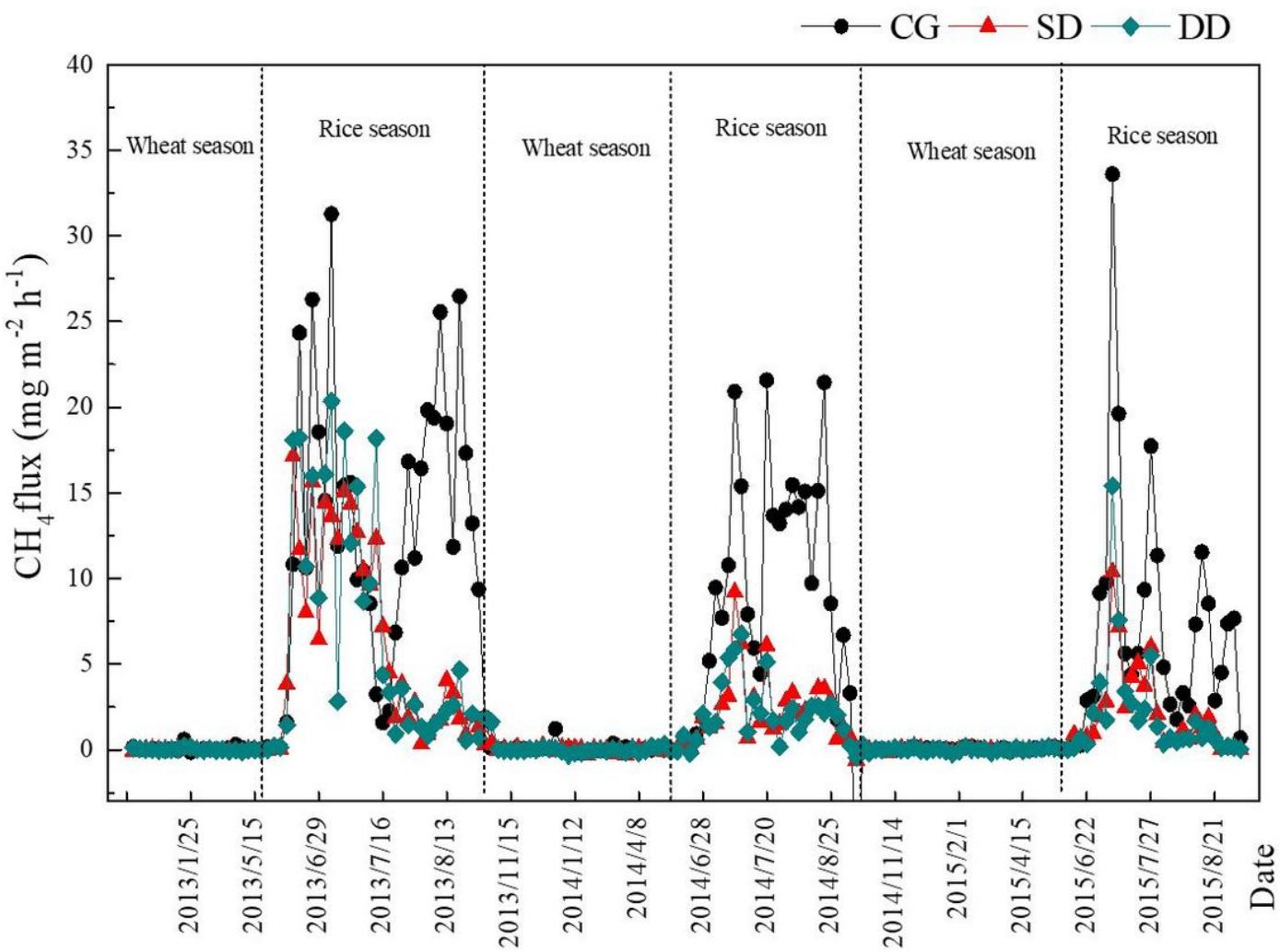


Figure 2

CH_4 emissions in each treatment in the rice-wheat seasons in the three years. CG, SD, and DD CG, SD, and DD represent the treatment of ditches of different depths for drainage during the wheat season, CG: control group; SD: shallow ditch; DD: deep ditch. The same as below.

