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CH_4 and N_2O Emission and Grain Yield Performance of Three Main Rice-Farming Patterns in Central China

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Abstract: This study focuses on the development of more cropping systems in response to global warming and food security concerns. A two-year field experiment (2017–2018) was conducted to investigate the effects of greenhouse gases (GHGs), soil environmental factors and yield on traditional double-cropping rice (DR), maize rice (MR) and ratooning rice (Rr). The results showed a significant annual effect of temperature and rainfall on GHG emissions under different cropping systems. Annual CH_4 emissions under MR and Rr were significantly lower than under DR. Compared to DR, the highest cumulative N_2O emissions were observed in MR (14.9 kg·ha^{-1}) with a reduction of 23.7% in Rr. In addition, the upland crops significantly reduced CH_4 emissions for late rice, while N_2O emissions increased by 20.6%. Compared with DR and Rr, global warming potential (GWP) and greenhouse gas intensity (GHGI) were significantly lower for MR ($p < 0.05$). Meanwhile, the annual yield of MR (16.40 t·ha^{-1}) was 8.1% and 2.4% higher than that of DR and Rr, respectively. This study further found that soil temperature and $NH_4{}^+$-N content were positively correlated with CH_4 and N_2O emissions, and soil moisture was positively correlated with N_2O emission. Thus, we concluded that MR has the greatest potential to improve crop yield and mitigate GHG emissions in central China.

Keywords: double-cropping rice; maize rice; ratooning rice; GHG; yield; yield-scaled GWP

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1. Introduction

CH_4 and N_2O are two major greenhouse gases (GHGs) in the atmosphere and increasing their concentration leads to the changes in atmospheric components and accelerates the rate of global warming [1]. Atmospheric concentrations of CH_4 and N_2O are increasing at a rate of 0.6% and 0.2–0.3% per year, respectively [2]. Their global warming potential (GWP) on a 100-year scale is 29.8 and 273 times greater than those of CO_2, respectively [3]. Rice fields have been identified as a major agricultural source of CH_4 and N_2O emissions, accounting for 7–11% of soil N_2O emissions and 10.5% of total CH_4 emissions, respectively [4]. China accounts for 22% of the global rice area and 34% of rice output [5], and CH_4 and N_2O emissions from rice cultivation are estimated to be about 6.4 Tg·y^{-1} and 180 Gg·y^{-1}, respectively [6]. Therefore, it is particularly important to evaluate CH_4 and N_2O emissions in China's rice fields and to propose effective reduction measures through field activities.

Increasing extreme weather events, such as waterlogging, are threatening crop security [7], prompting farmers to switch from traditional double-cropping rice to rice-upland patterns or ratooning rice. Rice and maize are two key food crops in China. The different planting conditions not only improve the utilization rate of agricultural land, but also result in different levels of GHG emissions [8]. Ratooning rice (Rr) is the practice that uses what is left over from previous main rice for budding, booting and harvesting again. The ratooning rice area gradually increases due to its low expenditure, high income and lower water demand. Compared with rice-wheat rotation, the total greenhouse gas emissions and GHGI of Rr were reduced by 36.3% and 15.9%, respectively [9]. Zhang et al. [10] found that CH_4 emissions and N_2O emissions yielded from ratooning rice were 33.89% and 23.02% lower than those from double-cropping rice, respectively. Both CH_4 and N_2O emissions from rice-based systems contribute significantly to GHG emissions, with aerobic cereal crops releasing mostly N_2O and little CH_4 [11]. The crop rotation with maize rice and sweet sorghum rice significantly reduced CH_4 emissions by 78~84%, and net CO_2-eq emissions were reduced by 68~78% compared to double rice [12]. Although annual N_2O emissions increased two to threefold with the incorporation of upland crops, the larger reduction in CH_4 resulted in a significantly lower annual GWP compared to the double-rice-cropping system [13]. In addition, previous studies have reported that CH_4 emissions are closely related to soil temperature [14], especially in 5 cm soil layers [15]. This is mainly because anaerobic microbial activity in soil is related to the production and consumption of CH_4. Studies have observed that CH_4 emissions increase significantly in paddy fields under flood conditions, while N_2O emissions are low [16]. Therefore, it is particularly important to reduce CH_4 emissions from paddy fields by controlling water flooding. Furthermore, nitrogen fertilizer is an important factor in regulating N_2O production and emission [17]. Zhou et al. [18] found that high N rates contribute to greater N_2O emissions with improved N substrate availability.

Therefore, we conducted a two-year study for the following reasons: (i) to verify the impact of different crop rotation systems on greenhouse gas emissions; (ii) to estimate CH_4 and N_2O in the overall impact of global warming potential; (iii) and to estimate the impact of the management activities of paddy fields on soil properties. These provide the theoretical basis to support China's emissions reductions and to assess the economic benefits or risks of diversified rice-cropping systems.

