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Effects of dose nitrogen on yield and global warming potential in a typical rice-wheat rotation system in China

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Abstract: A three-year field experiment was carried out to investigate the methane (CH_4) and nitrous oxide (N_2O) emissions and calculate the global warming potential (GWP) according to all energy input in response to the nitrogen (N) rate in the typical rice-wheat rotation system in Jiangsu, China. Four N treatments, including R220W180 (local practice), R220W140 (cutting 10% total N in wheat season), R180W180 (cutting 10% total N in rice season) and R180W140 (cutting 20% total N in rice and wheat seasons separately), were designed in the study. Results showed that annual CH_4 emission was decreased by 25.7% in response to cutting 20% N, which was ascribed to the 24.6% reduction of CH_4 emission in rice season ($P < 0.05$) compared to local practice. The mitigation of N_2O emissions in R220W140 and R180R180 treatments contributed to the 8.5% and 15.7% decrease in annual N_2O emission, which was the 23.5% decrease in cutting 20% N treatment compared to local practice, respectively. Specifically, under the same amount of N rate condition (10% N cutting), the transfer N from rice season (R220W140) to wheat season (R180W180) led to the 8.5% increase in N_2O emission ($P < 0.05$). In the end, the cutting of 20% N decreased GWP and yield-scale GWP by 19% and 17%, which mainly originated from CH_4 and N_2O emissions. However, cutting N did not significantly decrease grain yield ($P > 0.05$). These results suggested that the 180 kg N/ha for rice and 140 kg N/ha for wheat in one rotation season were the beneficial N rate to achieve the co-benefit of yield and GWP in the typical rice-wheat rotation system in Jiangsu, China.

Keywords: contribution; decreasing emission; fertilisation; *Oryza sativa* L.; *Triticum aestivum* L.

Nitrogen (N) fertiliser plays a key role in rapidly increasing food production to meet the fast global population growth (Erisman et al. 2008). As estimated, the amount of nitrogen application would increase three times by 2050 to meet the requirement of crop production (Khampuang et al. 2021). However, the inappropriate and excessive N fertilisation has led to serious environmental issues, e.g., emissions of nitrous oxide (N_2O) and methane (CH_4), global warming, eutrophication (Sutton et al. 2011, Cheng et al. 2022, Guo et al. 2022, Wang et al. 2023). The first two contributors to global warming are N_2O and CH_4 emissions (Wang et al. 2021), and the global warming potential (GWP) of them is 265 and 28 times CO_2 on the centennial scale (Lan et al. 2020). Therefore, it is critical to exploit knowledge-based N practices to balance the co-benefit of yield and GWP.

Rice-wheat rotation is recommended as a crucial cropping pattern for increasing crop yield and land use efficiency in East China (Bi et al. 2009). N fertiliser is the main driver in the development of rice and wheat yield in the system. Due to the periodically flooded cycle, the rice season has become the major source of N_2O and CH_4 (Hadi et al. 2010), which contributed to about 20% of the global agricultural CH_4 emission (IPCC 2013) and 8–11% of N_2O emission of Chinese

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rice-field (Zou et al. 2009). Concerns about the emissions of N_2O and CH_4 associated with N fertiliser in rice fields have received increasing attention. Zhong et al. (2016) reported there was a close relationship between N_2O flux and N application rate. Moreover, GWP and rice yield increased with the increase in the N fertiliser rate. Lan et al. (2020) indicated that the 30% local nitrogen reduction (from 270 to 190 kg N/ha) decreased the N_2O emission by 26.0–34.4% in the rice-wheat rotation system but had no effect on CH_4 emission. In the wheat system, Zhao et al. (2015) indicated that the 6% increase in wheat yield with N application would increase 36–115% N_2O emission and confirmed that 180 kg N/ha was the proper N rate in their study condition. Liu et al. (2012) reported that the N rate application from 270 kg N/ha to 430 kg N/ha increased wheat yield by 3% and N_2O emission by 35%. According to the influence of N on yield and N_2O and CH_4 emission, the meta-analysis of 174 published studies suggested the suitable N rate was 180 kg N/ha and 130 kg N/ha for wheat and rice, respectively (Guo et al. 2022). However, the local N rates are 190–270 kg N/ha and 150–230 kg N/ha for rice and wheat fields in Jiangsu province, China (Jiang et al. 2020, Yang et al. 2022, Song et al. 2022, 2023). Therefore, it is expected that the GWP of the rice-wheat rotation system could be decreased by reducing the N rate with little or no yield penalty.

In order to fulfil the co-benefit of yield and GWP in response to N application, four N rates (220–180, 220–140, 180–180, 180–140 kg N/ha for rice and wheat seasons, respectively) were applied to the rice-wheat rotation system of Jiangsu province, China. The research objective of this study was to evaluate the emissions of CH_4 and N_2O, as well as the yield and GWP to the N reduction in a three-year continuous rice-wheat rotation system. Further, the study explored the key factors driving the GWP and recommended a suitable N rate for the rice-wheat rotation system in the region. We hypothesised that the 180–140 kg N/ha could meet the rice-wheat growth requirement and might realise the co-benefit of the yield and GWP in the rotation system.

