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Investigation into the Effects of Straw Retention and Nitrogen Reduction on CH_4 and N_2O Emissions from Paddy Fields in the Lower Yangtze River Region, China

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Abstract: Straw retention is a widely used method in rice planting areas throughout China. However, the combined influences of straw retention and nitrogen (N) fertilizer application on greenhouse gas (GHG) fluxes from paddy fields merits significant attention. In this work, we conducted a field experiment in the lower Yangtze River region of China to study the effects of straw retention modes and N fertilizer rates on rice yield, methane (CH_4) and nitrous oxide (N_2O) emission fluxes, global warming potential (GWP), and greenhouse gas intensity (GHGI) during the rice season. The experiments included six treatments: the recommended N fertilizer—240 kg N·ha^{-1} with (1) no straw, (2) wheat straw, (3) rice straw, and (4) both wheat and rice straw retentions; in a yearly rice–wheat cropping system (N1, WN1, RN1, and WRN1, respectively); as well as both wheat and rice straw retentions with (5) no N fertilizer and (6) 300 kg N·ha^{-1} conventional N fertilizer (WRN0, WRN2). The results showed that CH_4 emissions were mainly concentrated in the tillering fertilizer stage and accounted for 54.2%–87.5% of the total emissions during the rice season, and N_2O emissions were primarily concentrated in the panicle fertilizer stage and accounted for 46.7%–51.4% total emissions. CH_4 was responsible for 87.5%–98.5% of the total CH_4 and N_2O GWP during the rice season, and was the main GHG contributor in the paddy field. Although straw retention reduced N_2O emissions from paddy field, it significantly increased CH_4 emissions, which resulted in a significant net increase in the total GWP. Compared with the N1 treatment, the total GWP of WN1, WRN1, and RN1 increased by 3.45, 3.73, and 1.62 times, respectively; and the GHGI increased by 3.00, 2.96, and 1.52 times, respectively, so the rice straw retention mode had the smallest GWP and GHGI. Under double-season's straw retentions, N fertilizer application increased both CH_4 and N_2O emissions, and the WRN1 treatment not only maintained high rice yield but also significantly reduced the GWP and GHGI by 16.5% and 30.1% ($p < 0.05$), respectively, relative to the WRN2 treatment. Results from this study suggest that adopting the "rice straw retention + recommended N fertilizer" mode (RN1) in the rice–wheat rotation system prevalent in the lower Yangtze River region will aid in mitigating the contribution of straw retention to the greenhouse effect.

Keywords: straw retention mode; N fertilizer rate; GHG emissions; GWP; rice–wheat rotation

Highlights

- We investigated the effects of straw retention modes and N fertilizer rates on rice yield and CH_4 and N_2O emissions in a rice–wheat cropping system.

- Straw retention enhanced CH_4 emissions, but reduced N_2O emissions.
- CH_4 and N_2O emissions increased with increasing N fertilizer application.
- The single rice straw retention had the smallest GWP and GHI among three straw retention modes.
- Double-season's straw retentions with the recommended N maintained rice yield and reduced GWP and GHGI.