2. Materials and Methods

2.1. Experimental Site

The field experiments were conducted from March 2017 to November 2018 at Sanhu Experimental Farm (30°12′ N, 112°31′ E) in Jiangling County, Hubei Province. The region has a north subtropical monsoon humid climate, with mean annual rainfall of 900–1100 mm and temperature of 16.0–16.4 °C. The experimental field was cultivated under a rice-fallow system. The soil was loam, and the physical and chemical properties of the soil at 0–20 cm were as follows: organic matter, 28.59 $g \cdot kg^{-1}$; TN, 2.44 $g \cdot kg^{-1}$; TP, 0.38 $g \cdot kg^{-1}$; and pH, 6.9. The precipitation and daily air temperature during the 2017–2018 experimental period are shown in Figure 1.

2.2. Experimental Design

Three patterns, including double-cropping rice (DR), maize rice (MR) and ratooning rice (Rr), were selected in a completely random block design. Each plot area was 98 m^2 (14.0 m × 7.0 m) with three replications, and a 0.40 m wide ridge was placed around the plot for isolation.

Maize was planted by direct seeding at 60 cm × 30 cm spacing. Rice was planted by artificial transplanting at a density of 27 cm × 17 cm. Water management was carried out by flooding in the pre-tillering stage, drying in the late tillering stage and alternate drying and wetting in the filling stage. The cultivars, including early rice Liangyou 287, late rice Jinyou 207, ratooning rice Liangyou 6326 and maize Zhengdan 958, were used in this study. The different field management activities are shown in Table 1.

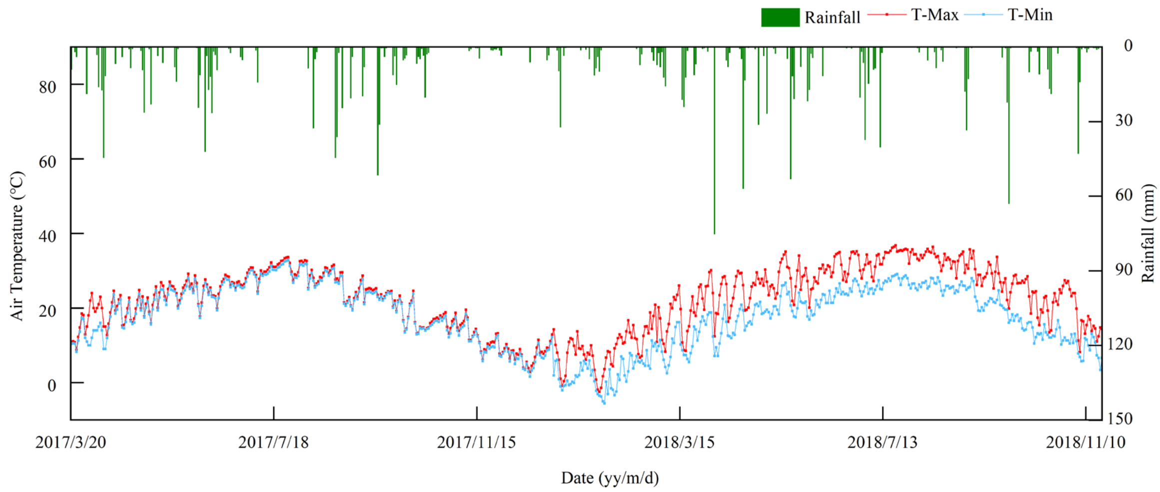

Figure 1. Daily air temperature and precipitation in the cropping system during the 2017–2018 experimental period.

Table 1. Crop management in this experiment.

Crop Management Activities		**2017**	**2018**
Crop cultivation			
First season	Maize	29 Mar: sowing, 23 Apr: transplanting, 15 Jul: harvesting	30 Mar: sowing, 22 Apr: transplanting, 16 Jul: harvesting
	Early rice	29 Mar: sowing, 2 May: transplanting, 20 Jul: harvesting	25 Mar: sowing, 3 May: transplanting, 18 Jul: harvesting
	Ratooning rice	29 Mar: sowing, 2 May: transplanting, 15 Aug: harvesting	25 Mar: sowing, 3 May: transplanting, 10 Aug: harvesting
Second season	Late rice	27 Jun: sowing, 27 Jul: transplanting, 3 Nov: harvesting	22 Jun: sowing, 27 Jul: transplanting, 1 Nov: harvesting
	Regeneration of season	3 Nov: harvesting	23 Oct: harvesting
Fertilizer application			
First season	Maize	29 Mar: NPK (345 kg·ha^{-1})	30 Mar: NPK (345 kg·ha^{-1})
	Early rice	1 May: NPK (563 kg·ha^{-1}) 7 May: Urea (78 kg·ha^{-1}) 14 Jun: Urea (117 kg·ha^{-1})	2 May: NPK (750 kg·ha^{-1}) 10 May: Urea (52 kg·ha^{-1}) 2 Jun: Urea (78 kg·ha^{-1})
	Main rice	1 May: NPK (628 kg·ha^{-1}) 7 May: Urea (88 kg·ha^{-1}) 26 Jun: Urea (130 kg·ha^{-1}) 28 Jul: Urea (163 kg·ha^{-1})	2 May: NPK (750 kg·ha^{-1}) 10 May: Urea (69 kg·ha^{-1}) 24 Jun: Urea (103 kg·ha^{-1}) 1 Aug: Urea (162 kg·ha^{-1})
Second season	Late rice	26 Jul: NPK (450 kg·ha^{-1}) 4 Aug: Urea (157 kg·ha^{-1}) 30 Aug: Urea (78 kg·ha^{-1})	26 Jul: NPK (450 kg·ha^{-1}) 4 Aug: Urea (155 kg·ha^{-1}) 23 Aug: Urea (78 kg·ha^{-1})
	Ratooning rice	25 Aug: Urea (163 kg·ha^{-1})	20 Aug: Urea (162 kg·ha^{-1})

