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Effects of Typical Cropping Patterns of Paddy-Upland Multiple Cropping Rotation on Rice Yield and Greenhouse Gas Emissions

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Abstract: In response to the limitations of traditional double rice cropping models, this study constructed five typical rice planting models in the middle reaches of the Yangtze River, namely "Chinese milk vetch-early rice-late rice (CK/CRR), Chinese milk vetch—early rice—sweet potato | | late soybean (CRI), rapeseed—early rice—late rice (RRR), rapeseed—early rice—sweet potato | | late soybean (RRI) and potato—early rice—late rice (PRR)" to study the annual emission characteristics of greenhouse gases under different planting models. The results showed the following: (1) From the perspective of total yield in two years, the CRI treatment reached its maximum, which was significantly higher than that of other treatments by 9.30~20.29% in 2019 (p < 0.05); in 2020, except for the treatment of RRI, it was significantly higher than other treatments by 20.46~30.23% (p < 0.05). (2) The cumulative emission of CH_4 in the double rice treatment is generally higher than that in paddy-upland rotation treatment, while the cumulative emission of N_2O in the paddy-upland rotation treatment is higher than that in the double rice treatment, but the total amount is much lower than the cumulative emission of CH_4. Therefore, CH_4 emissions from rice fields still occupy most of the GHGs. (3) The global warming potential (GWP) and greenhouse gas emission intensity (GHGI) of different planting patterns in rice fields in 2020 were higher than those in 2019, and the GWP and GHGI of double rice cropping treatment is higher than that of paddy-upland rotation treatments. During the two years, the GWP of CRR treatment reached its maximum and was significantly higher than that of other treatments by 48.28~448.90% and 34.43~278.33% (p < 0.05). The GHGI of CRR was significantly higher than that of CRI and RRI by 3.57~5.4 and 1.4~3.5 times (p < 0.05). Based on the comprehensive performance of greenhouse gas emissions over the two experimental years, RRI and CRI have shown good emission reduction effects, which can significantly reduce greenhouse gas emissions from paddy fields, are conducive to reducing global warming potential and greenhouse gas emission intensity and conform to the development trend of "carbon neutrality". Therefore, considering high-yield, low-temperature chamber gas emissions, the Chinese milk vetch—early rice—sweet potato | | late soybean model performs well and has the best comprehensive benefits. It is of great significance for optimizing the rice field planting mode in the middle reaches of the Yangtze River.

Keywords: multiple cropping; paddy-upland rotation; nitrous oxide; methane; *Oryza sativa* L.; the middle reaches of the Yangtze River

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1. Introduction

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are greenhouse gases (GHGs), which are the main causes of the greenhouse effect [1]. Agricultural production is considered to be one of the main sources of greenhouse gas emissions [2]. Among them, CH_4 and N_2O from paddy fields account for 30% and 11% of global agricultural CH_4 and

N_2O emissions, respectively [3]. Carbon sequestration in farmland soil is considered to be one of the important ways to achieve greenhouse gas emission mitigation [4]. China has a rice planting area of about 26.67 million ha, making it the second largest country in the world in terms of rice planting area. China's paddy soil is considered to have high carbon sequestration potential [5]. Therefore, the key to promoting the development of a sustainable rice system is to maintain the steady growth of the soil carbon pool, achieve greenhouse gas emission reduction, and achieve carbon sequestration and emission reduction while achieving stable or increased rice yields.

Greenhouse gas emissions from paddy fields are mainly affected by rotation systems [6], water management [7], nutrient management [8], straw returning methods [9] and other factors. Some studies have found that compared with the winter fallow field, the accumulated CH_4 emissions of rice–rapeseed rotation and rice–vegetable rotation were significantly reduced, but the accumulated N_2O emissions were significantly higher; the CH_4 emission flux during the drying period of the rice season was significantly lower than that during the flooding period, while the N_2O emission flux peaked during the field drying period, but contributed little to the greenhouse gas warming potential (GWP) during the entire growing season. The total CH_4 emission of the upland crops (rape and cabbage) in cropping season was extremely low, but the total N_2O emission was significantly higher than that during the rice season [10]. Zhou Wei et al. [11] found that, comparing the greenhouse gas emissions of paddy-upland rotation cropping models such as winter fallow–rice, ryegrass–rice, Chinese milk vetch–rice, wheat–rice, and rapeseed–rice, the total greenhouse gas emissions during the rice season were significantly higher than those during the upland cropping season.

The focus of reducing emissions in paddy fields was to reduce CH_4 emissions. Lars et al. [12] found that compared with conventional rotation (winter rape–winter wheat–beet–winter wheat), the N_2O emission of organic crop rotation (clover–winter wheat–winter rye–oat and clover–winter wheat–winter rye–spring pea–winter rye) decreased by 0.7 $t \cdot ha^{-1} \cdot a^{-1}$, which reduced the N_2O emission potential. However, there are few other studies on the greenhouse gas emissions of typical planting patterns in the middle reaches of the Yangtze River.

We hypothesize that paddy-upland multiple cropping rotation can contribute to the increase in rice yield and reduce greenhouse gas emissions. Therefore, the objectives of the research are as follows: (1) To clarify the greenhouse gas emission mitigation effect of different planting patterns of paddy-upland multiple cropping rotation. (2) To comprehensively analyze the greenhouse gas emission law to reduce the greenhouse gas emissions of the paddy field rotation system. (3) To clarify the effect of different planting patterns of paddy-upland multiple cropping rotation on rice yield. The research will be of great significance to continuing to optimize the rotation mode in the middle reaches of the Yangtze River.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted in the rice experimental field (28°46′ N, 115°55′ E) of Jiangxi Agricultural University Science and Technology Park from September 2018 to December 2020. The experimental site belongs to a subtropical monsoon humid climate, with rain and heat in the same period and sufficient light. The average annual total solar radiation was 6330.25 $MJ \cdot m^{-2}$, and the light distribution was basically synchronized with the rice growing season. The daily accumulated temperature of $\geq$0 °C was 6997.7 °C, the effective accumulated temperature of $\geq$10 °C was 4087.4 °C, and the average annual precipitation was 1921.4 mm. The tested soil was red clay. The basic chemical properties of the soil in the experimental field were as follows: pH value, 5.22; organic matter content, 28.56 $g \cdot kg^{-1}$; total nitrogen content, 1.79 $g \cdot kg^{-1}$; alkali-hydrolyzed nitrogen, 151.8 $mg \cdot kg^{-1}$; available phosphorus, 27.48 $mg \cdot kg^{-1}$; and available potassium, 103.74 $mg \cdot kg^{-1}$. The daily average temperature and precipitation changes (from the climate station of Jiangxi Agricultural University Science Park) during the test period are shown in Figure 1.