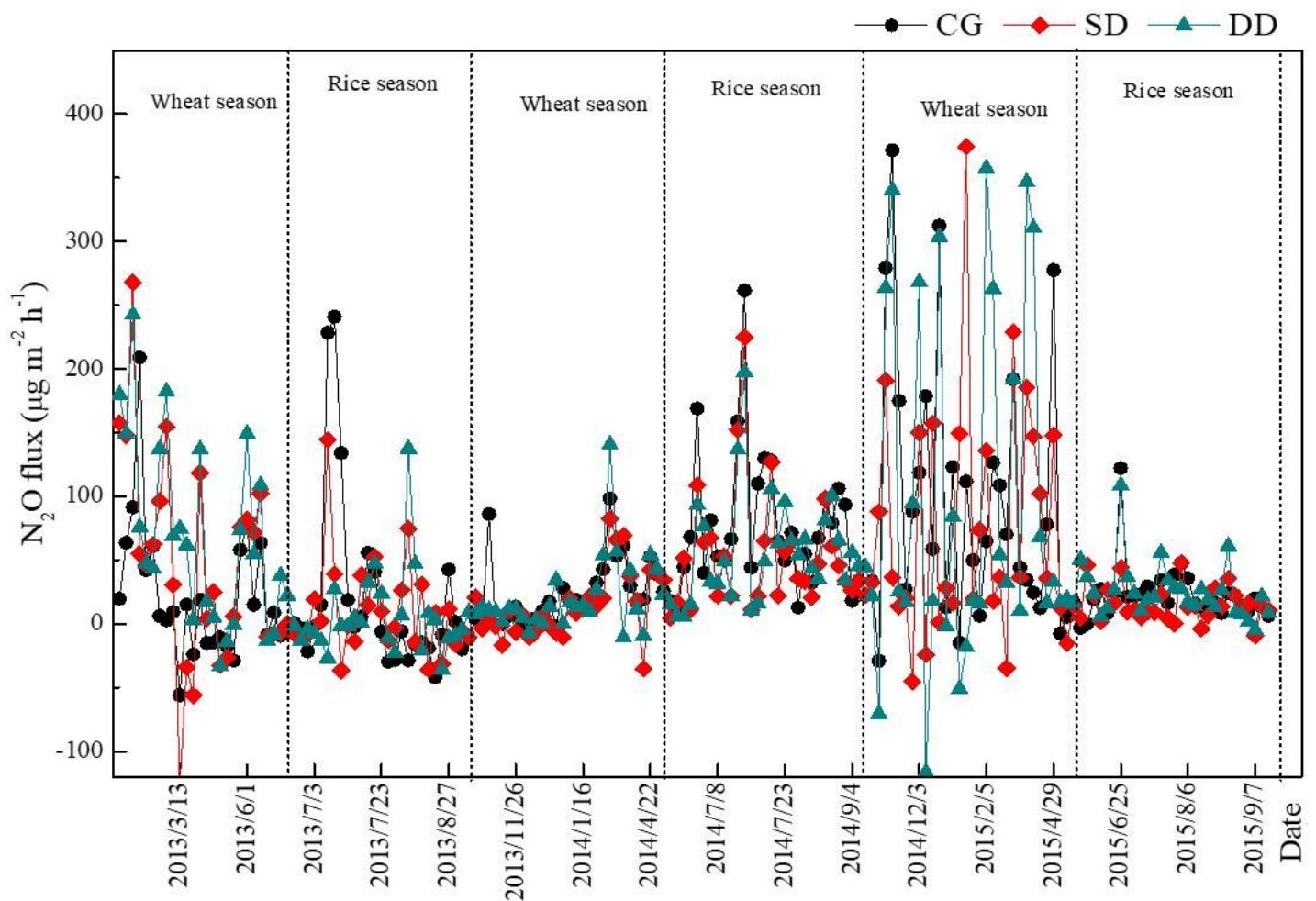


Figure 3

Seasonal variation of N_2O emission flux during the rice growth period in the three years.