The compound fertilizer NPK is a combination of N:P_2O_5:K_2O (16:10:22). Urea is 46:0:0 of nutrient (NPK) contents.

2.3. Gas Sample Collection and Analysis

The CH_4 and N_2O fluxes were simultaneously monitored throughout the 2017 and 2018 growing seasons using the static chamber method [19]. The base of the closed chamber area was 45 cm × 45 cm and it was installed in the plot before planting. The height of the static chamber could be adjusted according to the plant stage. The outer layer was wrapped in aluminum foil to prevent rapid temperature rise inside the box. Bamboo rows were placed in each plot before planting to avoid field disturbance. Sampling was conducted at 7 d intervals during the rice and maize season, and 2–3 consecutive samples were taken after fertilization and rainfall. Samples were taken between 9:00 and 11:00 at regular intervals of 8 min (0, 8, 16 min) with 100 mL syringes repeatedly extracted 5 times and transferred to a 500 mL gas bag. The samples were analyzed using an Agilent 7890B gas chromatograph. CH_4 and N_2O emitted were calculated according to Equation (1):

$$F = \rho \times h \times \Delta C/\Delta t \times 273/(273 + T) \quad (1)$$

where F is the greenhouse gas emission rate (N_2O, $\mu g \cdot m^{-2} \cdot h^{-1}$; CH_4, $mg \cdot m^{-2} \cdot h^{-1}$); ρ is the gas density in the standard state (N_2O, 1.964 $kg \cdot m^{-3}$; CH_4, 0.714 $kg \cdot m^{-3}$); h is the height of the static chamber (m); $\Delta C/\Delta t$ is the gas mixing ratio concentration ($mg \cdot m^{-2} \cdot h^{-1}$); and T is the mean air temperature inside the chamber (°C).

The cumulative seasonal CH_4 and N_2O emissions were calculated according to Equation (2):

$$CE = \sum[(F_n + F_{n+1})/2] \times 24 \times t \quad (2)$$

where CE is the seasonal emission of CH_4 or N_2O ($kg \cdot ha^{-1}$); F_n and F_{n+1} are the emission rate of CH_4 or N_2O ($mg \cdot m^{-2} \cdot h^{-1}$ or $\mu g \cdot m^{-2} \cdot h^{-1}$) at two consecutive sampling days; and t is the number of days between two consecutive sampling days (d).

The global warming potential (GWP, t CO_2 -eq ha^{-1}) and GHGI (t CO_2-eq t^{-1} yield) were calculated according to Equations (3) and (4) (IPCC, 2021):

$$GWP = CH_4 \times 29.8 + N_2O \times 273 \quad (3)$$

$$GHGI = GWP/Y \quad (4)$$

$$Y\text{: crop yield } (t \cdot ha^{-1}) \quad (5)$$

2.4. Yield Measurement, Soil Sampling and Analysis

At maturity, three 1 m^2 plots of rice in each plot were harvested, threshed and weighed. Two consecutive ears of twenty were harvested before the maize harvest in each plot, and grains per ear were weighed at 1000 grain weight.

Soil samples (0–20 cm) were collected randomly in each plot after harvest. The content of dissolved organic carbon (DOC) was analyzed using potassium the dichromate external heating method on fresh soil samples. Soil pH was measured in 1:2.5 (soil: water) suspension using the Mettler Toledo portable. The content of ammonium (NH_4^+-N) and nitrate (NO_3^--N) was analyzed using the indophenol blue colorimetric method and the ultraviolet spectrophotometry method.

2.5. Statistical Analysis

Data were analyzed and sorted by Excel 2019 and plotted by Origin 2018, and LSD was used for mean separation by SPSS 24.0. Pearson's correlation coefficient (r) was used to analyze the correlation between each environmental index and CH_4 and N_2O emitted.

3. Results

3.1. CH_4 Emissions

It was observed for two consecutive years that CH_4 emissions contributed to the rice season, while it was lower in the maize season, and the two years had similar emission rules. CH_4 emissions gradually increased after rice planting, rapidly reduced during the drainage drying stage and remained low until maturity.