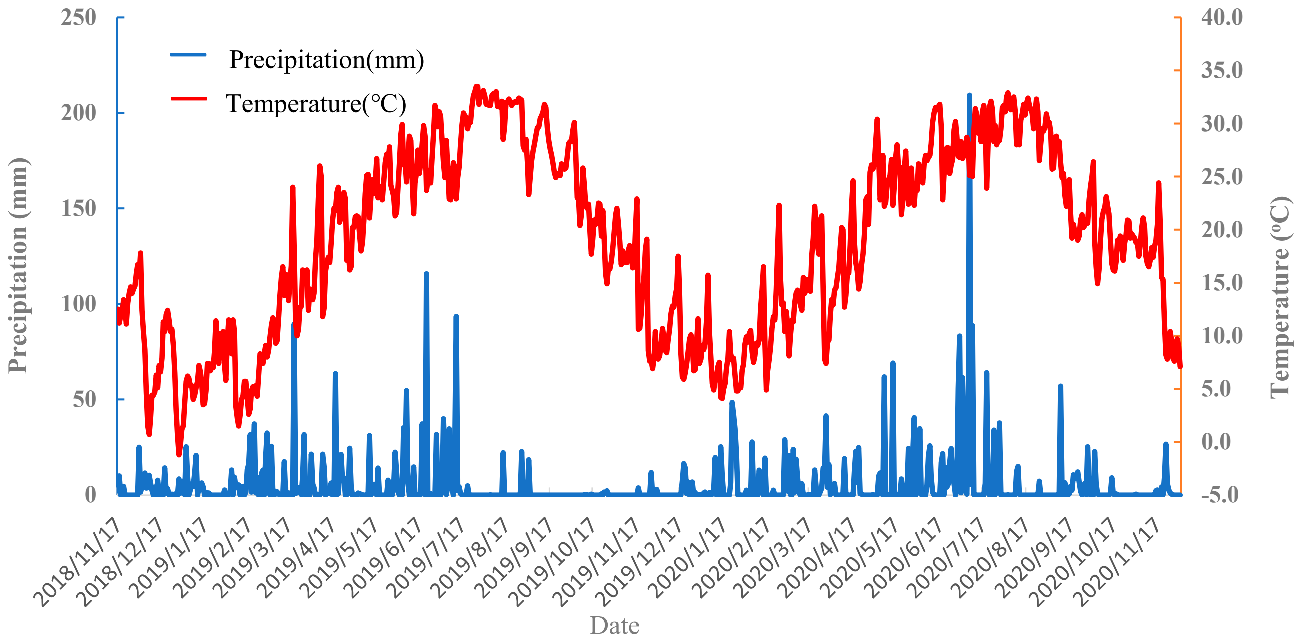

Figure 1. Mean daily temperature and precipitation during the test period. From April to October, with simultaneous high temperature and rainy weather, the region was very suitable for double rice (early rice and late rice) growth. The temperature showed the same tendency, but there was high rainfall in July 2020.

2.2. Experimental Design

In total, five treatments were designed in the experiment, with "Chinese milk vetch-double cropping rice" as the control, and four different planting patterns were set up (Table 1). Each treatment was repeated three times, with a total of 15 plots. The plot area was 33 m^2, and the plots were separated by a 30 cm high cement ridge. Chinese milk vetch and rape were evenly sown and potato slices were soaked, planted and covered with straw. The sowing rate of Chinese milk vetch and rape were 37.5 $kg \cdot ha^{-1}$ and 15 $kg \cdot ha^{-1}$, respectively, and potato was transplanted; the planting density of potato was 73,000 $plants \cdot ha^{-1}$. All winter crop straws were incorporated into the field 15 days before rice transplanting, and the amount of winter crop straw returning is shown in Table 2. Rice seedlings were raised for 25~30 days before transplanting. When transplanting, the row spacing of rice was 0.2 m and the plant spacing was 0.2 m. Sweet potato and late soybean were planted via furrowing and ridging. The ridge width was 1.2 m and the ridge height was 0.35 m. Each ridge was planted with 4 rows of soybeans, 1 row of sweet potato, 2 rows of soybeans on both sides of sweet potato, a 0.3 m row spacing, 0.25 m plant spacing, 0.2 m row spacing and 0.2 m plant spacing between soybeans. The specific planting time, fertilization amount and fertilization method are shown in Table 3, and the other form of field management was the same as that used in general field practice.

Table 1. Details of experimental treatments used in study.

Treatment	Cropping Pattern
CRR (CK)	Chinese milk vetch-early rice-late rice
CRI	Chinese milk vetch-early rice-sweet potato ∣∣ late soybean
RRR	Rape-early rice-late rice
RRI	Rape-early rice-sweet potato ∣∣ late soybean
PRR	Potato-early rice-late rice

Note: "-" represents continuous planting. "∣∣" represents intercropping. In this paper, "Chinese milk vetch-early rice-late rice, Rape-early rice-late rice, Potato- early rice-late rice" are referred to as a "double cropping rice" pattern. "Chinese milk vetch-early rice-sweet potato ∣∣ late soybean, Rape- early rice-sweet potato ∣∣ late soybean" are collectively referred to as a "early water-late drought" pattern in the middle reaches of the Yangtze River in China.

Table 2. Quantity of winter crop straw (kg·ha^{-1}) returned to field during both years of study.

Treatments	Crops	2019		2020	
		Fresh Weight	Dry Weight	Fresh Weight	Dry Weight
CRR(CK)	Chinese milk vetch	31,527.9 b	6107.53 ab	33,528.87 b	6405.92 ab
CRI	Chinese milk vetch	34,651.37 a	6583.76 a	36,690.28 a	6812.34 a
RRR	Rape	20,611.89 d	5173.58 c	23,148.61 c	5902.90 c
RRI	rape	23,169.33 c	5757.57 b	24,327.47 c	6348.51 b
PRR	Potato	18,435.17 d	3746.03 d	20,314.5 d	4022.27 d

Note: Different small letters in the same column indicate significant differences among treatments ($p < 0.05$).

Table 3. Details of field management practices performed during study.

Crop	Variety	Sowing or Transplanting Date, Harvest Date	Cropping Pattern	Fertilizing Amount
Chinese milk vetch	Yujiang big leaf seed	30 September 2018–7 April 2019, 30 September 2019.9.30–7 April 2020	broadcast sowing	calcium magnesium phosphate 45 kg·ha^{-1}
rape	Deyou 558	8 November 2018–7 April 2019, 6 November 2019–7 April 2020	broadcast sowing	N 63.75 kg·ha^{-1}, P_2O_5 45 kg·ha^{-1}, K_2O 225 kg·ha^{-1}
potato	Dongnong 303	26 November 2018–10 April 2019, 28 November 2019–10 April 2020	drill seeding	N 63.75 kg·ha^{-1}, P_2O_5 45 kg·ha^{-1}, K_2O 225 kg·ha^{-1}
soybean	Kuixian II	1 August 2019–25 October 2019, 18 August 2020–18 August 2020	hole seeding	N 150 kg·ha^{-1}, P_2O_5 150 kg·ha^{-1}, K_2O 375 kg·ha^{-1}
sweet potato	Guangshu 87	1 August 2019–31 October 2019, 18 August 2020–17 November 2020	drill seeding	N 80 kg·ha^{-1}, P_2O_5 375 kg·ha^{-1}, K_2O 80 kg·ha^{-1}
early rice	Zhongjiazao 17	26 April 2019–24 July 2019, 4 May 2020–30 July 2020	transplanting	N 180 kg·ha^{-1}, P_2O_5 90 kg·ha^{-1}, K_2O 120 kg·ha^{-1}
late rice	Tianyou Huazhan	3 August 2019–30 October 2019, 2 August 2020–3 December 2020	transplanting	N 180 kg·ha^{-1}, P_2O_5 90 kg·ha^{-1}, K_2O 120 kg·ha^{-1}