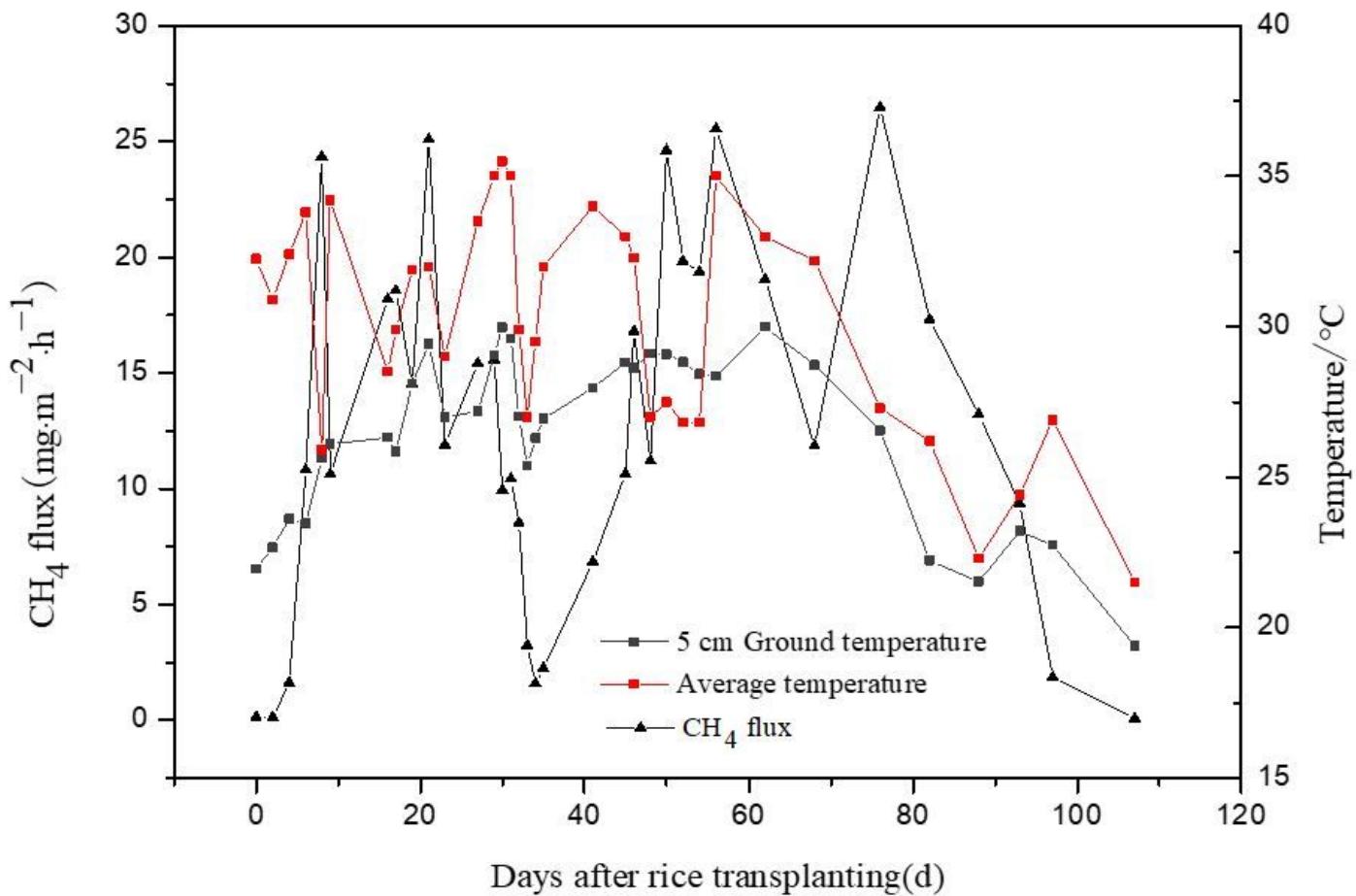


Figure 4

Relationship of the atmospheric temperature, 5 cm ground temperature, and seasonal variation of CH_4 emissions in the rice season.