During the first growing season, CH_4 emissions ranged from 0.04 to 17.80 $mg \cdot m^{-2} \cdot h^{-1}$ in all treatments, and the seasonal mean CH_4 fluxes of DR, MR and Rr were 4.92, 1.01 and 6.70 $mg \cdot m^{-2} \cdot h^{-1}$, respectively (Figure 2). Compared to DR, CH_4 emissions increased by 64.68% in Rr and decreased by 82.65% in MR. (Table 2). The highest cumulative CH_4 emissions were observed at 82.64~273.18 $kg \cdot ha^{-1}$ under DR in the second season, and there was no significant difference between MR and Rr in the second season (Table 2). In addition, CH_4 emissions were 66.83% lower in MR than in DR in the late rice season. Annual CH_4 emissions under different treatments were significantly higher in 2017 than in 2018, possibly due to the temperature and rainfall. As opposed to DR, annual CH_4 emissions decreased by 72.63% and 18.12% under MR and Rr, respectively.

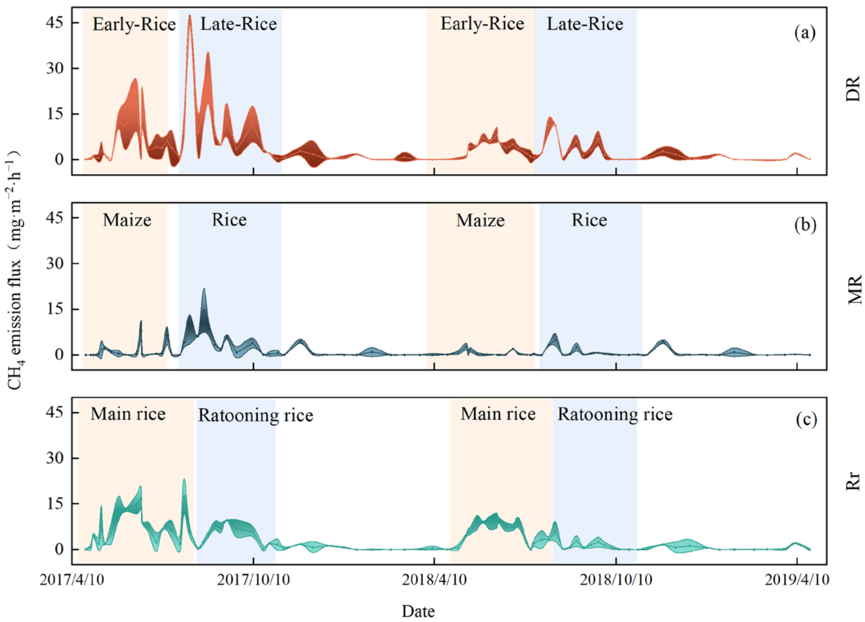

Figure 2. Average daily CH_4 flux (n = 3) of three different cropping systems from 2017 to 2018: (**a**) DR: double-cropping rice; (**b**) MR: maize rice; (**c**) Rr: ratooning rice. The shaded part represents the standard deviations of the means.

Table 2. Seasonal and annual cumulative of CH_4 and N_2O under different cropping systems from 2017 to 2018 ($kg{\cdot}ha^{-1}$).

Year	Treatment	1st Season		2nd Season		Annual	
		CH_4	N_2O	CH_4	N_2O	CH_4	N_2O
2017	DR	129.96 ± 24.19 b	1.32 ± 0.05 c	273.18 ± 98.00 a	4.19 ± 0.72 a	403.15 ± 124.89 a	5.51 ± 0.25 b
	MR	23.83 ± 4.00 c	5.28 ± 1.35 a	95.62 ± 2.57 b	5.21 ± 1.88 a	119.45 ± 11.22 c	10.49 ± 0.05 a
	Rr	198.69 ± 46.55 a	3.94 ± 0.40 b	97.58 ± 17.34 b	1.21 ± 0.18 b	296.27 ± 13.70 b	5.15 ± 2.96 b
2018	DR	76.23 ± 5.14 b	4.89 ± 2.02 b	82.64 ± 11.50 a	7.18 ± 0.30 a	158.87 ± 16.64 a	12.06 ± 2.44 b
	MR	11.94 ± 1.07 c	10.96 ± 2.50 a	22.41 ± 3.26 b	8.48 ± 2.21 a	34.35 ± 7.95 b	19.44 ± 2.58 a
	Rr	140.88 ± 3.68 a	3.85 ± 0.08 b	23.06 ± 4.04 b	4.41 ± 1.49 b	163.94 ± 4.89 a	8.27 ± 2.22 b
Average	DR	103.10 ± 9.53 b	3.10 ± 0.99 b	177.91 ± 43.25 a	5.68 ± 1.51 a	281.01 ± 52.78 a	8.79 ± 1.04 b
	MR	17.89 ± 1.02 c	8.12 ± 2.39 a	59.01 ± 1.46 b	6.85 ± 2.23 a	76.90 ± 6.91 bc	14.97 ± 3.43 a
	Rr	169.79 ± 24.78 a	3.90 ± 1.41 b	60.32 ± 19.83 b	2.81 ± 1.51 b	230.10 ± 66.09 a	6.71 ± 1.11 b

Mean ± SD: different letters within the same column indicated significant differences in CH_4 and N_2O cumulative emissions among treatments during the 2017–2018 period ($p < 0.05$).