2.3. Determination Items and Methods

2.3.1. Greenhouse Gas Emissions Measurement and Calculation

Greenhouse gas emissions were measured via static chamber–gas chromatography. The cross-sectional area of the static box bottom was 0.5 m × 0.5 m. The sampling box was made of stainless steel, and the height of the box increased with the height of the rice. A small electric fan was installed in the sampling box to mix the gas in the box. There were three elastic valves on the top of the box, which were the fan battery interface, the thermometer socket and the vent, respectively. The outside was covered with a white sponge cover to prevent excessive temperature changes inside the box caused by sunlight exposure. Before sampling, the sampling box was placed on the pre-buried base. During sampling, a 100 mL syringe was used for pumping back and forth 5–10 times to mix the gas, and then a 50 mL gas sample was taken into the air bag. Four continuous samples were collected at 0, 10, 20 and 30 min after the box was sealed, and the temperature in the box and the height from the base to the water surface in the box were recorded. The concentrations of CH_4 and N_2O were determined via Agilent gas chromatography, A7890 b, within three days in the Key Laboratory of Crop Physiology, Ecology and Genetic Breeding of Jiangxi Agricultural University.

Greenhouse gas emission flux was calculated using the following formula:

$$F = \rho \times H \times \Delta C/\Delta t \times 273/(273 + T)$$

F is the greenhouse gas emission flux, unit: kg·m^{-2}·h^{-1}; ρ is the density of greenhouse gases in the standard state, unit: kg·m^{-3}; H is the height of closed box, unit: m; $\Delta C/\Delta T$ is the change in greenhouse gas concentration in a sealed box per unit time, unit: h^{-1}, and T is the average temperature in the sealed box, unit: °C [13]. The emission fluxes of two greenhouse gases were calculated according to the relationship between gas concentration and time, and then the total greenhouse gas emissions in the winter crop growing season and rice growing season were calculated [13].

In terms of the global warming effect, the comprehensive warming effect of CH_4 and N_2O on the 100-year scale was calculated using the comprehensive warming potential recommended by the IPCC. The emissions of CH_4 and N_2O were multiplied by 25 and 298, respectively, and then added to obtain the CO_2 emission equivalent (CO_2-eq), which was the comprehensive warming potential (GWP, unit: $kg \cdot ha^{-1}$) of the two greenhouse gases. The calculation formula is as follows [14]:

$$GWP = fCH_4 \times 25 + fN_2O \times 298$$

The comprehensive emission intensity of greenhouse gases was calculated in accordance with the formula [15] (GHGI, unit: CO_2 $kg \cdot kg^{-1}$):

$$GHGI = GWP/Y$$

Y is biomass.

2.3.2. Yield and Biomass Measurement

In terms of Chinese milk vetch and rapeseed, during the mature period, samples were taken using the five-point method, with one square meter of fresh weight taken from each plot. The average value was taken to calculate the actual yield. In terms of potato, 10 plants (including plants and tubers) were selected at maturity and weighed for determining the fresh weight to calculate the actual yield.

During the mature period, rice seeds were tested, and the yields of rice and upland crops were measured in each plot. The yields of potatoes, sweet potatoes, and soybeans were calculated based on their economic yield, and the yields were compared and analyzed using the conversion standard for raw grains. All the straw and grains were weighed during the maturity period of all crops, and some fresh samples were taken to be weighed. They were combusted in an oven at 105 °C for 30 min, and then dried at 80 °C to a constant weight before weighing to calculate the moisture content.

2.4. Data Analysis

Microsoft Excel 2019 was used to process data. SPSS20.0 system software was used for data processing and statistical analysis. Least significant difference (LSD) was used to compare the difference in sample averages, and Origin 8.5 software was used for making figures.

3. Results

3.1. Effects of Different Planting Patterns on Rice Yield in Paddy Field

From Table 4, it can be seen that in 2019, the early rice yield of PRR was the highest, reaching 8086.87 $kg \cdot ha^{-1}$. Except for the control treatment, CRR, the early rice yield of PRR was significantly higher than that of other treatments by 17.32% to 36.34% ($p < 0.05$); in 2020, the early rice yield of CRI was the highest, being significantly higher than that of RRR by 17.33% ($p < 0.05$). These show that planting winter crops such as potatoes and Chinese milk vetch can help increase the yield of early rice. The tendency of the yield of late rice was relatively consistent over the past two years, with the highest yield being that of CRI among all treatments. Except for RRI, the yield of late rice with CRI was significantly higher than that with the other three treatments by 27.76–35.13% and 34.80–40.27% ($p < 0.05$). This may be have been due to the balanced utilization of nutrients when planting upland crops in the late rice season, which therefore improved crop yield.

From the perspective of total yield in two years, the yield of CRI reached its maximum among all treatments, being significantly higher than that of other treatments by 9.30–20.29% in 2019 ($p < 0.05$); in 2020, except for the RRI treatment, the yield with CRI was significantly higher than that with other treatments by 20.46–30.23% ($p < 0.05$). Therefore, the winter planting of Chinese milk vetch and potatoes had a certain yield increase effect on early rice. The early water cropping–late upland cropping model (CRI and RRI) could achieve higher and more stable yields in the late rice season, and the annual total yield was more stable.

Table 4. Effect of different cropping patters on rice yield (kg·ha^{-1}).

Year	Treatment	Early Rice Yield	Late Rice Yield	Total Yield
2019	CRR(CK)	7559.6 ± 243.09 ab	10,176.67 ± 141.60 b	17,736.26 ± 362.95 c
	CRI	6892.93 ± 240.25 bc	13,752.37 ± 465.95 a	20,645.30 ± 342.01 a
	RRR	6512.12 ± 155.71 bc	10,650.33 ± 140.94 b	17,162.45 ± 383.28 c
	RRI	5931.31 ± 624.74 c	12,957.64 ± 468.63 a	18,888.95 ± 381.63 b
	PRR	8086.87 ± 187.3 a	10,763.44 ± 415.51 b	18,850.31 ± 421.75 b
2020	CRR(CK)	7467.89 ± 327.93 ab	8702.02 ± 207.31 b	16,169.91 ± 437.29 b
	CRI	7832.57 ± 494.70 a	12,026.60 ± 366.79 a	19,859.18 ± 452.29 a
	RRR	6675.84 ± 322.59 b	8573.74 ± 300.30 b	15,249.58 ± 292.04 b
	RRI	7362.82 ± 611.19 ab	11,559.51 ± 453.78 a	18,922.33 ± 778.40 a
	PRR	7564.94 ± 346.86 ab	8921.62 ± 239.71 b	16,486.15 ± 522.88 b

Note: in terms of the price of winter crops; the yield of late rice treated with CRI and RRI is converted from the yield of dry crops into the yield of late rice in accordance to the price ratio of the current season. In 2019 and 2020, the purchase price of late rice was 2.60 and 2.54 yuan·kg^{-1}, the price of late soybean was 4.75 and 5.04 yuan·kg^{-1}, and the price of sweet potato was 1.35 and 1.50 yuan·kg^{-1}. Different small letters in the same column indicate significant differences among treatments ($p < 0.05$).