1. Introduction

Of global rice production, 30% comes from China, making it one of the world's most important rice producers [1,2]. In order to improve soil quality and stabilize rice yield, in recent years, the Chinese government has promoted straw retention over large areas during the rice planting process [1,3,4]. Thus, alongside science and technology development and the promotion of agricultural machinery, the land area subjected to straw retention has rapidly grown in China, reaching 2.28×10^7 ha in 2008. Rice–wheat cropping is a high productivity system in the middle and lower reaches of the Yangtze River. As of 2012, the rice–wheat rotation system covered 1.60×10^6 ha in the Jiangsu Province along the lower Yangtze River, accounting for 40% of the crop planting area (part of the area had up to 100%) [5]. Many studies have demonstrated that straw retention offers favorable ecological and economic benefits, such as reducing chemical fertilizer inputs, increasing soil nutrients and enzyme activities, and improving crop yields [6–10]. However, straw retention undoubtedly produces more greenhouse gas (GHG) emissions than chemical fertilizer treatment [11–13]. For instance, Liu et al. [13] reported that straw retention increased methane (CH_4) emissions by 110.7% in paddy fields and nitrous oxide (N_2O) emissions by 8.3% in upland soil. Barker et al. [14] found that 15%–20% of global anthropogenic CH_4 emissions came from rice fields, and Chinese rice fields were believed to be a particularly important source of CH_4 and N_2O [15]. The total annual emissions of CH_4 and N_2O from rice fields in China range from 7.7 to 8.0 Tg $CH_4 \cdot yr^{-1}$ and from 88.0 to 98.1 Gg $N_2O \cdot yr^{-1}$, respectively [16–19]. Thus, concerns about the environmental repercussions of anthropogenic GHG emissions are increasing [20]. To meet the increasing food demand, China has become the world's largest consumer of chemical N fertilizer [1]. Xing et al. [21] showed that the annual N fertilizer application was up to 500–600 kg $N \cdot ha^{-1}$ in the rice–wheat cropping system along the Yangtze River region. The field's N_2O emissions undoubtedly increased in response to increasing N application [1,22–25]. However, the effect of N fertilizer application on CH_4 remains unclear. Schimel [26] reported that N fertilizer increased the soil's CH_4 emission by increasing plant growth and carbon (C) supply to the CH_4 producers. However, some researchers surmised that N fertilizer reduced the paddy field's CH_4 emission by stimulating the methanotroph's growth and activity [27,28]. Therefore, knowledge of how GHG emissions and rice yields respond to straw retention and N management is helpful to assess the potential of rice–wheat rotation system to sustain rice yields and mitigate GHG emissions [29].

To date, most straw retention mode studies have focused on investigating how rice yield and soil C sequestration are affected by the implementation of this method [3,10,30–32]. However, in recent years, studies assessing the effects of straw retention on GHG emissions have begun to appear in large numbers. Ma et al. [33] reported that wheat straw incorporation significantly increased CH_4 emissions by 3–11 times and reduced N_2O emission by 30% in comparison with the fertilizer treatment in the rice–wheat rotation system. In double-rice-cropping systems, straw retention also significantly increased CH_4 and reduced N_2O emission [34]. However, Wang et al. [35] and Wu et al. [36] showed that rice straw incorporation increased the field's N_2O emissions. GHG emissions in paddy fields were sensitive to the straw retention mode, for instance, emissions of CH_4 and N_2O in paddy fields with straw mulching were lower than those with straw incorporation into the soil [37]. Theoretically, straw retention affects CH_4 and N_2O emissions by changing the soil's physical and chemical properties. Straw incorporation can decrease the soil's oxygen content during the rice season and provide organic substrates for microbial methanogens, thereby increasing the paddy field's CH_4 emissions [1,11,34,35,38]. The effect of straw incorporation on N_2O emission is still controversial [1]. Some researchers believe that returning straw to the field reduces N_2O emissions [1,33,34,39], whereas others believe the exact opposite [35,36]. This controversy stems from the fact that paddy fields rich in N easily produce N_2O via the nitrification process, while N_2O emissions are reduced in a strong reducing environment because N_2O can be transformed into N_2 during the denitrification process [40]. Xia et al. [8] showed that the effects of straw retention on N_2O emissions were influenced by soil properties, the residue's C:N ratio, N fertilizer application rate, and the mode of straw retention.

However, because the full straw was being continuously and mechanically returned to the field, sowing the crops was difficult and the soil's oxidation–reduction environment deteriorated in the early stage of the rice season [41]. With the introduction of straw collection and baling machinery, the straw returning mode applied to the rice–wheat rotation system was improved and single wheat or rice straw retention was carried out in the double-cropping system in select places within this region. Nevertheless, the effects of single wheat/rice and double-season straw retention on crop yields and GHG emissions have yet to be adequately investigated. To date, there are no reports of field studies examining the effects of different straw retention modes in rice–wheat cropping systems on GHG changes.

