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Full Length Article

Rice-Rape Rotation Benefits to Improve Radiation and Heat Use Efficiencies and Mitigate Global Warming Potential of Paddy Cropping Systems in Central China

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Abstract

Replacing bare fallow by rotation with winter cereal crops such as winter wheat and oil rape have been used to improve annual productivity in paddy cropping system in central China. However, the effects of rotation on light and heat resources utilization and greenhouse gases have yet to be measured. A two-year field experiment was conducted to compare solar radiation and heat use efficiencies, methane (CH_4) and nitrous oxide (N_2O) emissions and global warming potential (GWP) of two winter rotations: rice-wheat and rice-rape taking rice-fallow as a check. The results of this study showed that rice-wheat had the highest annual grain yield (two-year means were 16.2 t ha^{-1}) and annual above ground biomass (32.9 t ha^{-1}) followed by rice-rape and by rice-fallow. No significant effect was observed for winter rotation on the performance of rice grain yield and growth, in spite of a large quantity of straw returning by winter crops. Solar radiation and heat resources utilization and their production efficiency were improved in the winter season by rotation with winter crops. Rice-wheat and rice-rape also increased light and heat resources utilization efficiency from the annual perspective. Compared with rice-fallow, CH_4 flux in the rice season among the two studying years was increased by 42.0% by rice-wheat but was decreased by 35.6% by rice-rape. For the annual level, CH_4 flux was promoted by 40.9% by rice-wheat and declined by 35.5% by rice-rape. For the rice season the N_2O seasonal flux was increased by 54.2 and by 8.3% in rice-wheat and rice-rape plots, respectively. The values for GWP and for yield-scaled GWP were highest in rice-wheat and lowest in rice-rape system. In conclusion, rice-rape system could be a better choice to increase solar radiation and heat resources utilization and mitigate greenhouse gases emission.

Keywords: Sustainability; Paddy cropping system; Rotation; Greenhouse gases; Central China

Introduction

Agriculture development is now facing a worldwide concern for sustainability mostly in three aspects: 1) food supply for an increasing population; 2) improving resources utilization efficiency and 3) mitigating detrimental items emission into the environment such as greenhouse gases (GHG). As one of the most important staple food, rice (*Oryza sativa* L.) feeds more than 50% of the world's population (Zhou and Sun 2017). According to FAO (2019), China accounts for approximately 28% of the global rice production and 18% of the world's planting area. Food supply, resources utilization and environmental issues in paddy ecosystems, especially in central and south China are getting more and more concerns.

Previous research has confirmed that rotation in paddy cropping systems, especially those with legumes could play an important role in promoting nutrient cycling, improving soil fertility and maintaining food production by reducing fertilizer investment (Nie *et al*. 2019). The release of environmental hazard compounds such as NO_3^- leaching and N_2O emission from farmland could also be reduced by rotation (Yu *et al*. 2014; Machado *et al*. 2021), or by replacing winter fallow with cover crops (Zhu *et al*. 2016). Fewer N losses were observed from crop residues than from chemical fertilizers when residues were incorporated into the soil in different rotation systems (Congreves *et al*. 2017; Taveira *et al*. 2020).

Studies on agricultural resources utilization have been focused on artificial nonrenewable resource inputs such as nitrogen fertilizer (Liu and Zhang 2011), irrigation water (Jia *et al*. 2020), *etc*. The local non-renewable climate resources including solar radiation and heat are usually evaluated for single season crop production (Du *et al*. 2019). The analysis of cropping effects on solar radiation and cumulative temperature use efficiency from an annual perspective are quite few but in urgent need. As reported by Zhang *et al.* (2013), food production potential of paddy ecosystems in central China has been increased greatly in the past decades because of an increasing air temperature. The most popular paddy cropping system in central China is single rice followed by winter fallow or rotated with a winter crop such as winter wheat (*Triticum aestivum* L.) and oil rape (*Brassica campestris* L.). Therefore, the effects of rotation on radiation and accumulative temperature use efficiency need to be clarified to make a better use of resource potential.