3.2. N_2O Emissions

It was found that N_2O emissions mainly occurred during the upland cropping season, after fertilization and during the alternate dry and wet stage of the paddy field, while it decreased during the long-term flood condition. For the first growing season, N_2O emissions ranged from approximately −214.79 to 1052.73 $ug{\cdot}m^{-2}{\cdot}h^{-1}$, and the mean N_2O emissions of MR was significantly higher than that of DR and Rr. The highest N_2O flux was recorded at 5.28 and 10.96 $ug{\cdot}m^{-2}{\cdot}h^{-1}$ at MR in 2017 and 2018, respectively, likely due to the facilitation of soil nitrification under aerobic conditions (Figure 3). During the second growing season, the average N_2O emissions were 231.32, 283.03 and 152.46 $ug{\cdot}m^{-2}{\cdot}h^{-1}$ at DR, MR and Rr, respectively, and the seasonal N_2O emissions ranged from approximately 1.21 to 8.48 $kg{\cdot}ha^{-1}$ in 2017 and 2018. Compared with DR, MR significantly increased the annual cumulative N_2O emissions by 70.31%, while Rr had a reduction of 23.66%.

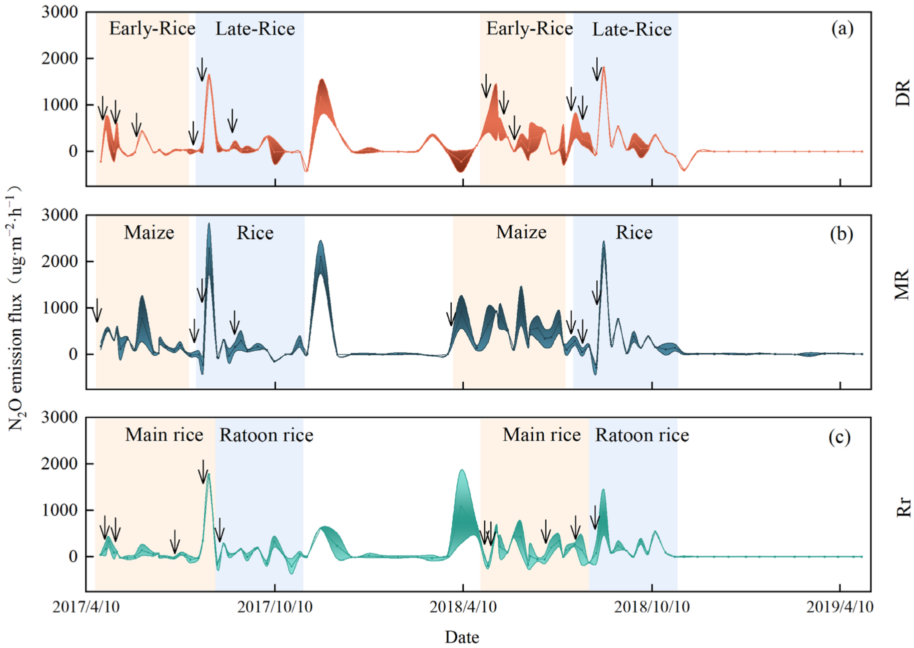

Figure 3. Average daily N_2O flux (n = 3) of three different cropping systems from 2017 to 2018: (**a**) DR: double-cropping rice; (**b**) MR: maize rice; (**c**) Rr: ratooning rice. The arrows indicate the time of N fertilizer application in the different cropping systems. The shaded part represents the standard deviations of the means.

3.3. Crop Yield

In a two-year experiment, the highest yield was observed in Rr during the first growing season, and it was significantly higher than MR and DR by 21.08% and 37.81%, respectively (Figure 4). There was no significant difference between DR and MR during the second growing season, and these were significantly higher than Rr. In general, the annual crop yields of DR, MR and Rr were higher in 2018 than in 2017, which may be due to the difference in climate. Compared with DR, the annual yield of MR and Rr was significantly higher by 8.06% and 7.30%, respectively.