MATERIAL AND METHODS

Site description and experimental design. The field experiment was carried out at the Agriculture and Meteorology Experimental Station (32.31°N, 118.71°E; elevation 18 m a.s.l.) of Nanjing University of Information Science and Technology, Nanjing, China. This location is characterised by a subtropical monsoon climate with an annual precipitation and temperature of 1 100 mm and 15.6 °C, respectively. Summer rice and winter wheat are widely planted on the site. The soil is classified as Luvisols, according to FAO. The soil of 0–20 cm depth contained sand, silt and clay at 29, 16 and 55%. It had an initial pH_{H_2O} of 6.78, total organic C of 11.46 g/kg and total N of 1.15 g/kg, available phosphorus of 17 kg P/kg, and available potassium of 33 kg K/ha, respectively.

The experiment was performed in a typical rice-wheat rotation system in the site and started at the beginning of the rice season in June 2020. The average temperature and precipitation from June 2020 to June 2023 are shown in Figure 1. A randomised block design was employed with four treatments: (1) local conventional N level (220/180 kg N/ha for rice/wheat, R220W180); (2) cutting 10% total N in wheat season (220/140 kg N/ha for rice/wheat, R220W140); (3) cutting 10% total N in rice season (180/180 kg N/ha for rice/wheat, R180W180); (4) cutting 20% total N in both rice and wheat seasons (180/140 kg N/ha for rice/wheat, R180W140). Plot size was 36 m^2 (12 m × 3 m) with three field replications (n = 3). All treatments were continued for three consecutive integrated rice-wheat rotation cycles. The cultivars of rice and winter wheat were Nanjing 5055 and Sumai 188 (density of 2.8 × 10^5 plant/ha for rice and 2.25 × 10^6 plant/ha for wheat). The time to apply the basic N, P and K fertiliser for rice on 18, 20, and 21 June and on 9, 11, and 18 November for wheat season in 2020, 2021 and 2022, separately. N fertiliser was applied as an experimental design with urea and was split into 50% basal fertiliser, 25% tillering fertiliser and 25% panicle fertiliser. Phosphorus and potassium were applied at the rates of 20 kg P/ha and 64 kg K/ha for the rice season and 43 kg P/ha and 64 kg K/ha for the wheat season, respectively. The basal fertiliser was homogeneously incorporated into the 0–20 cm layer, and other fertiliser was surface-applied. Field management was adopted into local practice. Briefly, the water requirement for wheat growth depends on rainfall. During rice season, irrigation starts from transplanting and continues for 40 days, then drying soil for 10 days, followed by re-irrigation for 60 days, and drainage at the last stage (almost 20 days).

Sampling and analysis. The emissions of CH_4 and N_2O were measured with static chamber gas chromatography technique over the 3-rotation period from June 2020 to May 2023. The static chamber

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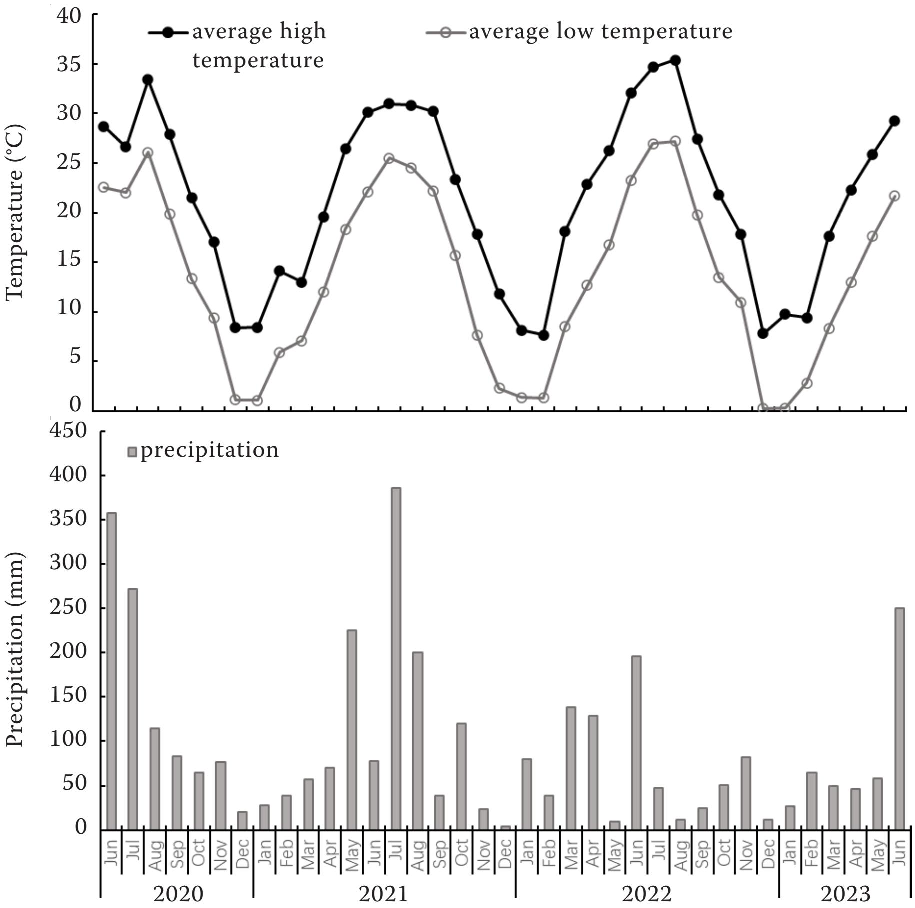