Agriculture is considered as a major anthropogenic source of CH_4 and N_2O, accounting for 50 and 60% of total CH_4 and N_2O emissions, respectively (Smith *et al*. 2007). About 30% of agricultural CH_4 and 11% of N_2O emissions released to the atmosphere are generated from rice paddies over the world (Mer and Roger 2001). Compared with fallow, rotation with cereals such as wheat, or with a winter cover may have profound effects on CH_4 and N_2O emissions from paddy field by altering organic or inorganic fertilizers application (Tellez-Rio *et al*. 2017) and complex soil conditions (Kamp *et al*. 2001). The effects of rotation on CH_4 and N_2O emissions from paddy soils are yet to be measured to make a more sustainable rice production.

Rotation with winter crops has been recognized as effective to promote nutrient cycling and reduce N_2O emission from paddy fields (Yu *et al*. 2014; Zhu *et al*. 2016). However, the effects of winter crops rotation on radiation and heat use efficiencies, and global warming potential of paddy systems are not well reported. Therefore, this two-year field study was designed with the hypothesis that winter rotations can improve resource use efficiencies and mitigate GHG emissions compared with winter fallow in paddy systems of central China.

Materials and Methods

Site description

The field experiment (2017–2019) was conducted in a farmer's field in Jiangling County (30°12'N, 112°31'E), Hubei province, central China. This region is in the middle reaches of Yangtze River, one of the most important rice planting areas in China. The climate is humid and mid-subtropical monsoon with an average temperature ranged from 16.0 to 16.4°C and an annual rainfall of 900–1100 mm. The soil is fluvo-aquic, and before the start of the experiment the soil fertility was: 26.44 g kg^{-1} total carbon, 2.44 g kg^{-1} total nitrogen, 170.9 mg kg^{-1} alkaline hydrolyzed nitrogen, 0.38 g kg^{-1} total phosphorus, 12.7 mg kg^{-1} Olsen extractable phosphorus, 159.0 mg kg^{-1} available potassium, and pH (H_20) 6.9.

Treatments and agronomic details

The study was started at October 28 in 2016, before that the cropping system in the experimental field was one season rice followed by winter fallow for more than 10 years. In this study three rice cropping systems were compared: rice-winter fallow (RF), rice-winter wheat (RW) and rice-rape (RR). The treatments were arranged in a completely randomized block design with three replications. Nine plots of 98 m^2 (14 m × 7 m) per individual plot were used. Plots were separated by 0.5 m wide ridges covered with plastic film to avoid water and nutrients runoffs.

Winter crops were transplanted or hand broadcast after rice harvest and straw incorporation by a rotary tiller in late October. For RR plots, rape seedlings (*cv.* Huayouza62, 30d) were transplanted at a density of 30 cm × 30 cm with a single seedling per hill. Wheat (cv. Zhengmai9023) seeds were hand broadcast at a rate of 225 kg ha^{-1} in RW plots. The rape and wheat received the same base fertilizer application: 96 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1} and 132 kg K_2O ha^{-1} (16:10:22% compound fertilizer). The rape was applied with twice top dressings as 36 kg N ha^{-1} (urea) and 7.5 kg B ha^{-1} ($Na_2B_4O_7 \cdot 10H_2O$) each time while the wheat was top dressed with urea at a rate of 45 kg N ha^{-1}. RF plots were kept fallow during the whole winter season. In early June, after winter crops harvest and soil management, rice seedlings (cv. Longliangyouhuazhan, 30d) were transplanted at a spacing of 26 cm × 16 cm with 3 plants per hill. Rice plants received a fertilizer application in the form of 225 kg N ha^{-1} (urea), 75 kg P_2O_5 ha^{-1} (calcium superphosphate), and 180 kg K_2O ha^{-1} (potassium chloride). The fertilizer distribution was 40% N, 100% P_2O_5 and 50% K_2O for base fertilizers; 30% N for topdressing at tillering stage; 30% N and 50% K_2O for the second topdressing at grain filling stage. The rice field was flooded by a 3–5 cm depth of water except for the mid-season drainage.

At maturity, grain yield of each crop was measured by randomly selected two 4 m^2 areas for each plot. The above-ground biomass was separated into straw and grains and measured after oven drying at 75°C to constant weight.