3.2. Effects of Different Cropping Patterns on Greenhouse Gas Emissions in Paddy Field

3.2.1. Annual Characteristics of CH_4 Emissions from Paddy Field

Figures 2 and 3 show that the CH_4 emission flux of different planting patterns varies greatly in different periods, and is higher in the rice season and lower in the winter green manure period. The CH_4 emissions showed the same trend in the two years. The CH_4 emission flux of the early water cropping–late upland cropping model (CRI and RRI) was much lower than that of the double-cropping rice treatment (CRR, RRR, and PRR), and there was no obvious emission peak. In the winter cropping season of 2019 and 2020, different planting patterns had less CH_4 emissions. On 12 January 2019, CRR had a peak emission of 0.69 mg·m^{-2}·h^{-1}, and PRR had the peak emission of 0.94 mg·m^{-2}·h^{-1} on 29 December 2020. The CH_4 emission flux of each treatment increased continuously after early rice transplanting. In the early stage of early rice growth, the emission flux was generally low. The emission fluxes of CRR, RRR and PRR were higher in 2019, and the emission fluxes of CRR, CRI and RRR were higher in 2020. The first peak appeared after transplanting, and the CRR treatment reached the highest, at 18.25 mg·m^{-2}·h^{-1} and 28.12 mg·m^{-2}·h^{-1}, respectively. On 27 May, it was at the tillering stage of rice. The decomposition of tillering fertilizer made the CH_4 emission reach the second peak, and the CRR reached the highest, at 28.77 mg·m^{-2}·h^{-1} and 27.39 mg·m^{-2}·h^{-1}, respectively.

In the early rice season of 2020, the third peak appeared on July 5 with the peak value of 21.72 mg·m^{-2}·h^{-1} of the CRR treatment, and then entered the rice maturity stage, the field water holding capacity was small, and the CH_4 emission showed a downward trend. After the early rice harvest, the CH_4 emission was close to that at the pre-transplanting level. Methane emissions increased rapidly after the transplanting of late rice. The trends of CRR, RRR and PRR were basically the same in double-cropping rice treatment, and basically there was no emissions from CRI and RRI in the early water cropping and late upland cropping treatment.

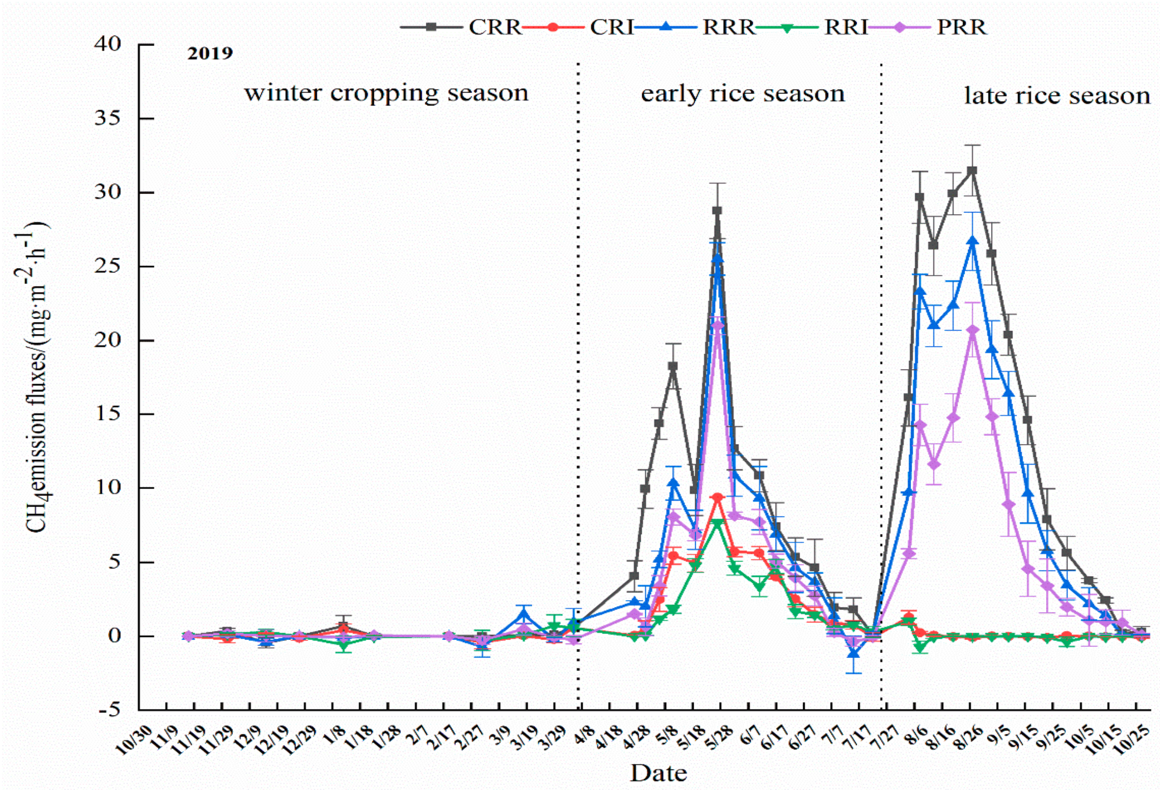

Figure 2. Dynamic changes in CH_4 emission flux under different cropping patterns in 2019. Note: the data in Figures 2–5 begin with the winter crop in 2018 and end in late rice in 2019.