Figure 1. The information of temperature and precipitation across 2020–2023 during rice and wheat growing season

in the field has the dimensions of 50 cm, 50 cm height for rice and 100 cm height for wheat. Gases were sampled once a month during the growing season. To collect a gas sample from the chamber, headspace air was removed by inserting a gas-tight syringe through a septum of the sampling port. For each sample event, a 20 mL gas sample at 0, 10, 20 and 30 min was taken from each chamber and immediately transferred to pre-evacuated vials (18 mL). This was done consistently from 10:00 to 11:00 a.m. each sampling day. The concentrations of CH_4 and N_2O were determined by gas chromatography on a Shimadzu Model GC 2010 equipped with an ECD and a TCD (Kyoto, Japan). The CH_4 and N_2O flux rates and cumulative emissions were calculated according to the closed-chamber equation and trapezoidal method proposed by Zheng et al. (2008) and Qiao et al. (2014), respectively. Each harvest season, the rice/wheat plants were sampled from a random area of 6.0 m^2 within one plot. The seeds were collected and weighed, and the yield was weighed after drying at 80 °C.

GWP and yield-scale GWP calculation. The calculation method of GWP was the same as a previous study by Qiao et al. (2014) and Lan et al. (2020), where the total global warming potential (GWP) of a cropping system is given as:

$$GWP = GWP_{fertiliser} + GWP_{pesticides} + GWP_{agriculture\ machinery} + GWP_{seed\ production} + GWP_{CH_4} + GWP_{N_2O}$$

where: $GWP_{fertiliser}$ = 1.53 × N dosage + 1.63 × P dosage + + 0.65 × K dosage,

$GWP_{pesticides}$ = 12.4 × pesticide dosage,

$GWP_{agriculture\ machinery}$ = 4.1 × diesel oil dosage (fuel consumption and equipment maintenance),

$GWP_{seed\ production}$ = 1.84 × seeding rate (IPCC 2021)

$GWP_{CH_4} + GWP_{N_2O}$ = CH_4 (kg CH_4/ha) × 28 + N_2O (kg N_2O/ha) × 265 (Lan et al. 2020)

where: 28 and 265 were reported by IPCC for the conversion of CH_4 and N_2O into their CO_2 equivalent, respectively.

Yield-scale GWP = GWP/yield (Jiang et al. 2020)

Statistical analyses. Analysis of variance was performed using the one- or two-way ANOVA in Origin software (OriginPro 2023b) to test the effects of N application on the emissions of CH_4 and N_2O, and yield, GWP and yield-scale GWP, followed by Fisher

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test with a significance level of 5%. All figures were prepared using Excel 2010 software (Seattle, USA).

RESULTS

Greenhouse gas emission. The CH_4 fluxes in four treatments fluctuated during the rice-wheat growing season, and relatively higher fluxes were shown in June and July in the rice season (Figure 2A). The CH_4 flux fluctuated at an extremely low rate throughout the wheat growing season. The cumulated CH_4 emission in the rice season was higher relative to that in the wheat season (Figure 3A). In the three rice seasons, only the cumulated CH_4 emission in the R180W140 treatment was lower than those in the other three treatments ($P < 0.05$), and there are no significant differences across R220W180, R220W140 and R180W180 treatments ($P > 0.05$). In the wheat season, the cumulative CH_4 emission was not influenced by the N rate ($P > 0.05$, Figure 3A). In the end, the three-year mean CH_4 emission showed the lowest value in the R180W140 treatments, and no significant difference across the other three N rate treatments ($P > 0.05$, Table 1).

The N_2O fluxes in the four treatments also fluctuated during the rice-wheat growing season (Figure 2B). The flux peaks appeared in August, September, November, December, and March during the rotation period, and there were higher N_2O emissions in the wheat season than in the rice season. In the rice