CH_4 and N_2O flux measurements

CH_4 and N_2O fluxes were measured from June 2017 to May 2019, by using a closed chamber/gas chromatography method (Sun *et al*. 2018). The closed chamber (45 cm × 45 cm × 100 cm) was put into the groove of a base which was fixed into the soil in each plot. Thereafter, water was filled into the groove to seal the chamber so no gas leaking will happen between the chamber and the covered field. A battery-driven fan was used to mix the air inside the chamber. For each flux measurement, three gas samples intervals were collected from 9:00 to 11:00 am by using a 25-mL syringe at 0, 8 and 16 min respectively, after the chamber was placed on the fixed base. The chamber was removed from its base after each gas sampling event. Gas samples were taken at 10–15 d intervals during the winter season and at 7–10 d intervals in the rice season.

CH_4 and N_2O concentrations were determined by using a gas chromatograph (Agilent 7890B, CA, USA) equipped with a hydrogen flame ionization detector (FID) and an electron capture detector (ECD). The oven and FID were operated at 50 and 300°C, respectively. The temperatures for the column and ECD detector were maintained at 40 and 300°C, respectively.

Calculations for resource use efficiency and GHG emissions

The CH_4 and N_2O fluxes (F_i) were calculated based on the changes of concentration (ΔC) over the time duration (Δt) (Mosier *et al*. 2006). Cumulative CH_4 and N_2O emissions (CE_i) were calculated *via* the trapezoidal integration of the mean flux over sampling intervals (Mosier *et al*. 2006).

$$F_i = \rho \times (V/A) \times (\Delta C/\Delta t) \times 273/(273+T) \quad (1)$$

$$CE_i = \sum_{i=1}^{n}(Fi \times Di \times 24) \quad (2)$$

Where ρ is the density of CH_4 or N_2O, V is the volume of the chamber above the enclosed soil with the area of A. T is the temperature inside the chamber (°C). D_i is the interval in days of the adjacent two sampling events and 24 are the hours in a day.

Based on a 100-year time frame, the GWP coefficient is 25 for CH_4 and 298 for N_2O to CO_2 equivalent (IPCC 2007). We calculated the combined GWP for 100 years using Eq. (3):

$$GWP = 25 \times CE(_{CH_4}) + 298 \times CE(_{N_2O}) \quad (3)$$

The yield scaled GWP was calculated according to Shang *et al*. (2011).

Yield-scaled GWP = GWP/Y (4)

Where, Y is the crop grain yield for the gas sampling season. Data of radiation and temperature use efficiencies, including radiation production efficiency (RPE), radiation use efficiency (RUE), accumulative temperature production efficiency (ATPE) and accumulative temperature use efficiency (ATUE) of ≥10°C were calculated by Chang *et al*. (2016).

RPE (g MJ^{-1}) = grain yield/solar radiation (5)

RUE (%) = primary productivity/solar radiation (6)

ATPE (kg hm^{-2} °C^{-1} d^{-1}) = grain yield/accumulative temperature (7)

ATUE (%) = accumulative temperature during crop season / annual accumulative temperature (8)

Statistical analysis

Data were analyzed by using the PROC ANOVA procedure in S.A.S. version 9.3 (S.A.S. Institute Inc., Cary, NC, USA). Means of rice yield, cumulative GHG emissions, GWP, yield-scaled GWP, crop yield and resources utilization efficiency were compared based on the least significant difference (LSD) test at the 0.05 probability level.

Results

Yield performance

Across the 2-year observation, no significant difference was detected for grain yield and above-ground biomass in the rice season between rice-fallow and rotation systems of rice-wheat or rice-rape (Fig. 1a, b). In spite of longer growing seasons for the winter crops, their grain yields were much smaller than those of rice (Fig. 1a). Wheat showed significant higher ($P \leqslant 0.05$) grain yields than rape in paddy rotation systems in both years (Fig. 1a). When it came to the annual total grain yield, rice-wheat and rice-rape rotations had greater values than rice-fallow in both years. As shown in Fig. 1b, rice-wheat had the highest annual above-ground biomass because of a higher residue production from winter crops.