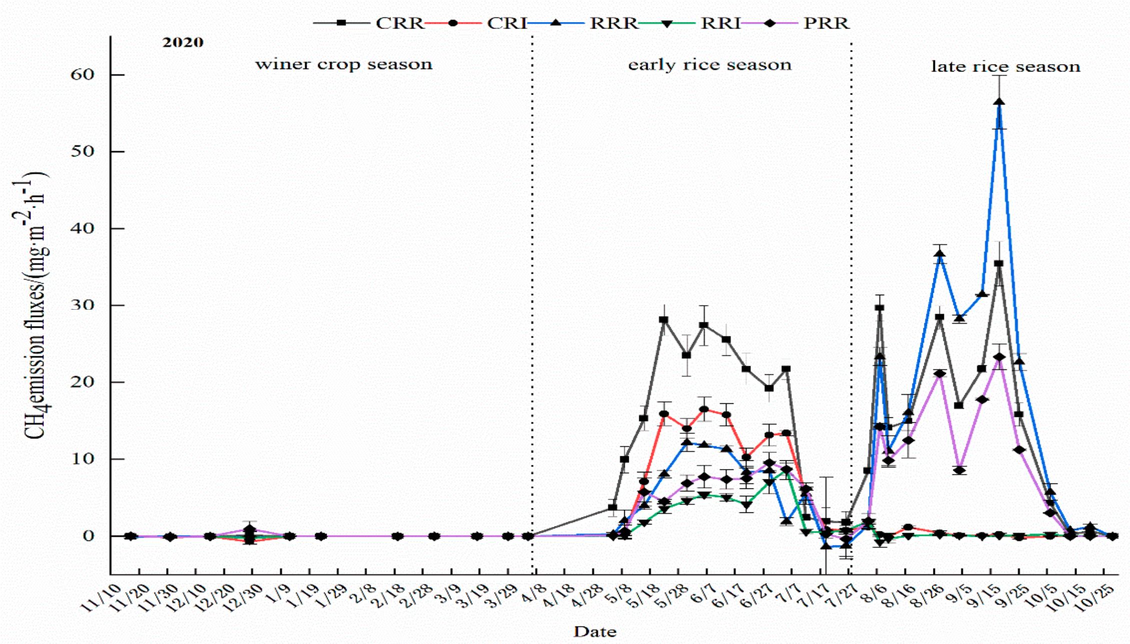

Figure 3. Dynamic changes in CH_4 emission flux under different cropping patterns in 2020.

The trend of CH_4 emissions from CRR, RRR and PRR in 2019 was basically the same as that of early rice. The emission peaks were reached on 8 August, 20 August and 27 August, respectively, and the peaks were 29.67 $mg{\cdot}m^{-2}{\cdot}h^{-1}$, 29.93 $mg{\cdot}m^{-2}{\cdot}h^{-1}$ and 31.84 $mg{\cdot}m^{-2}{\cdot}h^{-1}$, respectively. The three peaks in 2020 were 29.67 $mg{\cdot}m^{-2}{\cdot}h^{-1}$ for CRR on August 7, 36.67 $mg{\cdot}m^{-2}{\cdot}h^{-1}$ for RRR on August 28, and 56.46 $mg{\cdot}m^{-2}{\cdot}h^{-1}$ for RRR on September 18. In the two-year late rice season, the CH_4 emissions of CRI and RRI were lower, ranging from−0.74~0.65 mg·m^{-2}·h^{-1} to−0.32~1.94 mg·m^{-2}·h^{-1}. The reason may be that the field capacity of upland crops (sweet potato and late soybean) is low, and the activity of methanogens is weak, so the emissions are low. The two-year results showed that CH_4 emissions from paddy soils under the double-cropping rice treatment (CRR, RRR, and PRR) were dominant, and the early water cropping and late upland cropping treatment (CRI and RRI) significantly reduced CH_4 emissions in the late rice season without significant emission peaks.

3.2.2. Annual Characteristics of N_2O Emissions from Paddy Field

It can be seen from Figures 4 and 5 that the N_2O emissions varied greatly in different periods. The emission flux was high in the rice season, and lower in the winter green manure period. The N_2O emission flux in the winter green manure growing season was much lower than that in the rice season. The N_2O emission flux of the early water cropping and late upland cropping treatment (CRI and RRI) was much higher than that of the double rice cropping treatment (CRR, RRR, and PRR).

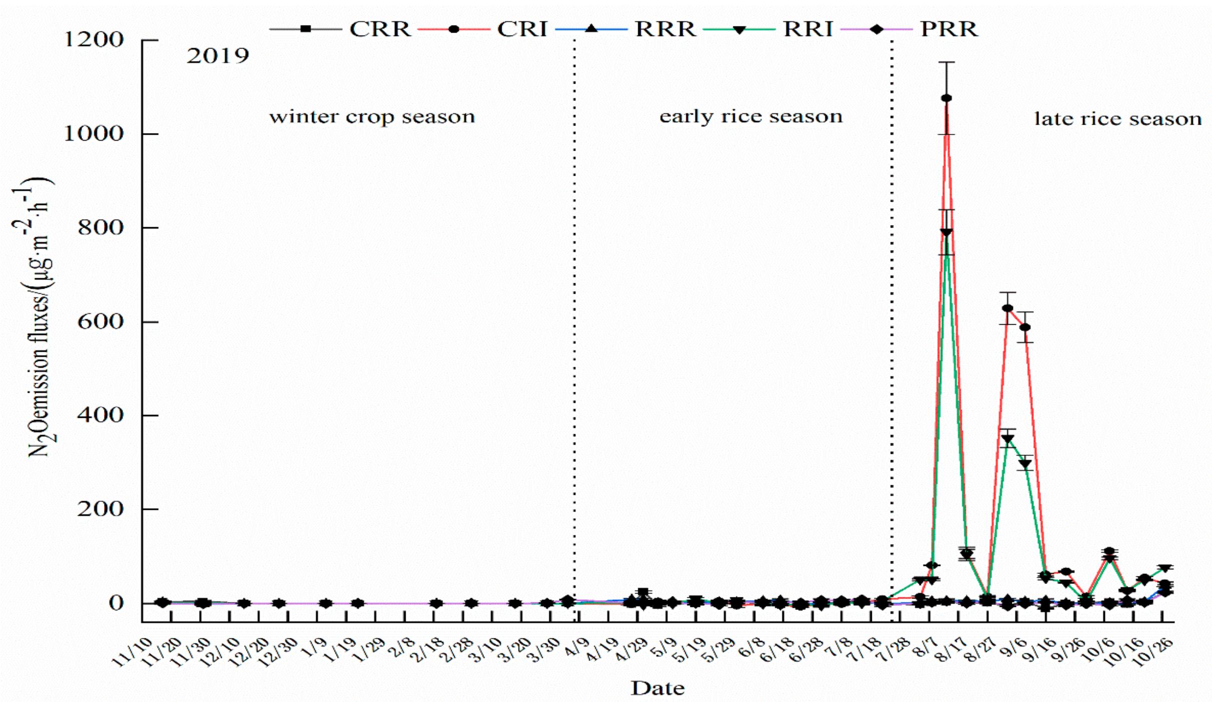

Figure 4. Dynamic changes in N_2O emission flux under different cropping patterns in 2019.

From the perspective of the winter season, due to the low temperature, N_2O emissions were lower in 2019, and the emission flux was − 2.13~6.97 μg·m^{-2}·h^{-1}. In 2020, the N_2O emissions in the winter cropping season increased. On 29 December, the N_2O emissions of the PRR treatment was 306.63 μg·m^{-2}·h^{-1}, and the peak emission of RRR was 213.94 μg·m^{-2}·h^{-1}.

During the two years, the N_2O emissions in the early rice season were at a low level. Due to the flooded state of the paddy field for most of the period, the N_2O emissions of each treatment were lower, with only a small peak. The peak in 2019 was for the CRR treatment, and the emission flux was 24.43 μg·m^{-2}·h^{-1}. The peak in 2020 was for the RRR treatment, and the peak was 59.38 μg·m^{-2}·h^{-1}. From the perspective of the late rice season, there were three emission peaks in 2019 and 2020, and among the emission from all the treatments CRI ranked the first. In 2019, the emission peaks appeared on 13 August (1076.42 μg·m^{-2}·h^{-1}), 3 September (629.19 μg·m^{-2}·h^{-1}) and 13 September (588.25 μg·m^{-2}·h^{-1}), respectively. The emission flux of early water cropping and late upland cropping treatments (CRI and RRI) was higher, and there was little emission in the double rice cropping treatment.