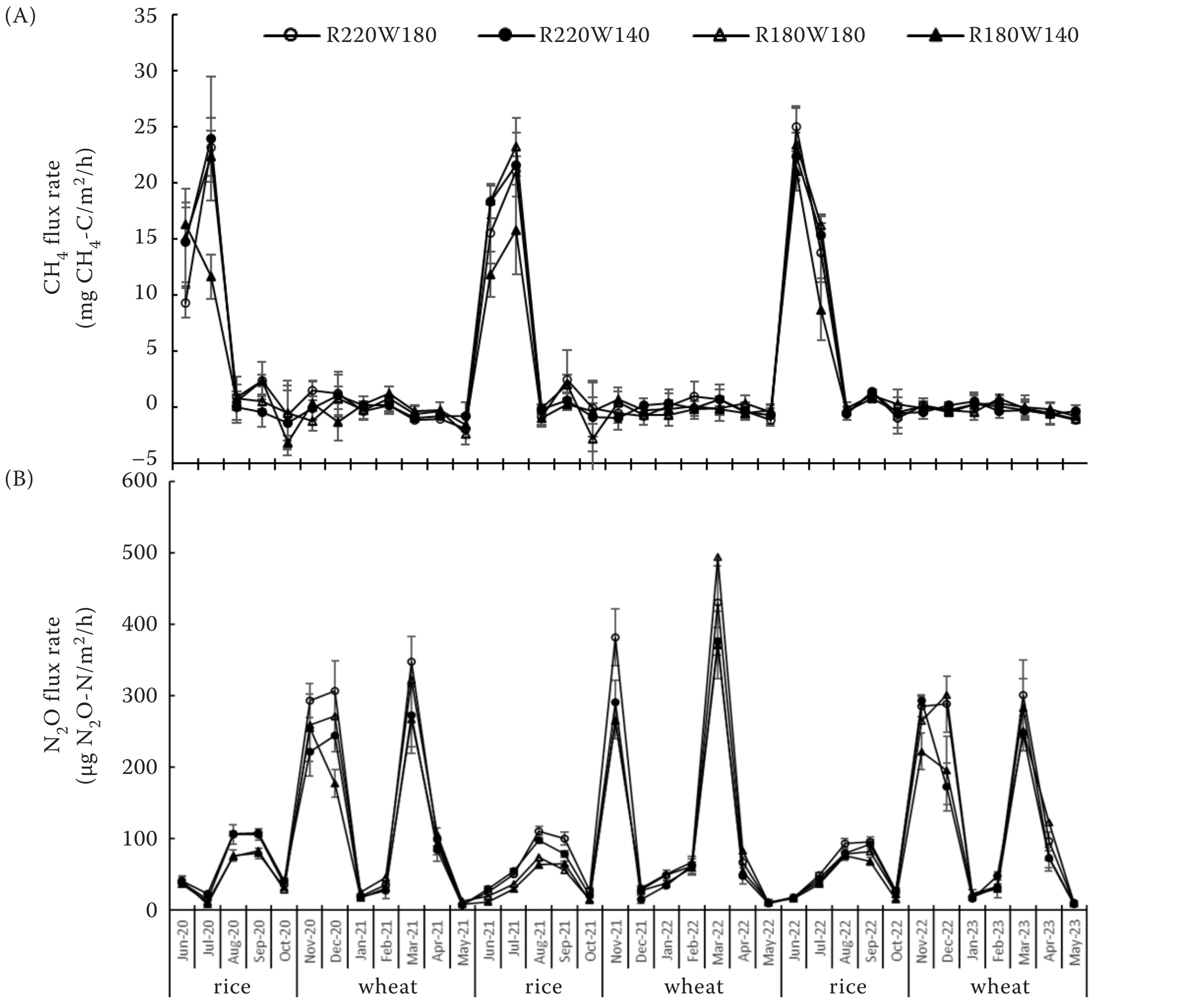

Figure 2. Dynamics of CH_4 and N_2O emissions of different N-fertilised treatments during the rice-wheat rotation field experimental period of 2020–2023. The data shown are the averages of three replicates for each treatment with standard errors. R220W180, R220W140, R180W180, R180W140 refer to the N application of 220–180, 220–140, 180–180 and 180–140 kg N/ha in rice and wheat growing season, respectively

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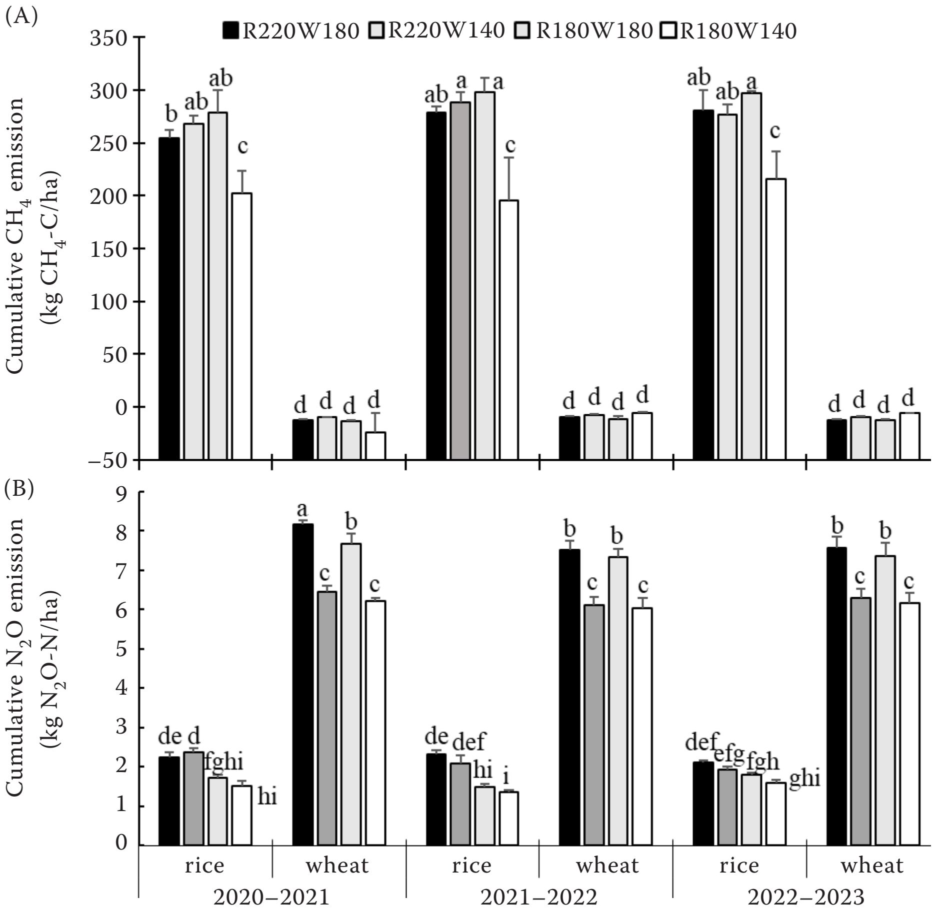