Solar radiation and heat efficiency

Indicators such as radiation production efficiency (RPE), radiation use efficiency (RUE), accumulative temperature production efficiency (ATPE) and accumulative temperature use efficiency (ATUE) of ≥10°C were successfully used for solar radiation and heat resources utilization comparisons among different farming systems. In this study, no significant difference was observed for RPE and ATPE during the rice season (Table 1). In the winter season, RPE and ATPE values were zero for rice-fallow because no crop was planted or harvested during winter seasons. For rice-wheat and rice-rape, wheat showed greater ($P \leqslant 0.05$) RPE and ATPE values than rape (Table 1), mainly due to the higher grain yields and dry matter accumulation in rice-wheat plots (Fig. 1). The lower values for RPE and ATPE in the winter seasons could be attributed to the lower temperature in wheat and rape growing seasons. When compared with rice-fallow, the annual RPE and ATPE were significantly increased ($P \leq 0.05$) by rice-wheat and by rice-rape in both years (Table 1). By calculation based on above ground dry matter accumulation, RUE values ranged from 0.80–1.68% (Table 1). The highest RUE values were observed in rice-wheat rotation plots, followed by rice-rape and rice-fallow. No significant diffidence was shown for RUE between rice-rape and rice-fallow in 2018–2019. Both the rotation treatments improved ATUE values significantly ($P \leq 0.05$) than rice-fallow. Rice-wheat and rice-rape plots had similar ATUE values because of the same growing stages for the winter seasons.

The CH_4 and N_2O fluxes and GWP

According to the two-year observation, CH_4 emission rates ranged respectively from 0.05 mg m^{-2} h^{-1} to 21.52 mg m^{-2} h^{-1} for the rice seasons and from 0 mg m^{-2} h^{-1} to 1.98 mg m^{-2} h^{-1} for the winter seasons (Fig. 2a). The three treatments showed a similar CH_4 emission trend during the rice seasons.

Table 1: The 2-year (2017–2019) radiation and temperature production efficiency and use efficiency of different cropping patterns

Year	Treatment	RPE (g MJ^{-1})			RUE (%)	ATPE (kg hm^{-2}°$C^{-1}d^{-1}$)			ATUE (%)
		Rice season	Winter season	Annual		Rice season	Winter season	Annual	
2017–2018									
	RF	0.51 ± 0.02 a	0 c	0.26 ± 0.01 b	0.91 c	5.17 ± 0.3 a	0 c	3.70 ± 0.18 b	71.63 b
	RR	0.52 ± 0.01 a	0.16 ± 0.00 b	0.35 ± 0.00 a	1.23 b	5.24 ± 0.1 a	4.68 ± 0.61 b	5.15 ± 0.05 a	93.88 a
	RW	0.52 ± 0.01 a	0.26 ± 0.03 a	0.40 ± 0.01 a	1.68 a	5.25 ± 0.1 a	7.71 ± 0.77 a	5.74 ± 0.16 a	95.23 a
2018–2019									
	RF	0.45 ± 0.02 a	0 c	0.24 ± 0.02 b	0.80 b	4.4 ± 0.2 a	0 c	3.18 ± 0.17 b	72.87 b
	RR	0.47 ± 0.02 a	0.15 ± 0.00 b	0.29 ± 0.01 a	1.01 b	4.62 ± 0.2 a	4.32 ± 0.05 b	4.55 ± 0.18 a	92.71 a
	RW	0.47 ± 0.02 a	0.25 ± 0.03 a	0.37 ± 0.01 a	1.48 a	4.65 ± 0.2 a	7.57 ± 0.66 a	5.32 ± 0.16 a	92.01a

Mean ± standard deviation. Different lower-case letters indicate the significantly differences ($P < 0.05$) based on LSD multiple range tests. RF represents rice-fallow, RR represents rice-rape, RW represents rice-wheat. RPE represents radiation production efficiency, RUE represents radiation use efficiency, ATPE represents accumulative temperature production efficiency of ≥10°C, ATUE represents accumulative temperature use efficiency of ≥10°C