The emission peaks in 2020 appeared on 28 August (1005.81 μg·m^{-2}·h^{-1}), 4 September (760.52 μg·m^{-2}·h^{-1}) and 25 September (774.40 μg·m^{-2}·h^{-1}), respectively, which may have been due to fertilization and temperature.

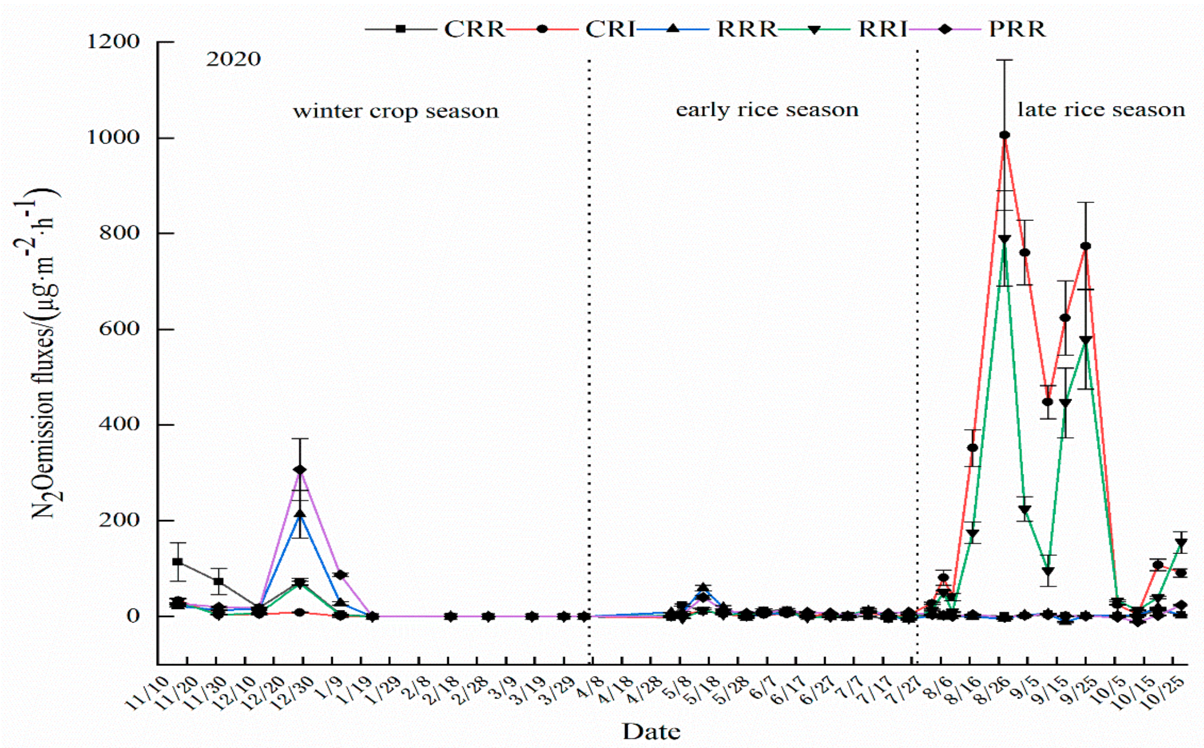

Figure 5. Dynamic changes of N_2O emission flux under different cropping patterns.

In summary, the N_2O emission flux of early water cropping and late upland cropping treatments (CRI and RRI) was much higher than that of the double rice cropping treatment (CRR, RRR, and PRR). There were three emission peaks in the late rice season in both years, and the emission flux in 2020 was higher than that in 2019.

3.2.3. Cumulative Emissions of Greenhouse Gases from Paddy Fields, Global Warming Potential and Emission Intensity

The cumulative emissions of CH_4 in the double-cropping rice treatment were higher than those in the early water and late drought treatment (Table 5). The cumulative emissions of N_2O in the early water cropping and late upland cropping treatments were higher than those of the double-cropping rice treatments, but the total amount was far lower than that of the cumulative emissions of CH_4. Therefore, CH_4 emissions from paddy fields still dominated.

Table 5. Cumulative emissions of CH_4 and N_2O for different cropping patterns (kg·ha^{-1}).

Year	Treatment	CH_4 Cumulative Emissions					N_2O Cumulative Emissions				
		Winter Crop Season	Early Rice Season	Late Rice Season	Total	Average	Winter Crop Season	Early Rice Season	Late Rice Season	Total	Average
2019	CRR(CK)	2.82 ± 1.85 a	197.94 ± 48.24 a	303.43 ± 42.71 a	504.19 ± 92.39 a	168.06 ± 21.78 a	0.22 ± 0.37 a	−0.27 ± 0.12 a	0.06 ± 0.11 b	0.02 ± 0.41 b	0.00 ± 0.10 b
	CRI	−0.41 ± 2.27 ab	82.20 ± 21.37 b	0.41 ± 0.40 d	82.19 ± 23.60 d	27.40 ± 5.56 c	−0.03 ± 0.47 a	0.02 ± 0.16 a	4.34 ± 1.74 a	4.33 ± 1.35 a	1.44 ± 0.32 a
	RRR	−8.06 ± 6.31 b	113.10 ± 18.67 b	231.53 ± 24.01 b	336.56 ± 35.87 b	112.19 ± 8.45 b	−0.02 ± 0.19 a	0.20 ± 0.06 a	0.12 ± 0.10 b	0.30 ± 0.30 b	0.10 ± 0.07 b
	RRI	0.59 ± 4.13 ab	61.00 ± 4.84 b	−1.62 ± 0.91 d	59.97 ± 7.01 d	19.99 ± 1.65 c	0.06 ± 0.05 a	0.15 ± 0.02 a	2.51 ± 1.26 a	2.73 ± 1.09 a	0.91 ± 0.26 a
	PRR	1.02 ± 2.07 a	89.69 ± 7.19 b	130.45 ± 52.25 c	221.16 ± 54.65 c	73.72 ± 12.88 b	0.07 ± 0.25 a	0.42 ± 0.08 a	0.04 ± 0.02 b	0.53 ± 0.15 b	0.18 ± 0.04 b
2020	CRR(CK)	0.15 ± 1.26 a	323.37 ± 29.40 a	193.70 ± 4.86 b	517.21 ± 30.91 a	172.40 ± 7.29 a	0.78 ± 0.03 b	0.61 ± 0.24 b	0.05 ± 0.00 c	1.43 ± 0.24 c	0.48 ± 0.05 e
	CRI	−2.83 ± 1.37 a	184.15 ± 11.97 b	4.84 ± 0.61 d	186.16 ± 12.59 d	62.06 ± 2.97 d	0.12 ± 0.01 c	0.70 ± 0.22 b	6.00 ± 0.01 a	6.82 ± 0.22 a	2.28 ± 0.05 a
	RRR	−1.03 ± 4.14 a	116.74 ± 6.13 c	252.65 ± 6.21 a	368.37 ± 7.10 b	122.79 ± 1.67 b	0.93 ± 0.10 b	1.47 ± 0.29 a	0.04 ± 0.00 c	2.44 ± 0.31 c	0.81 ± 0.07 d
	RRI	−1.23 ± 4.15 a	68.69 ± 3.60 d	1.19 ± 1.94 d	68.65 ± 15.27 e	22.88 ± 3.6 e	0.33 ± 0.04 c	0.90 ± 0.04 b	4.85 ± 0.06 b	6.09 ± 0.19 a	2.03 ± 0.05 b
	PRR	2.61 ± 4.83 a	106.24 ± 5.31 c	141.44 ± 8.95 c	250.29 ± 27.44 c	83.43 ± 6.47 c	1.46 ± 0.17 a	1.87 ± 0.18 a	0.03 ± 0.00 c	3.36 ± 0.21 b	1.12 ± 0.05 c

Note: Different small letters in the same column indicate significant differences among treatments (p < 0.05).