In this work, we carried out simultaneous measurements of CH_4 and N_2O emissions in paddy fields during the rice season under different straw retention modes and N fertilizer rates. The variations in straw retention modes and N fertilizer rates were selected based on a straw retention experiment established in 2012 in the lower Yangtze River region, China. The objective of this study was to quantify the effects of straw retention mode and chemical N reduction on CH_4 and N_2O emissions, rice yield, global warming potential (GWP), and GHG intensity (GHGI) and to optimize an environmentally and economically friendly mode of straw retention for local agricultural production.

2. Materials and Methods

2.1. Experimental Site

The field experiment was carried out at the Changshu Agroecological Experimental Station (31°33′ N, 123°38′ E), Chinese Academy of Sciences, in Jiangsu Province, China. The location of the station is shown in Figure 1. This region has a subtropical humid monsoon climate with an annual average temperature of 15.5 °C and annual precipitation of 1038 mm. The paddy soil is classified as anthrosol and developed from lacustrine sediments. The shallow groundwater depth is –0.80 m. When the experiment began in May 2012, the following major soil properties were determined from samples obtained at a depth of 0–15 cm: pH (H_2O)—7.19, organic matter content—38.8 $g \cdot kg^{-1}$, total N content—2.32 $g \cdot kg^{-1}$, available P (Olsen) content—26.7 $mg \cdot kg^{-1}$, and available K (NH_4OAc) content—208 $mg \cdot kg^{-1}$. The crop rotation system was a yearly rice–wheat double-cropping system (winter wheat and summer rice) with good irrigation and drainage ability. Nanjing 46 (*Oryza sativa L.*) and Yangmai 16 (*Triticum aestivum L.*) were used for summer rice and winter wheat, respectively. Rice was usually transplanted in late June and harvested in late October, and wheat was seeded in early November and harvested in late May of the following year. Consistent with local practice, rice was irrigated intermittently using water from the nearby river, while wheat depended mainly on rain. During the rice season, the rice fields were typically continuously flooded to a depth of 5.0 cm after fertilizer application, and a period of midseason drainage was conducted for about one week from 31 July to 8 August, 2013. The daily mean temperatures during the rice growing season from June to October 2013 are shown in Figure 2.

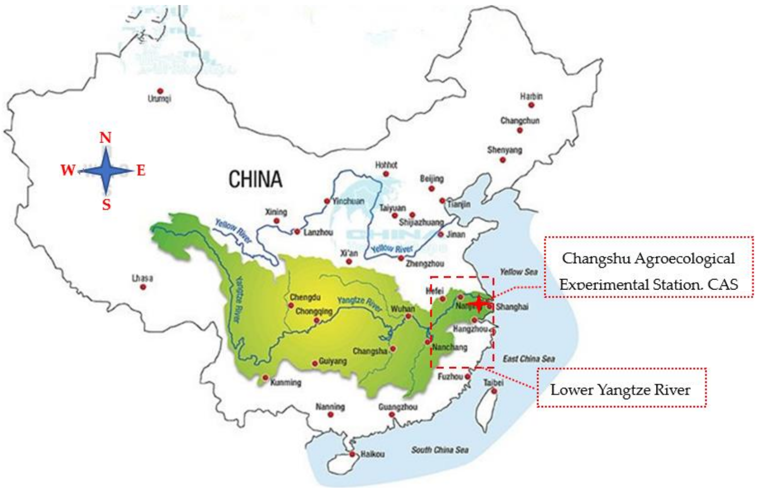

Figure 1. The location of the Changshu Agroecological Experimental Station, CAS.