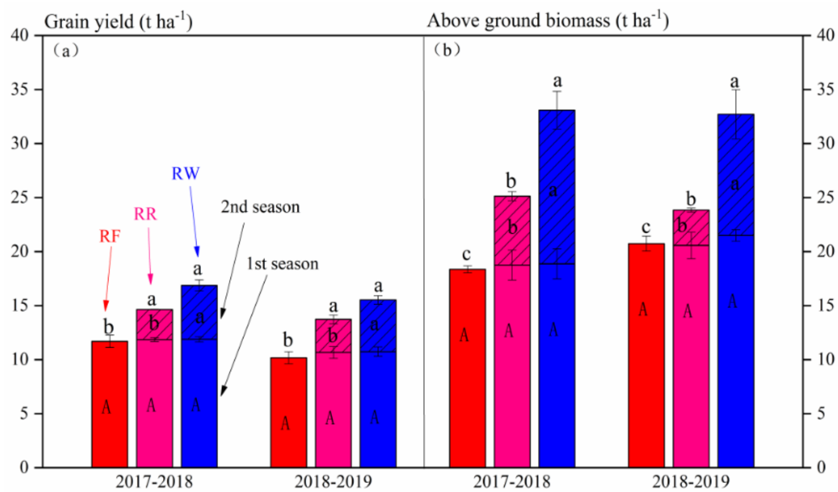

Fig. 1: Correlation between the average crop grain yield (**a**) and above ground biomass (**b**). RF represents rice-fallow, RR represents rice-rape, RW represents rice-wheat. The Correlation shows positive correlation between grain yield and above ground biomass

Two major peaks were detected for CH_4 emission for all the treatments in rice seasons both in 2017 and in 2018. CH_4 emission rates rose steadily after rice transplanting at early June and got its first peak at late June when rice plants were at full tillering stage. Thereafter, CH_4 emission decreased sharply nearly to zero in the mid-season drainage. CH_4 emission started to increase again when the field was flooded with water and got the second peak at middle August when rice plants were at flowering stage. Little CH_4 emission was observed for the three treatments during the winter crop growing seasons (Fig. 2a). CH_4 fluxes were calculated for the rice season, the winter season and the annual level, respectively. As shown in Table 2, the two-year average values for CH_4 flux in the rice season was increased by 42.0% by rice-wheat but was decreased by 35.6% by rice-rape when compared with rice-fallow. For the annual level, CH_4 flux was promoted by 40.9% by rice-wheat and declined by 35.5% by rice-rape.

N_2O emission rates ranged respectively from 0 to 420.7 μg m^{-2} h^{-1} for the rice seasons and from 0 to 169.5 μg m^{-2} h^{-1} for the winter seasons (Fig. 2b). In general, N_2O rates were greater in the rice seasons than in the winter seasons in the two-year observation. Dramatically different N_2O emission patterns were measured among treatments and years. In the rice seasons and the beginning of the winter season in 2017, most of the N_2O rates were higher than 100 μg m^{-2} h^{-1} for rice-wheat plots. For the year 2018, the rice season's N_2O rates showed an impulse trend regardless of the treatments. N_2O emission peaks were obviously higher in 2018 than those in 2017 (Fig. 2b). When compared with rice-fallow, N_2O seasonal flux in the rice season was increased by 54.2 and 8.3% in rice-wheat and rice-rape plots, respectively. For the annual level, N_2O emission was promoted by 66.7 and 26.3% in rice-wheat and rice-rape plots, respectively (Table 2).

Global warming potential (GWP) was calculated based on the data for CH_4 and N_2O annual emissions to make an integrated estimation of the global warming effects of the greenhouse gases emitted from the field. In this study, GWP values of CH_4 and N_2O were highest in rice-wheat treatment and lowest in rice-rape treatment during both years (Table 2). The increased GWP could be a result of a greater annual CH_4 emission as CH_4 emission contributed the most part of GWP. We also estimated yield-scaled GWP which was calculated as GWP divided by grain yield. As shown in Table 2, yield-scaled GWP of rice-rape was the

Table 2: The 2-year (from 2017–2019) average grain yield, CH_4 and N_2O emissions, global warming potentials (GWP) and yield-scaled GWP by different planting patterns