The cumulative CH_4 emissions for CRR during the winter cropping season, early rice season and late rice season in 2019 and early rice season in 2020 were the highest, except for those of the winter cropping season in 2019, which were significantly different from those of other treatments ($p < 0.05$). From the perspective of annual cumulative emissions, the emissions for each treatment in 2020 were higher than those in 2019. The cumulative emissions of CRR, RRR and PRR in 2019 and 2020 were significantly higher than those of the lowest RRI treatment, with increases of 268.78~740.72% and 264.59~653.40%, respectively ($p < 0.05$).

As for the cumulative emissions of N_2O, there was no significant difference between the treatments in the winter cropping season and early rice season in 2019 ($p > 0.05$). In 2020, the cumulative emissions for PRR in the winter cropping season and early rice season were the largest, and they were significantly higher than those of other treatments by 56.99−1116.67% and 107.78–206.56% (except RRR) ($p < 0.05$); in the late rice season, the cumulative N_2O emissions for CRI and RRI in the paddy-upland multiple cropping treatment were significantly higher than those for the CRR, RRR and RRI in the double rice cropping treatment. The cumulative emissions for CRI were the highest in both years, and the cumulative emissions of CRI and RRI were significantly higher than those of other treatments by 35.17~107.5 times and 19.92~61.75 times ($p < 0.05$). The annual cumulative emissions were consistent with the trend of the late rice season, and the cumulative emissions for CRI were the highest in both years. In summary, the winter planting of Chinese milk vetch and rape increased CH_4 emissions in the early rice season. The upland cropping of the early water cropping and late upland cropping treatments, CRI and RRI, in the late rice season could significantly reduce CH_4 emissions, but increased N_2O emissions in the late rice season.

It can be seen from Table 6 that the global warming potential (GWP) of different planting patterns in paddy fields in 2020 was higher than that in 2019. In both years, CRR had the maximum GWP, which was significantly higher than that of other treatments by 48.28–448.90% and 34.43–278.33% ($p < 0.05$). The GWP of CRR, RRR and PRR in the double rice cropping treatment was significantly higher than that of CRI and RRI in the early water and late upland cropping treatment. From the perspective of the contribution rate, CH_4 played a major role in the contribution of the global warming potential, which was significantly higher than that of N_2O. The contribution rate of CH_4 was 61.42–99.96% in 2019 and decreased to 48.61–96.81% in 2020, and the contribution rate of the double-cropping rice treatment was greater than that of the early water and late upland cropping treatment. The contribution of N_2O to the global warming potential was small, accounting for 0.04–38.58% in 2019, and increased in 2020. The contribution rate of the early water and late upland cropping treatment was greater than that of the double rice cropping treatment. The double rice cropping treatment (CRR, RRR, and PRR) significantly increased the greenhouse gas emission intensity (GHGI), while the emission intensity of the early water and late upland cropping treatment (CRI and RRI) was lower.

During the two years, the GHGI of CRR was significantly higher, by 3.57–5.4 times and 1.4–3.5 times, than that of CRI and RRI ($p < 0.05$). The emission intensity of each treatment in 2020 was higher than that in 2019, while the increase for RRI was the smallest. Therefore, based on the performance of greenhouse gas emissions in the two years, the treatments RRI and CRI have better emission reduction effects, and the treatment RRI has the best performance, indicating that winter rapeseed and paddy-upland rotation are conducive to reducing greenhouse gas emissions.

Table 6. Global warming potential (GWP) and emission intensity of greenhouse gases (GHGI) for different cropping patterns.

Year	Treatment	GWP /(CO_2 kg·ha^{-1})			Contribution Rate/%		Biomass (kg·ha^{-1})	GHGI (CO_2 kg·kg^{-1})
		CH_4	N_2O	Total	CH_4	N_2O		
2019	CRR (CK)	12,604.60 ± 1633.29 a	4.66 ± 0.58 b	12,609.21 ± 1603.68 a	99.96	0.04	39,458.42 b	0.32 ± 0.08 a
	CRI	2054.71 ± 417.11 c	1290.75 ± 284.81 a	3345.46 ± 198.34 d	61.42	38.58	45,773.38 a	0.07 ± 0.01 cd
	RRR	8414.07 ± 634.11 b	89.66 ± 23.37 b	8503.73 ± 696.01 b	98.95	1.05	39,761.99 b	0.21 ± 0.02 b
	RRI	1499.28 ± 123.89 c	814.10 ± 180.61 a	2314.04 ± 258.64 d	64.79	35.21	43,780.54 a	0.05 ± 0.01 d
	PRR	5529.07 ± 966.09 b	158.10 ± 31.27 b	5687.17 ± 936.37 bc	97.22	2.78	40,884.73 b	0.14 ± 0.02 bc
2020	CRR(CK)	12,930.21 ± 946.30 a	426.27 ± 50.73 e	13,356.48 ± 547.03 a	96.81	3.19	36,720.24 b	0.36 ± 0.04 a
	CRI	4654.07 ± 222.53 d	2033.10 ± 47.16 a	6687.17 ± 194.79 c	69.60	30.40	44,262.04 a	0.15 ± 0.01 d
	RRR	9209.28 ± 217.38 b	726.04 ± 64.37 d	9935.31 ± 141.22 b	92.69	7.31	36,945.74 b	0.27 ± 0.01 b
	RRI	1716.21 ± 169.91 e	1814.14 ± 39.99 b	3530.34 ± 296.50 d	48.61	51.39	44,096.37 a	0.08 ± 0.01 e
	PRR	6257.13 ± 285.10 c	1001.72 ± 44.57 c	7258.85 ± 445.27 c	86.20	13.80	37,310.48 b	0.19 ± 0.01 c

Note: Different small letters in the same column indicate significant differences among treatments ($p < 0.05$).