Figure 3. Cumulative emissions of CH_4 and N_2O from different N-fertilised treatments during the rice-wheat rotation field experimental period of 2020–2023. The data shown are the averages of three replicates for each treatment with standard errors. R220W180, R220W140, R180W180, R180W140 refer to the N application of 220–180, 220–140, 180–180 and 180–140 kg N/ha in rice and wheat growing season, respectively. Different letters above the columns indicate significant differences among treatments ($P < 0.05$)

season, though there was lower N_2O emission, cutting the N rate significantly decreased the accumulated N_2O emission by 23–36, 35–36 and 14–18% when comparing two treatments with the same N level for the wheat season in 2020–2021, 2021–2022 and 2022–2023, respectively (Figure 3B).

In the wheat season, cutting the N rate decreased the accumulated N_2O emission by 19–21, 17–18, and 16–17% when comparing two treatments with the same N level for the rice season in 2020–2021, 2021–2022 and 2022–2023, respectively (Figure 3B). Moreover, cutting the N rate decreased the three-year mean N_2O emission by 24–33% in the rice season and 2–4% in the wheat season. In the end, the total N_2O emission was in the order of R220W180 > R180W180 > R220W140 > R180W140 (Table 1, $P < 0.05$).

Grain yield. During the three rotation periods, rice grain yields varied from 8.39 × 10^3 kg/ha to 9.53 × 10^3 kg/ha, and wheat grain yields varied from 6.92 × 10^3 kg/ha to 7.57 × 10^3 kg/ha (Figure 4). Although the rice grain yield showed a declining trend with N reduction, there was no significant difference, with the exception of a 12% decrease in the R180W140 treatment compared to the R220W180 treatment in 2021. Similarly, wheat grain yield also showed decreasing patterns with N reduction. No significant differences in wheat grain yields were observed among three rotation periods and across N rate treatments ($P > 0.05$, Figure 4).

The three-year mean yields of rice, wheat and total during the study period were not influenced by N rate ($P > 0.05$, Table 1). There also showed a declining trend of yield with N reduction.

GWP and yield-scale GWP. The GWP in rice season ranged from 3 227 kg C-equivalent/ha to 4 145 kg C-equivalent/ha across N treatments, and no statistical difference in the GWP among R220W180, R220W140 and R180W180 treatments (Table 1, $P > 0.05$). The GWP of R180W140 was lower by 21, 22 and 22% than that of R220W180, R220W140 and R180W180 treatments, respectively.

In wheat season, the GWP of R220W140 was lower by 13% than that of R220W180 treatment, and which of R180W140 was lower by 13% than that of R180W180 treatment ($P < 0.05$, Table 1). In contrast, the same N rate in the wheat season had a similar GWP irrespective of the N rate in the rice season.

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Table 1. Three-year mean values of the emissions of CH_4 and CO_2, yield, global warming potential (GWP) and yield-scale GWP in response to nitrogen application in a rice-wheat rotation system

Treatment	CH_4 (kg C/ha)			N_2O (kg N/ha)			Yield ($\times 10^3$ kg/ha)			GWP (kg C-equivalent/ha)			Yield-scale GWP ($\times 10^3$ kg C-equivalent/kg yield)		
	rice	wheat	total	rice	wheat	total	rice	wheat	total	rice	wheat	total	rice	wheat	total
R220W180	271.45 ± 5.71^{a}	−11.69 ± 0.24^{a}	259.76 ± 5.68^{a}	2.21 ± 0.05^{a}	7.75 ± 0.17^{a}	9.96 ± 0.19^{a}	9.31 ± 0.50^{a}	7.34 ± 0.23^{a}	16.65 ± 0.69^{a}	4 092 ± 59.93^{a}	2 000 ± 21.49^{a}	6 091 ± 41.13^{a}	441 ± 17.68^{a}	273 ± 8.85^{a}	367 ± 12.61^{a}
R220W140	277.85 ± 4.04^{a}	−8.93 ± 0.59^{a}	268.92 ± 4.60^{a}	2.12 ± 0.13^{a}	6.27 ± 0.11^{b}	8.40 ± 0.11^{c}	9.19 ± 0.23^{a}	7.06 ± 0.17^{a}	16.25 ± 0.36^{a}	4 145 ± 31.02^{a}	1 747 ± 12.29^{b}	5 893 ± 32.81^{a}	452 ± 9.72^{a}	248 ± 6.13^{a}	363 ± 6.67^{a}
R180W180	291.21 ± 9.46^{a}	−12.59 ± 1.57^{a}	278.62 ± 8.13^{a}	1.67 ± 0.03^{b}	7.45 ± 0.05^{a}	9.11 ± 0.06^{b}	8.80 ± 0.20^{a}	7.22 ± 0.16^{a}	16.02 ± 0.34^{a}	4 131 ± 93.79^{a}	1 952 ± 19.52^{a}	6 083 ± 81.36^{a}	470 ± 20.56^{a}	271 ± 3.62^{a}	380 ± 12.79^{a}
R180W140	204.72 ± 27.42^{b}	−11.80 ± 5.74^{a}	192.92 ± 26.2^{b}	1.48 ± 0.07^{b}	6.14 ± 0.18^{b}	7.62 ± 0.24^{d}	8.58 ± 0.31^{a}	7.03 ± 0.24^{a}	15.61 ± 0.55^{a}	3 227 ± 71.69^{b}	1 701 ± 19.71^{b}	4 928 ± 38.75^{b}	375 ± 18.94^{b}	243 ± 5.25^{a}	315 ± 4.30^{b}