Year	Treatment	CH_4 emission (kg ha^{-1})			N_2O emission (kg ha^{-1})			GWP (kg CO_2-equivalens ha^{-1})	Yield-scaled GWP (kgCO_2-equivales per kg grain)
		Rice season	Winter season	Annual	Rice season	Winter season	Annual		
2017–2018									
	RF	135.3±19.3 a	5.7 ± 1.3 b	141.0±18.9 b	0.9 ± 0.4 b	0.6 ± 0.4 b	1.5 ± 0.9 b	3979.9 ± 717.8 b	0.34 ± 0.1 a
	RR	86.4±16.4 b	5.9 ± 1.5 b	92.4 ± 20.3 c	1.3 ± 0.6 b	1.3 ± 0.2 a	2.6 ± 0.4 b	3074.0 ± 457.6 b	0.21 ± 0.1 b
	RW	169.9±16.1 a	13.0 ± 3.5 a	182.1±25.4 a	2.9 ± 1.1 a	1.4 ± 0.1a	4.4 ± 0.9 a	5848.7 ± 377.0 a	0.35 ± 0.1 a
2018–2019									
	RF	100.4±13.1 b	12.8 ± 2.2 a	113.2±17.5 b	3.9 ± 0.5 b	0.4 ± 0.2 b	4.2 ± 2.8 a	4092.5 ± 1267.9 b	0.40 ± 0.2 a
	RR	65.5±15.5 c	6.1 ± 2.0 b	71.6 ± 23.3 c	3.9 ± 0.4 b	0.8 ± 0.3 a	4.6 ± 0.3 a	3168.6 ± 514.2 b	0.23 ± 0.1 b
	RW	164.7±11.2 a	11.4 ± 3.8 a	176.1±22.4 a	4.5 ± 0.5 a	0.6 ± 0.1 ab	5.1 ± 2.0 a	5933.5 ± 697.8 a	0.38 ± 0.1 a

Mean ± standard deviation. Different lower-case letters indicate the significantly differences ($P < 0.05$) based on LSD multiple range tests. RF represents rice-fallow, RR represents rice-rape, RW represents rice-wheat

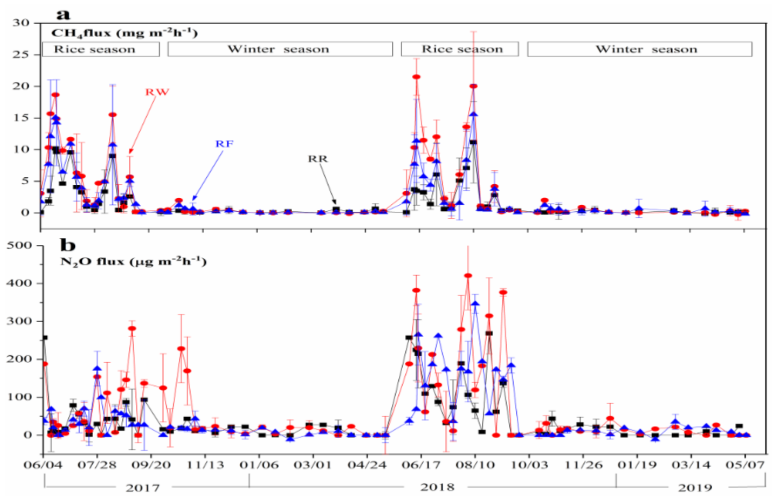

Fig. 2: Seasonal variations in CH_4 fluxes (**a**) and N_2O fluxes (**b**) during the rice and winter growing seasons from 2017 to 2019. RF represents rice-fallow, RR represents rice-rape, RW represents rice-wheat. The data shown in the panel are averages of the three represent for individual treatment. Vertical bars represent the standard errors of the three replicates

lowest while no significant difference was found between rice-wheat and rice-fallow.

Discussion

Although rotation with rape or with wheat showed no effect on radiation and heat use efficiencies during the rice season; however, rotation prompted the radiation and heat use efficiencies from the perspective of annual production. Moreover, the CH_4 and N_2O emissions from paddy soils differed with rotation with different winter crops (Table 2).

There were diverse reports on the effects of rotation on the main cereal crop yields when the same rotation pattern was applied continuously over years. Crops followed by legume rotations usually showed promoted nitrogen accumulation and higher grain yields (Yu *et al*. 2014; Zhu *et al*. 2016). Sometimes, yield reduction of the main crop resulted from rotation could be attributed to the competition for nitrogen after the incorporation of the second crop residue, such as rape and ryegrass because of a high carbon/nitrogen ratio (Armstrong *et al.* 1996; Nie *et al.* 2019), in spite that the rotation treatments were coupled with crop residue return, which means an additional nitrogen supply during the main rice crop season (Zhu *et al.* 2016). In this study, rotation with wheat or with rape had no significant effect on the grain yield and above ground biomass of rice for both years, possibly due to the high level of rice grain yields (ranged from 12.1 to 13.6 t ha^{-1}, Fig. 1a). However, rotation prompted crops production from the perspective of annual production.