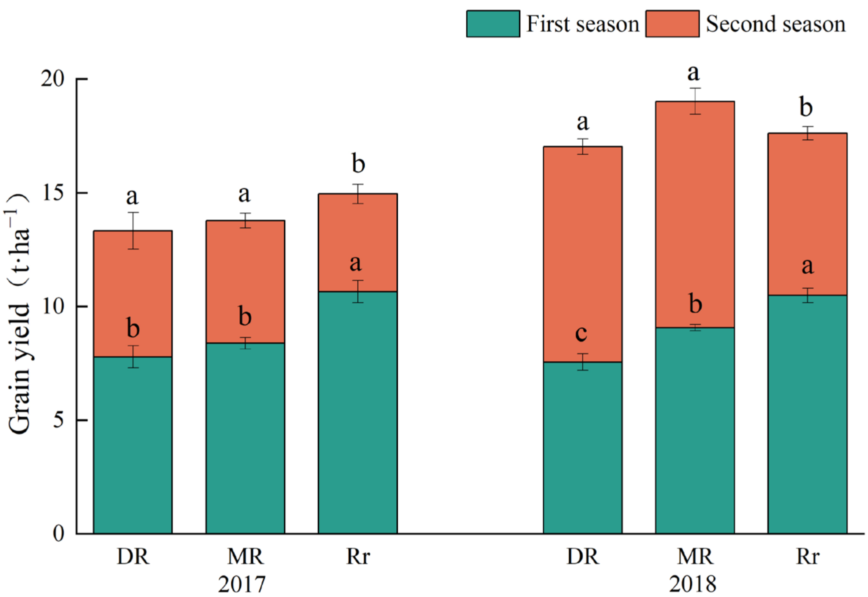

Figure 4. Seasonal yield under different cropping systems from 2017 to 2018. Significant differences of grain yield at $p < 0.05$ are indicated by different letters.

3.4. GWP and Yield-Scaled GWP

The average GWP calculated for the different cropping systems is shown in (Figure 5A). The CH_4 emissions during the rice season contributed 71.83% to the seasonal GWP, and a higher GWP was observed in 2017 than in 2018. Compared to DR, the annual GWP decreased by 40.81% and 26.59% for MR and Rr, respectively.

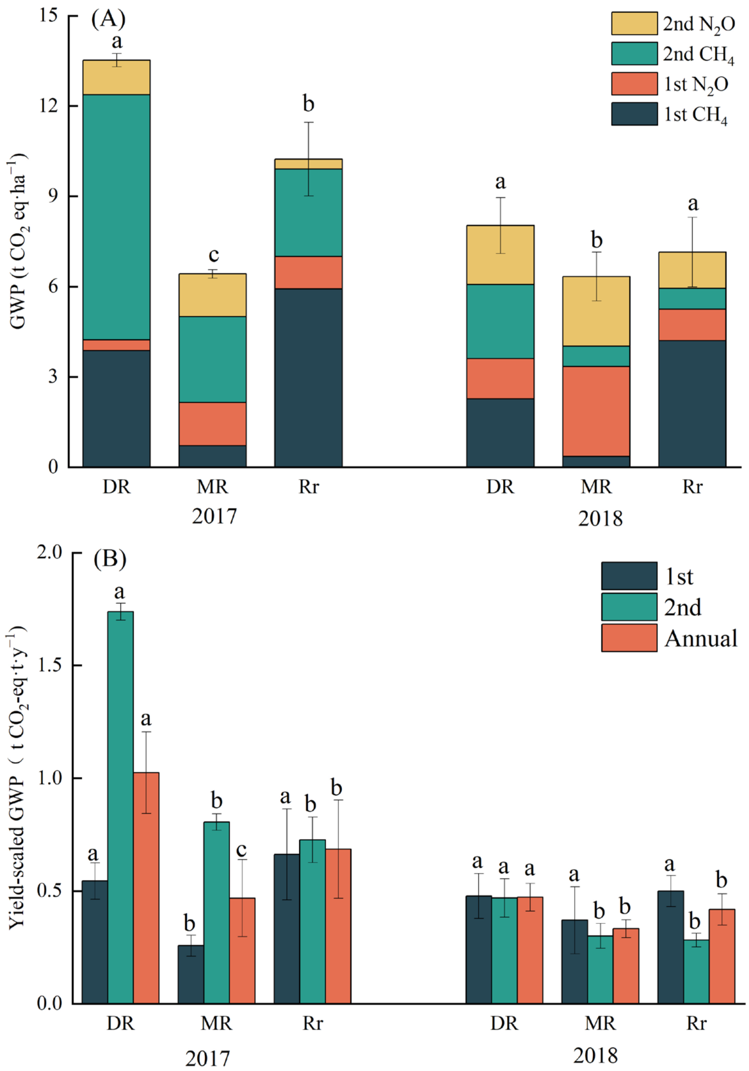

Figure 5. Global warming potential (GWP) (**A**) and yield-scaled GWP (**B**) under four different cropping systems in 2017–2018. Significant differences of GWP and GHGI at $p < 0.05$ are indicated by different letters.

Yield-scaled GWP was identified as GHG emissions per unit of grain production. The highest YS GWP was observed in DR for 1.74 and 0.47 (t CO_2-eq·t^{-1}) in 2017 and 2018, respectively. The annual YS GWP decreased by 11.46%~54.26% compared to DR. MR, particularly, had the largest decrease of 30.97% over two years, and this was due to the increase in emission being much greater than the yield (Figure 5B).