Different small letters between two treatments indicated significant difference at $P < 0.05$ level. All date was the average value of three replicates plus standard error

The total GWP of the rice-wheat rotation system showed a similar trend as that of rice season (Table 1). The total GWP of R180W140 was lower by 19, 16 and 19% than that of R220W180, R220W140 and R180W180 treatments, respectively ($P < 0.05$, Table 1).

The yield-scale GWP of the rice season and rice-wheat rotation system followed similar patterns as the GWP of rice in response to the N rate (Table 1). In rice season, the yield-scale GWP of R180W140 was lower by 15, 17 and 20% than that of R220W180, R220W140 and R180W180 treatments, respectively ($P < 0.05$, Table 1). The corresponding values in the rice-wheat rotation system were 14, 13 and 17%, respectively ($P < 0.05$, Table 1). However, the yield-GWP in the wheat season did not show a significant difference across N rates.

The fertiliser (N, P and K), pesticide, agriculture machinery, seed production and greenhouse gas (CH_4 and N_2O) contributed to the GWP in the rice-wheat rotation system (Figure 5). The most important three factors that contributed to the GWP were CH_4, N rate and N_2O in rice season, where the contribution of CH_4 was more than 64% (R180W140), and the N_2O, N rate and agriculture machinery in wheat season, where the contribution of N_2O was more than 45.85% (R220W140); and the CH_4, N_2O and N rate in rice-wheat rotation season, respectively, where the contribution of CH_4 was more than 39.51% (R180W140) and of N_2O was more than 18.20% (R220W140) (Figure 5).

DISCUSSION

Cutting 20% N was beneficial to mitigate CH_4 and N_2O emissions. As expected, cutting 20% N (R180W140) decreased the emissions of CH_4 and N_2O in the rice-wheat rotation system, which is consistent with the result reported by Jiang et al. (2020). The reduction in CH_4 emission by cutting the N rate was mainly ascribed to the lower CH_4 emission in rice season. These observations were supported by the report of Yao et al. (2013) that the CH_4 emission was mainly from rice fields but not wheat fields. The anaerobic environment in rice fields induced organic materials (SOM, plant and microbial residues, etc.) to convert into CH_4 by methanogens (Zhao et al. 2019). When cutting 20% N in rice season, the rice growth might be inhibited and further limit the transportation of root exudates and rice litter to the soil, which would reduce the CH_4 precursor (Zhao et al. 2019). Moreover, the thin rice growth might

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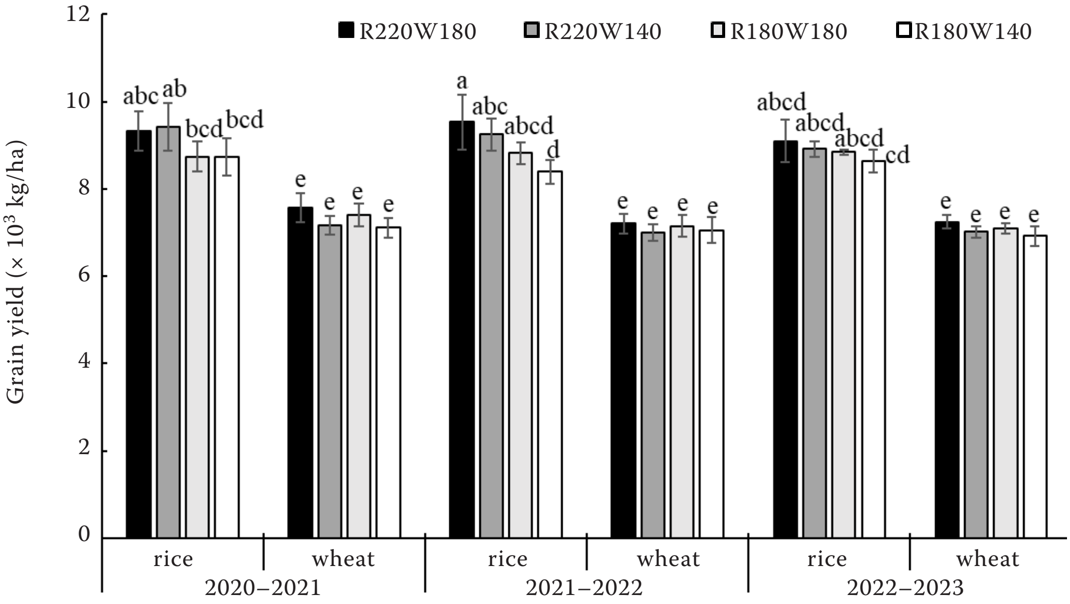