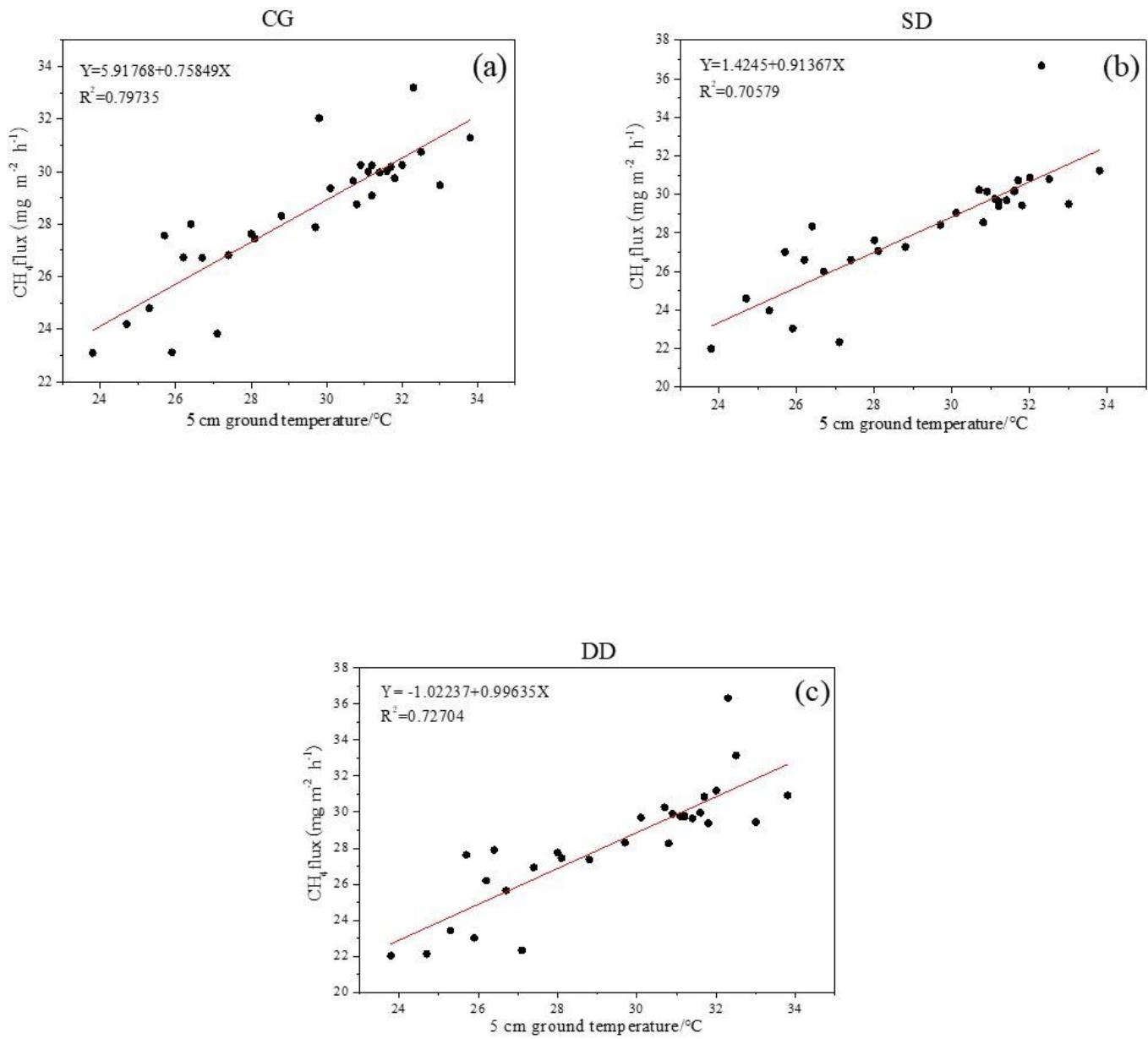


Figure 5

Relationship between the CH_4 emission flux and 5 cm ground temperature in each treatment.