Rotation might change climate resources utilization such as light and heat in two ways. First, when compared with fallow, rotation with winter crops could utilize the light and heat resources which would otherwise be wasted in the winter season (Chen *et al.* 2021). Second, the management of the winter crops might affect the growth of the following main summer crop (Huang *et al.* 2006). In this study, rotation systems are more productive than rice-fallow, mostly due to the winter crops utilization on light and temperature resources. The annual yield and biomass advantages of rice-wheat and rice-rape were mainly resulted from the significantly increased radiation and temperature use efficiency (Table 1). Because of no difference was found for rice grain yields, the yield based light and heat utilization indices such as radiation production efficiency and accumulative temperature production efficiency in the rice seasons were not significantly affected by rotation in this study. When it comes to the winter season, wheat had a greater potential than rape in improving light and temperature resources.

CH_4 and N_2O emissions are closely related to farming system changes including crop species, fertilizer application, water management and straw returning in paddy fields (Yao *et al*. 2017; Sumaira *et al*. 2019; Zhao *et al*. 2020). The CH_4 emission peaks observed in this study were similar with those measured in other studies based on cropping system management (Zhang *et al*. 2015; Xu *et al*. 2016), when the paddy soil was flooded and the rice plants were at a rapid growing stage. Winter rotation coupled with winter crops straw incorporation didn't change the CH_4 emission trend during the rice season. However, the seasonal CH_4 emission flux was dramatically different among different winter rotations when compared with fallow. The increased CH_4 emission for rice-wheat ranged 26.5–64.0% for the rice season and 29.1–55.6% for the whole year, respectively. The promoted CH_4 emission could be attributed to the enhanced above ground biomass yield of wheat and a larger quantity of straw returning into the soil after wheat harvest (Ma *et al*. 2009). Organic material incorporation, especially those with a high C/N ratio, provided available carbon substrate for CH_4 production methanogens.

Similar with CH_4 emission, N_2O emission flux was smaller in the winter seasons than in the rice seasons, possibly due to the lower temperature. N_2O production and emission from paddy soils are mainly happened during the processes of nitrification and denitrification (Wang *et al*. 2016). Crop rotations associated with different organic carbon and nitrogen management could change the substrate availability and the activity of functional microorganisms. Rice-wheat increased N_2O emission in the rice seasons while no significant difference for rice-rape and rice-fallow. The reason could be explained by the difference in the quality and quantity of straw returning into the soil followed by different winter crops.

Global warming potential could be a useful indicator to investigate integrative effects of different greenhouse gases from agricultural systems. The relationship of food production and greenhouse gases emission could be further measured by introducing the yield-scaled GWP. In spite that the global warming potential of N_2O is approximately 12 times larger than that of CH_4, the average CH_4 emissions was nearly 35 times that of N_2O, resulting in the major contribution for GWP from CH_4 emission (Table 2). Because of a significant increase of CH_4 emission, the GWP values were highest in rice-wheat, followed by rice-fallow and rice-rape. The yield-scaled GWP was decreased by rice-rape because of its lower CH_4 emission.

Conclusion

Annual grain yield, radiation and heat resources utilization and their production efficiency were improved by rotation with winter crops. The CH_4 emission from paddy soils as well as yield-scaled GWP was increased by rice-wheat and decreased by rice-rape system. These results suggested rice-rape could be more sustainable cropping pattern to increase solar radiation and heat resources utilization and mitigate greenhouse gases emission.

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Author Contributions

Gong Songling: Initial draft and data analysis; Li Chengwei: Data collection; Liu Zhangyong: Data analysis method; Zhu Bo: Framework and overall idea of the paper.

Conflicts of Interest

The authors declare there is no conflict of interest regarding the publication of this paper.

Data Availability

The data will be available upon reasonable request to the corresponding author.

Ethics Approval

Not applicable.

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