Figure 4. Grain yield of rice and wheat with different N-fertilised treatments during the rice-wheat rotation field experimental period of 2020–2023. The data shown are the averages of three replicates for each treatment with standard errors. R220W180, R220W140, R180W180, R180W140 refer to the N application of 220–180, 220–140, 180–180 and 180–140 kg N/ha in rice and wheat growing season, respectively. Different letters above the columns indicate significant differences among treatments (P < 0.05)

not be helpful to CH_4 release (Wang et al. 2023). These results suggested that the 20% N reduction might benefit the mitigation of CH_4 emissions in the studied region. In the present study, the two cutting 10% N treatments (R220W140, R180W180) did not decrease the CH_4 emission. This result was supported by the report of Lan et al. (2020) that N reduction showed a weak effect on CH_4 emission in the rice-wheat rotation system. The possible reason might be the N-induced variation of plant growth and methanogenic bacterial community was not enough to influence the balance between the formation and release of CH_4 (Han et al. 2013, Zhao et al. 2019, Wang et al. 2023). All these indicated that the N reduction could mitigate CH_4 emission, but it depended on the amount of N reduction. Interestingly, Wang et al. (2023) reported that the lower CH_4 emission was observed in all N-fertiliser treatments compared to the zero N treatment. The reason was that the promoted plant growth by N fertiliser enhanced oxygen to enter the rhizosphere and to oxidise CH_4 (Jiang et al. 2017). All these suggested that N might be an important factor in influencing CH_4 emission, but the real mechanism of N on CH_4 emission was driven by a series of complex soil microbial processes. The CH_4 emission was balanced by the CH_4 generation with methanogens and CH_4 uptake with methanotrophs. Bodelier and Laanbroek (2004) reported that enhanced soil N might stimulate methanotrophic activity. However, high levels of N inhibited soil CH_4 uptake (Zhuang et al. 2013). Though the mechanism of how CH_4 emissions respond to the N application is still under debate, the recommended N rate for mitigating CH_4 emission might be 180 kg N/ha for rice and 140 kg N/ha for wheat in the rice-wheat rotation system in Jiangsu, China.

Decreasing the N application rate was an effective strategy to minimise N_2O emission in the present rice-wheat rotation system, which was supported by the results of many previous studies (Zhong et al. 2016, Lan et al. 2020, Cheng et al. 2022, Guo et al. 2022, Wang et al. 2023). This is because the soil N from N fertiliser was quickly converted into NO_3^- (Han et al. 2020) and further into N_2O (Zhong et al. 2016). In the present study, cutting both 10% N and 20% N significantly decreased N_2O emission in the rice-wheat rotation system, which is mainly from the wheat season. However, the three-rotation mean N_2O emission ranged from 7.62 kg N/ha to 9.96 kg N/ha, where the N_2O emission from rice season accounted for 18–25%, which is supported by the results report of Zhou et al. (2017) and Lan et al. (2020). All these indicated that the N_2O emission from the rice season should be considered when quantifying the mean

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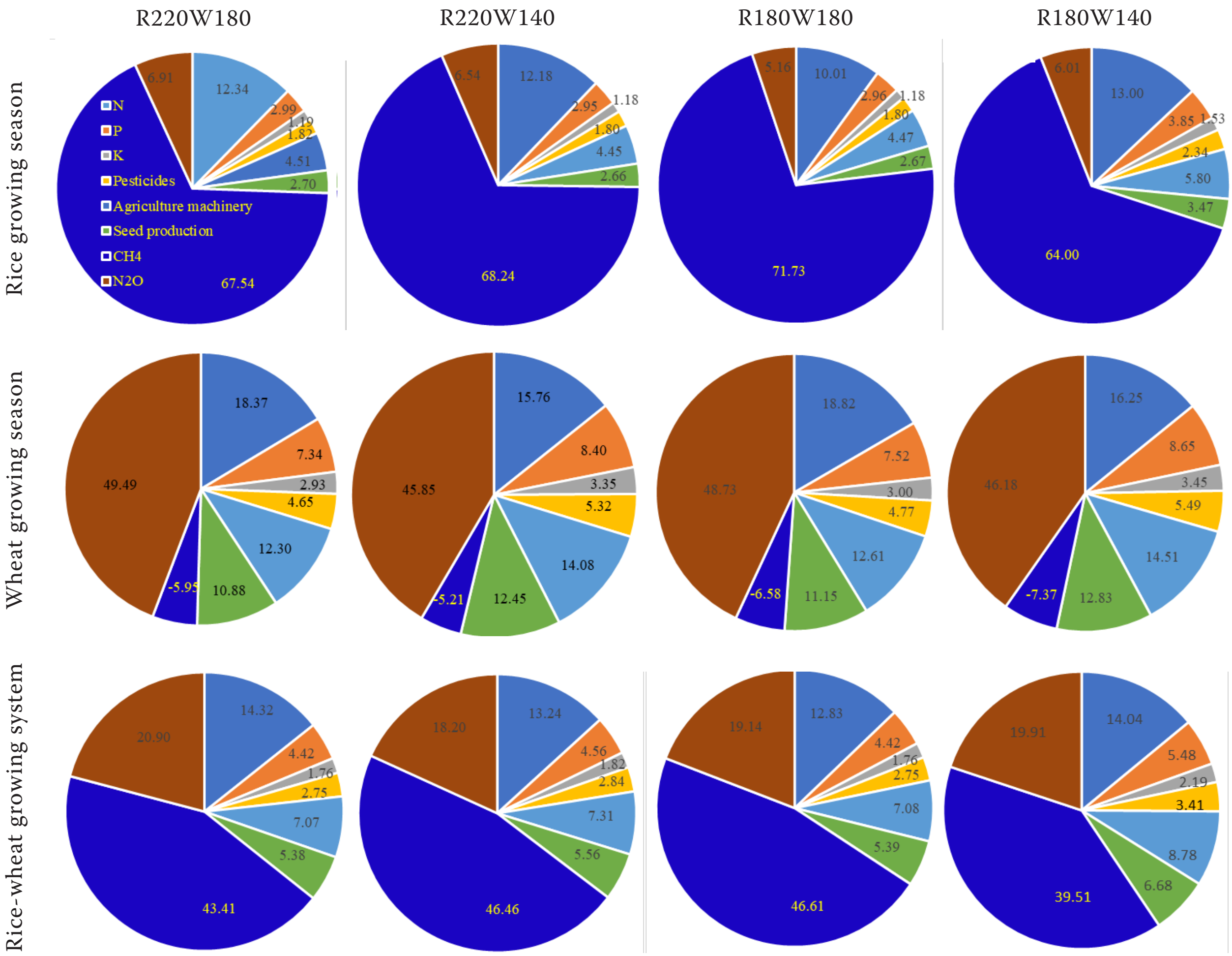