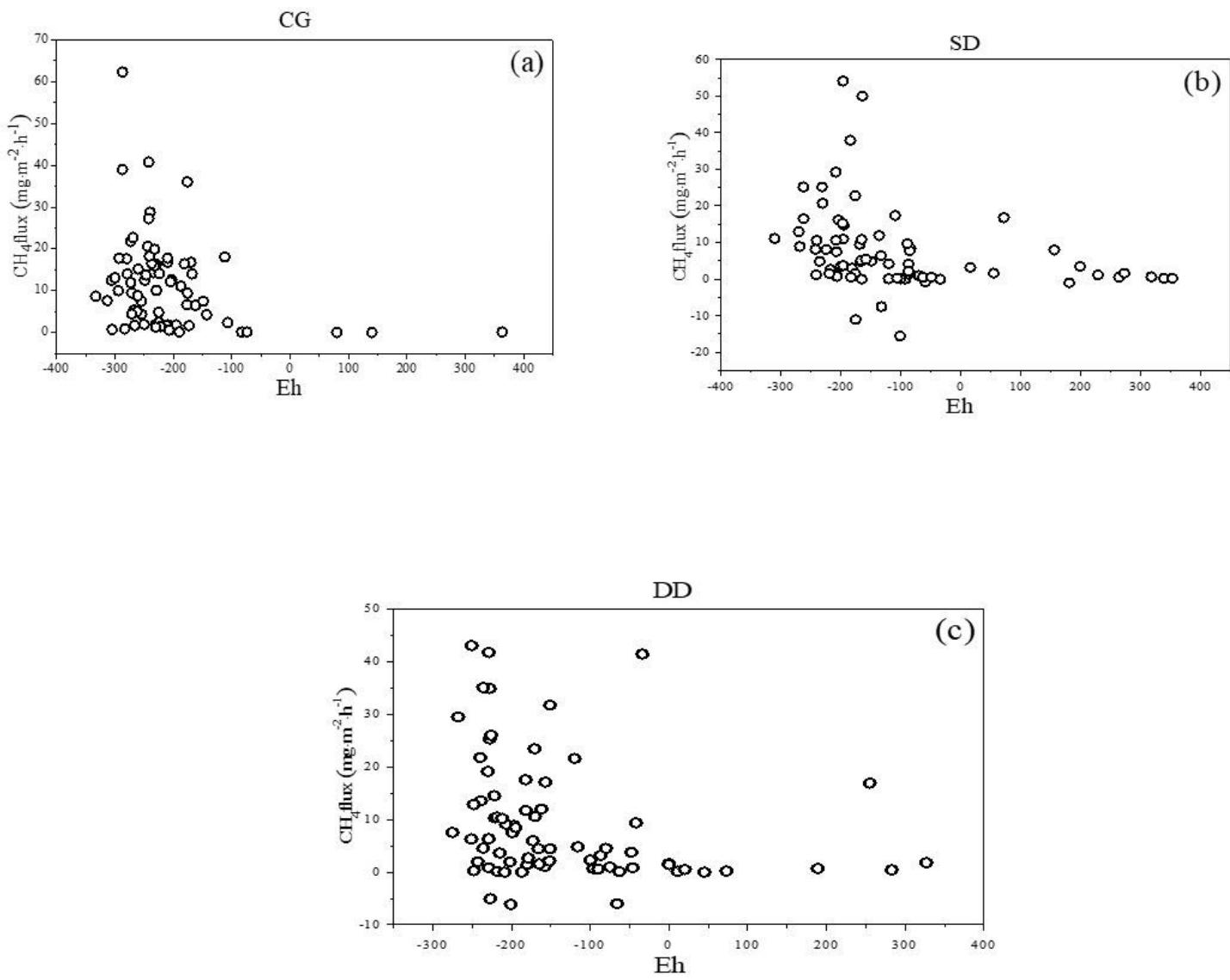


Figure 6

Relationship between the Eh value and CH_4 emission flux in each treatment (a, b & c)