3.5. Soil Characteristics and Correlation between CH_4 and N_2O Emissions

Compared with DR, the soil DOC concentration decreased by 20.75% and 44.64% in MR and Rr, respectively (Figure 6A). MR and Rr achieved NO_3^--N concentration growth of 26.01% and 11.90% compared to DR, with NH_4^+-N concentration growths of 15.73% and 38.75%, respectively (Figure 6C,D). No obvious effect of the cropping systems on soil pH was observed.

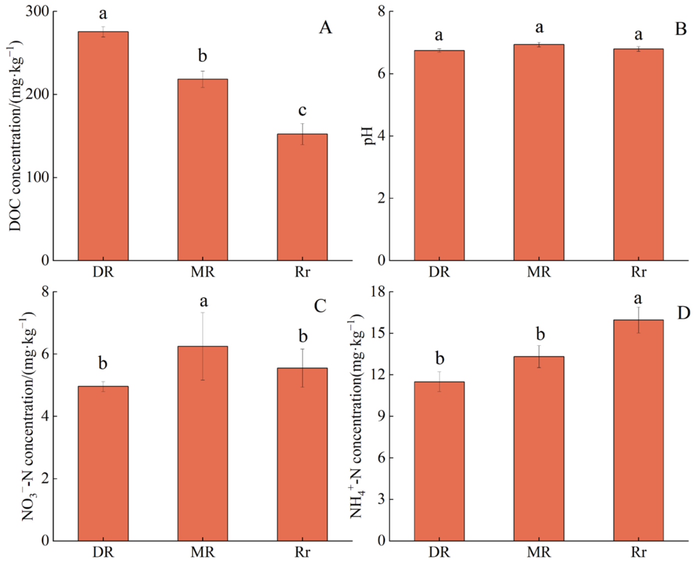

Figure 6. Soil-dissolved organic carbon (DOC) (**A**), pH (1:2.5H_2O) (**B**), NO_3^--N (**C**) and NH_4^+-N concentration (D) of different treatments after harvesting. Significant differences of soil characteristics at $p < 0.05$ are indicated by different letters.

There was a positive correlation between CH_4 emissions and NH_4^+-N, soil temperature and soil water content, and a negative correlation between NO_3^--N and pH. A positive correlation was found between N_2O emissions and soil temperature, and a non-significant correlation was found with NH_4^+-N (Figure 7).

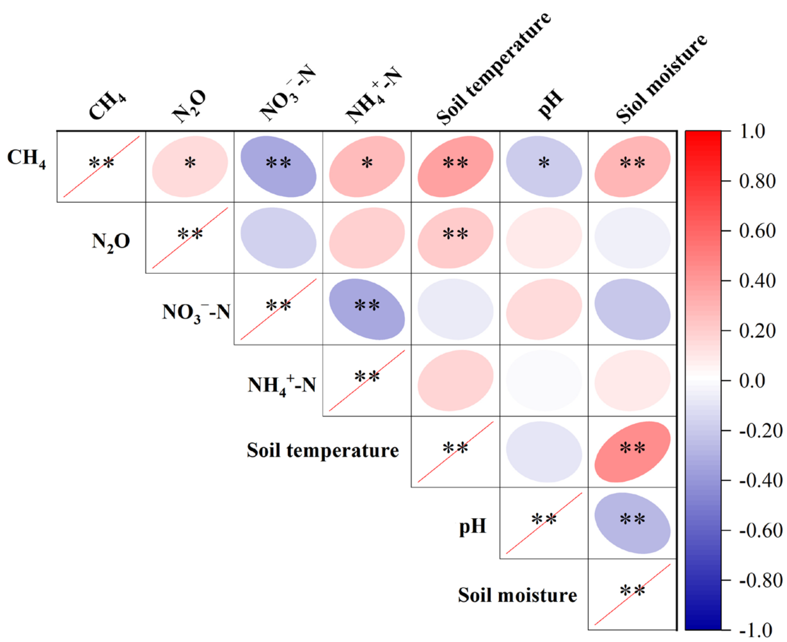

Figure 7. Correlation analysis of different factors with respect to CH_4 and N_2O (* $p < 0.05$, ** $p < 0.01$).