Figure 5. The mean contributions of N, P, K, pesticides, agriculture machinery, seed production, CH_4 and N_2O to total global warming potential (GWP) during a rice-wheat rotation system of three years. Data in the picture indicates the percentage of each factor (%) contributed to GWP. R220W180, R220W140, R180W180, R180W140 refer to the nitrogen application of 220–180, 220–140, 180–180 and 180–140 kg N/ha in rice and wheat growing season, respectively

N_2O emission from the rice-wheat rotation system (Lan et al. 2020).

More N allocated to the wheat season led to a notable increase in N_2O emission in the rice-wheat rotation system when comparing the same amount of N application treatments between R220W140 and R180W180. This could be supported by the view that upland croplands contributed much higher N_2O emissions than rice fields (Pittelkow et al. 2013, Aliyu et al. 2019). This might be ascribed to the higher N_2O emission factor in response to per 1 kg N in wheat fields than that in rice fields (Lan et al. 2020). In addition, soil redox conditions might play a key role in N_2O emission. Better soil aeration in wheat season relative to rice season favours aerobic microbial activities to generate N_2O (Shaaban et al. 2018). This suggests that transferring N from wheat season to rice season is a potential strategy to minimise N_2O emissions in the rice-wheat rotation system. All the above results indicated that a 20% N reduction, associated with more N allocated to rice season, had obvious mitigation of N_2O emission in the present rice-wheat rotation system.

Cutting 20% N was conducive to the co-benefit of yield and GWP. As per our speculation, cutting 20% N (180–140 kg N/ha) could meet the rice and wheat growth requirement and achieve a double-win in yield and GWP. This was supported by the analogous yield across N treatments and the decreased GWP in the cutting 20% N treatment compared to other N rate treatments. The yields of rice and wheat were 8.58×10^3 kg/ha and 7.03×10^3 kg/ha, which were slightly higher

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than the corresponding values of 7.47 × 10^3 kg/ha and 5.40 × 10^3 kg/ha in Jiangsu, China, respectively (Jiang et al. 2020). These assumed that the grain yield remained at a reasonable level with N reduction and indicated that there was still room for N reduction in the present rice-wheat rotation system.

The three-year mean GWP ranged from 11.83 × 10^3 kg g CO_2-equivalent/ha to 15.20 × 10^3 kg g CO_2-equivalent/ha for the rice season and from 6.24 × 10^3 kg g CO_2-equivalent/ha to 7.33 × 10^3 kg g CO_2-equivalent/ha for the wheat season. These values were higher than those of the reports of Yang et al. (2015), Lan et al. (2020) and the quantitative review and analysis based on 328 global observations (Linquist et al. 2012). The value gap between them might be mainly due to the different calculation methods of GWP. However, all these studies showed that it is possible to decrease the GWP with N reduction. In the present study, the GWP was calculated using the contributions of fertiliser (N, P, K), pesticides, agriculture machinery, seed production, and greenhouse gas emissions (CH_4 and N_2O). The annual GWP and yield-scale GWP of the rice-wheat rotation system were decreased by 16–19% and 13–17% by 20% N reduction, respectively, which were comparable with the 8.29–15.4% decrease in GWP with 30% N reduction (Lan et al. 2020). The main reason was the mitigation of CH_4 in rice season and N_2O in wheat season in response to the 20% N reduction. Specifically, the present study suggested the important roles of fertiliser, agriculture machinery use, and seed production in GWP mitigation in the rice-wheat rotation system. Thus, both CH_4 and N_2O emissions and agricultural management activities should be considered in evaluating GWP in the rice-wheat rotation system, which was also supported by the study in another rain-fed agricultural system (Qiao et al. 2014). Therefore, the cutting of 20% N accompanied by the N migration from wheat season to rice season should be given priority for the double-win in agronomy, economy and environment in the future rice-wheat rotation system in Jiangsu, China.

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