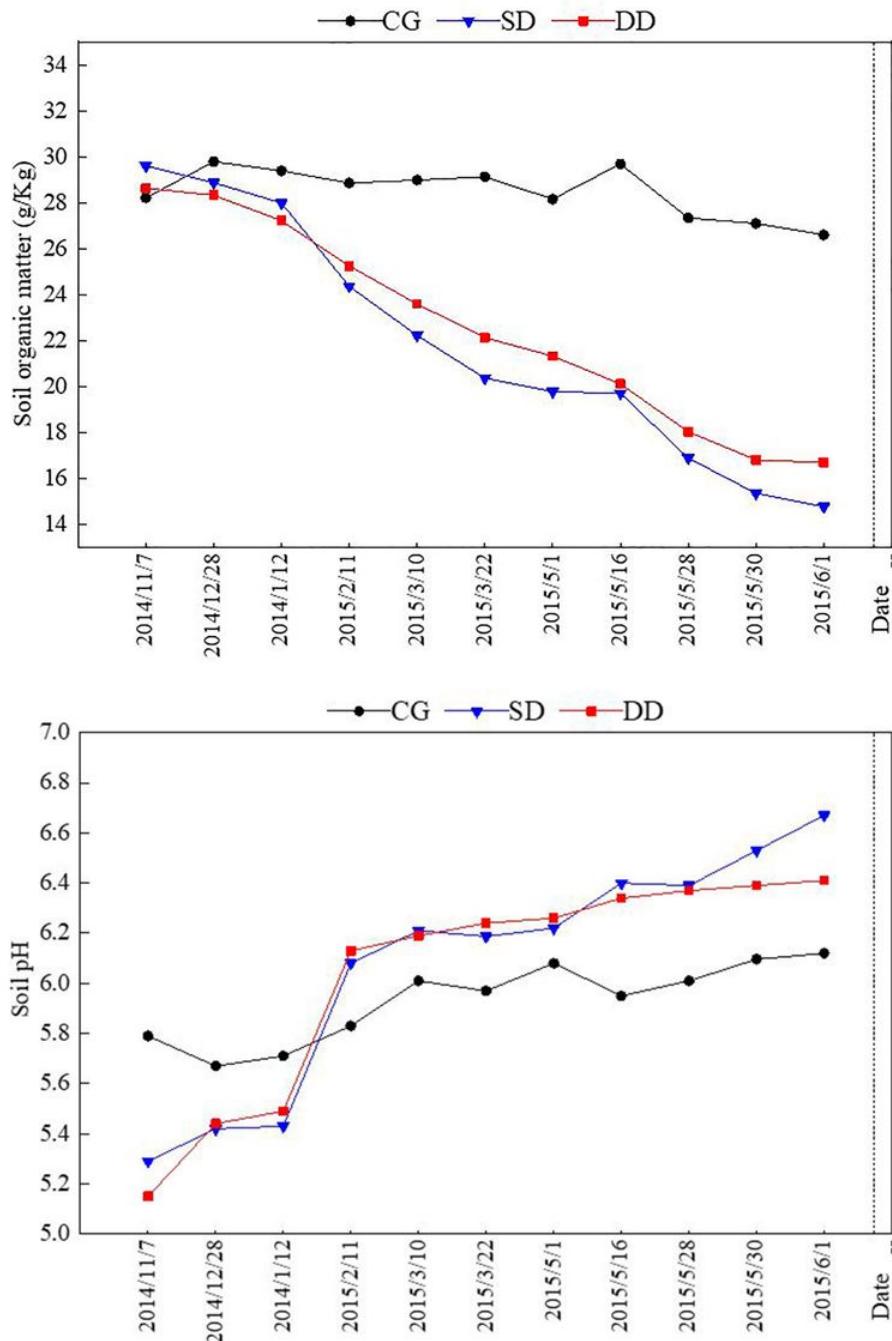


Figure 7

Changes of soil organic matter and soil pH in the wheat season in 2014-2015