4. Discussion

4.1. Impact of Crop Pattern on CH_4 Emissions

In the present study, it was found that CH_4 emissions increased steadily after rice transplantation and decreased after reaching the peak (Figure 2), which is well explained by the fact that flood depth regulates the fluctuations in soil oxidation-reduction conditions [20,21]. The CH_4 emission peak appeared during the tillering and filling stage during the rice season (Figure 2), possibly due to the rice roots that grew vigorously during the tillering stage with increased exudation, which provided substrates for methanogenic bacteria [22,23]. This second emission peak depended on the reduced oxidation of CH_4 for massive root death, with CH_4 emissions through the plant aerenchyma. In contrast to DR, the reduction in CH_4 emissions for MR and Rr was 72.63% and 18.12%, respectively (Table 2). This may be because of the positive correlation between CH_4 emissions and soil DOC content (Figure 6A). Some studies have shown that soil DOC provides sufficient substrates to produce CH_4 [24,25], which is consistent with the higher soil DOC that is associated with higher CH_4 emissions in this experiment. In the present study, CH_4 emissions from MR were 66.83% lower than that from DR in late rice (Table 2), mainly influenced by the soil aeration status and soil moisture, which affect the activity of methanogenic and methane-oxidizing bacteria [26–28]. There was a significant positive correlation with soil moisture, $NH_4{}^+$-N concentration and soil temperature (Figure 7). In addition, the redox potential (Eh) gradually increased due to the regeneration of oxidants, e.g., Fe^{3+} failed to recover in a short period during the maize season, which in turn resulted in CH_4 emission differences in the rice field [29]. In this study, the CH_4 emissions of all treatments were higher in 2017 than those in 2018 (Table 2), which is related to the climatic and precipitation conditions [30].

4.2. Impact of Crop Pattern on N_2O Emissions

A significant difference was found in N_2O emissions among the different rice patterns. Because soil aeration conditions and N fertilization provide favorable conditions for nitrification and denitrification [29,31], N_2O emissions are mainly concentrated in upland areas and after fertilization (Figure 3). In this study, annual N_2O emissions from each cropping system in the rice season (3.10–8.48 kg·ha^{-1}) were higher than the global average seasonal N_2O emissions for rice (1.38 kg N ha^{-1}) [16]. It also indicates that N_2O emissions during the rice season need to be evaluated [32]. The annual N_2O emissions of DR and Rr were 41.28% and 55.18% lower than those of MR (Table 2), respectively, associated with the prolonged anaerobic conditions limiting nitrification by microorganisms and the reduction in N_2O to N_2 [33,34]. In comparison, N_2O emissions from maize were significantly higher than those from rice (Table 2), which was due to the alternation of wet and dry soil, which increased the mineralization of organic matter and promoted N_2O emissions by stimulating microbial activity [31]. In the present study, N_2O emissions from MR were 20.60% higher than DR during the late rice season, and soil microbial activity was observed by incorporation from upland crop root residue, which is contrary to Baldur et al. [33]. The reason for this could be attributed to the increasing $NH_4{}^+$-N content in rice due to the nitrogen surplus in maize (Figures 6D and 7). The study found that N_2O flux was positively correlated with $NH_4{}^+$-N content, as $NH_4{}^+$-N provides substrate for soil nitrification [35]. N_2O emissions of all treatments were lower in 2017 than those in 2018 (Table 2), which is related to the temperature and precipitation conditions [32,36].

4.3. Impact of Crop Pattern on Yield, GWP and Yield-Scaled GWP

The combined impact of CH_4 and N_2O emissions, as calculated by GWP, was closely related to the crop component. In the present study, the GWP of the paddy pattern was determined by CH_4 emissions with a contribution of 56.16%~84.01% (Figure 5A), which supports previous studies [32,37]. Switching from traditional double rice to maize rice reduces CH_4 emissions but increases N_2O emissions. In contrast to MR, the GWP for DR and Rr increased by 68.93% and 36.23%, respectively (Figure 5A). As a result of long-term flooding, favorable conditions for CH_4 and N_2O emissions have been created. In our study, the MR system achieved the significantly highest annual grain yield (16.40 t·ha^{-1}) and lowest YS GWP (0.39 t CO_2-eq·t^{-1}) (Figures 4 and 5B) among the high productivity of maize. The YS GWP in our study is in good agreement with estimates reported in recent meta studies for maize and rice [16,38].

5. Conclusions

Rice farmers are forced to change traditional rice cultivation from flooded double-rice systems to the new cultivation pattern due to the increasing focus on reducing double carbon emissions. The results showed that CH_4 emissions accounted for 71.83% of GHG emissions from paddy fields. Compared to DR, annual CH_4 and N_2O emissions decreased by 18.12% and 23.66% under Rr, respectively. MR significantly reduced CH_4 emissions while reducing N_2O by 70.31%. The GWP for the different cropping systems was in the rank order of DR > Rr > MR, and it was lower for MR than for DR and Rr by 40.81% and 26.59%, respectively. MR had the highest annual yield and the lowest yield-scaled GWP was 0.39 (t CO_2-eq$\cdot$t^{-1}). Overall, MR can achieve increased production and reduce the greenhouse effect, which is a better planting mode in Central China. In consideration of rice as the first food crop, it is suggested to study the balance relationship between the yield increase and greenhouse gas emissions of ratooning rice in the future. Water and fertilizer management and agronomic measures can be adopted, or suitable planting patterns can be found according to different land environments.

Author Contributions: L.Y., B.Z. and Z.L. conceived and designed the experiments. C.L., J.Z., X.L., J.D., W.Y., Y.Z. and S.L. carried out the experiments and data collection. B.Z. and L.Y. guided the idea of the manuscript. C.L. and L.Y. analyzed the data and drafted the manuscript. All authors have read and agreed to the published version of the manuscript.

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