4. Discussion

4.1. Effects of Different Planting Patterns on Greenhouse Gas Emissions in Paddy Fields

Planting patterns, rice growth periods, water and fertilizer management and other factors can affect the emissions of CH_4 in paddy fields, and the emission peak is mainly in the tillering stage and booting stage of rice [16–18]. The results of this experiment showed that the total amount of CH_4 emissions from the Chinese milk vetch–early rice–late rice model (CRR) were the highest, and significantly higher than those for other treatments. The reason was that the returning of Chinese milk vetch as green manure increased CH_4 emissions from paddy fields [19]. The CH_4 emissions of the double rice cropping treatment (CRR, RRR, and PRR) were dominant, and there were three emission peaks at the tillering stage and booting stage of early and late rice, respectively. There were three emission peaks in the early rice season under early water and late drought treatment (CRI and RRI). The reasons for the peak value may be as follows: Firstly, in the tillering stage, the decomposition of the base fertilizer and tillering fertilizer was conducive to the growth of rice and its roots, and the increase in root exudates provided a sufficient substrate for the production of CH_4 [20]. Secondly, the temperature during the tillering and booting stages was relatively high, leading to the vigorous growth of rice and the development of its aerenchyma, which enhanced the ability of the rice plants to emit CH_4. Thirdly, the decomposition and fermentation of straw and dead branches and leaves of rice increased the methanogenic matrix, so the peak of CH_4 emissions appeared in the tillering stage. Fourthly, the application of nitrogen fertilizer increased the concentration of ammonium nitrogen in the soil. Ammonium nitrogen had an inhibitory and competitive effect on the oxidation of CH_4, which indirectly promoted the emission of CH_4 [17,21]. Within two years, the CH_4 emission of upland crops (sweet potato || late soybean) planted in the late rice season of CRI and RRI was basically zero. The reasons may be as follows: First, dry land soil was exposed to the air, resulting in low soil moisture content and the increased activity of methane-oxidizing bacteria. Methane-oxidizing bacteria oxidize CH_4 into CO_2, thereby reducing CH_4 emissions. Second, the amount of fertilizer (nitrogen fertilizer) applied to dry crops was reduced, which reduced the concentration of ammonium nitrogen in the soil and may have indirectly led to a reduction in CH_4 emissions [22,23]. The general rule of CH_4 emissions during the rice season in paddy fields is that they increase first and then decrease. The peak of CH_4 emissions occurs in the early growth stage, and the soil CH_4 emissions are relatively low from the stage of exposing the paddy field to sun to the rice maturity stage. The reason for the CH_4 emission pattern in this experiment may be related to the same water management mode when planting early and late rice [24–29].

The emission of N_2O in paddy fields is greatly affected by factors such as water and fertilizer management and planting patterns [30,31]. This study showed that under different planting patterns, the total amount of N_2O emissions was higher in the treatments with CRI and RRI, and were significantly higher than those of other treatments. The reason may be that the upland crops (sweet potato and late soybean) were planted in the late rice season, and the soil moisture content was low. Irrigation and precipitation caused dry and wet soil alternation, resulting in more oxygen entering the soil, changing the redox state of the soil, thereby promoting N_2O emissions [32]. In addition, when planting upland crops, there is no tillage, which reduces soil disturbance and reduces soil permeability, thereby creating a better anaerobic environment and promoting denitrification [33]. Moreover, the organic carbon content of CRI and RRI treatments is higher, which is more conducive to the production of N_2O in surface soil [34]. In two years, there were less N_2O emissions for CRR, RRR and PRR in late rice season, mainly because the soil had been submerged for a long time, resulting in a decrease in soil EH, and the strong anaerobic conditions promoted the denitrification process, which completely reduced NO_3^- to N_2 and inhibited N_2O emissions [35]. The soil N_2O emissions of the early water and late upland cropping treatments (CRI and RRI) in the late rice season of the two years were dominant, and there were three emission peaks. The reasons for the peaks may be as follows: First, the application of fertilizers provides material and energy for nitrification and denitrification, promotes the process of nitrification and denitrification [36], and increases soil N_2O emissions. Second, with the increase in temperature, the surface temperature of soil increases, microbial activity increases, and the rich organic matter in the soil stimulates nitrification and denitrification, resulting in an increase in the N_2O emission flux. In the two-year experiment, due to climate factors, there were significant differences in the cumulative emissions of CH_4 and N_2O under different planting modes. Further long-term experiments are needed to verify and clarify their emission rules.

4.2. Effects of Different Cropping Patterns on GWP and GHGI in Paddy Field

This study showed that the GWP of paddy fields with different planting patterns was significantly different. The GWP of CRR, RRR and PRR was significantly higher than that of CRI and RRI. The GWP of CRR was the highest in both years, being significantly increased by 48.28–448.90% and 34.43–278.33% compared with that of other treatments ($p < 0.05$). CH_4 emissions from CRR, RRR and PRR contributed 86.20~99.96% to GWP, and N_2O emissions contributed 0.04~13.80% to GWP, while CH_4 emissions from CRI and RRI contributed 48.61~64.60% to GWP, and N_2O emissions contributed 30.40~51.39% to GWP, which is similar to the research conclusions of Cheng Chen [16], Huang Taiqing [37] and Zhong Chuan [38]. The annual CH_4 emissions from CRI and RRI were lower. Although CH_4 emissions were significantly reduced, N_2O emissions were significantly increased, but the contribution rate to the overall GWP and GHGI was small [35]. Therefore, in order to promote greenhouse gas emission reduction in paddy fields, we should focus on exploring ways to reduce CH_4 emissions. As an evaluation index of low-carbon agriculture, GHGI needs to include a consideration of crop yield and comprehensive warming potential at the same time. In this study, the GWP of CRI and RRI was significantly lower than that of CRR, RRR and PRR, and the biomass of CRI and RRI was significantly higher than that of CRR, RRR and PRR, so the GHGI of paddy-upland rotation was significantly lower than that of double rice cropping. The GHGI of the RRI treatment in 2020 was significantly lower than that of the CRI treatment, and the GWP of the RRI treatment was significantly lower than that of the CRI treatment, but there was no significant difference in biomass between the RRI and CRI treatment. RRI treatment can reduce greenhouse gas emissions while ensuring yield. Therefore, the implementation of paddy-upland rotation can effectively reduce greenhouse gas emissions, and the organic carbon content of CRI and RRI is significantly higher than that of other treatments, which can achieve the dual effect of emission reduction and carbon sequestration. Based on the two-year gas emission performance, the RRI and CRI treatments have better emission reduction potential, among which the RRI treatment (rape–early rice–sweet potato || late soybean) performs best, indicating that winter rape, milk vetch and paddy-upland rotation are conducive to reducing greenhouse gas emissions.

5. Conclusions

Chinese milk vetch–early rice–sweet potato || late soybean has a better yield increase effect, and can significantly reduce greenhouse gas emissions from paddy fields, which is conducive to reducing the global warming potential and greenhouse gas emission intensity, in line with the development trend of "carbon neutrality". Under the comprehensive consideration of high yields, and low greenhouse gas emissions, the Chinese milk vetch–early rice–sweet potato || late soybean model performs better and has the best comprehensive benefits, which is of great significance to the optimization of the paddy field planting mode in the middle reaches of the Yangtze River. This paper only discusses the relationship between planting patterns and greenhouse gas emissions from the perspective of a planting system. In the future, the mechanism and effect of soil microbial community structure on greenhouse gas emissions under different cropping patterns can be explored.

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