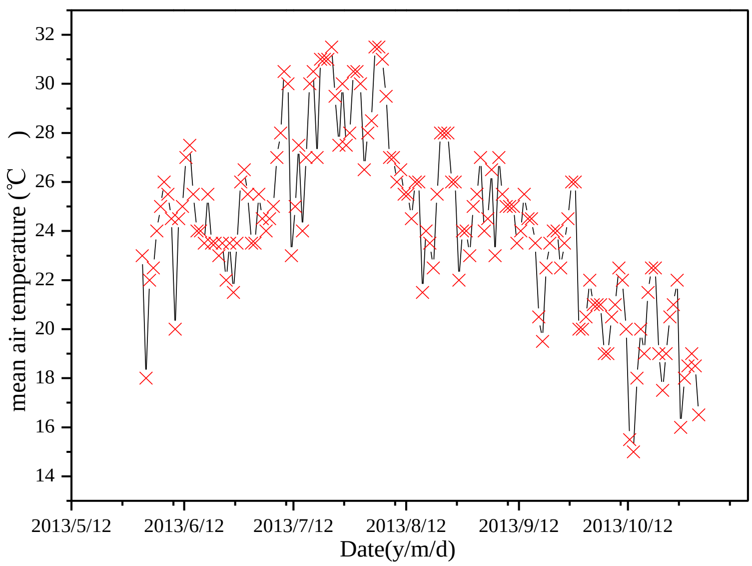

Figure 2. The daily temperature during the rice growing season from June to October 2013.

2.2. Field Experiment

The field experiment began in June 2012 by transplanting the rice seedlings. Six treatments were investigated: the reduced (recommended) chemical N fertilizer at 240 kg·ha^{-1} with (1) no straw retention, (2) harvested wheat straw retention, (3) harvested rice straw retention, and (4) harvested wheat and rice straw retention in a yearly double-cropping system (N1, WN1, RN1, and WRN1, respectively); and both wheat and rice straw retentions with (5) no N fertilizer and (6) 300 kg N·ha^{-1} conventional chemical N fertilizer (WRN0, WRN2). In the WN1 treatment, a single harvested wheat straw was pulverized by mechanical harvesters and then plowed into the soil by rotary tillage before rice transplanting. Furthermore, all the harvested rice straw was removed from the field. In the RN1 treatment, a single harvested rice straw was pulverized and then plowed into the soil before the wheat was sowed. In the WRN0, WRN1, and WRN2 treatments, each season's wheat and rice straw were pulverized and then plowed into the soil before the next crop was planted. The depth of straw retention by rotary tillage was –12 cm. The six treatments were arranged as a randomized complete block design with three replicate plots per treatment. Each plot was 7.0 m × 6.25 m. The plots were separated by soil ridges, which were covered with a plastic film to reduce water flow and side infiltration.

The application rates of the chemical fertilizers and crop straws are shown in Table 1. Urea, calcium superphosphate, and potassium chloride served as the sources of N, P, and K, respectively. During the rice season, N fertilizer was split into 40% basal fertilizer (BF), 20% tillering fertilizer (TF), and 40% panicle fertilizer (PF). P fertilizer was applied as BF at a rate of 15 kg P·ha^{-1}. K fertilizer was split into 50% BF and 50% PF at a rate of 60 kg K·ha^{-1}. The three N fertilization times were 24 June, 6 July, and 12 August, 2013. During the wheat season, N fertilizer was split into 40% BF, 20% TF, and 40% PF at the recommended rate of 200 kg N·ha^{-1} and a conventional rate of 250 kg N·ha^{-1}, while P fertilizer was applied as BF at a rate of 30 kg P·ha^{-1}, and K fertilizer was split into 50% BF and 50% PF at a rate of 30 kg K·ha^{-1}. The three N fertilization times were 5 November, 2012, 7 January, 2013, and 9 March, 2013. The wheat and rice straw retention's application rates were 5.50 and 10.0 t·ha^{-1}, respectively. The C concentration of the wheat and rice straw was 442 and 399 g·kg^{-1}, respectively. Therefore, the C input from the wheat and rice straw was 2431 kg C·ha^{-1} in the rice season and 3990 kg C·ha^{-1} in the wheat season. The C/N ratio of the wheat and rice straw was 95 and 51, respectively. The field management procedures followed the local farmers' practices.

Table 1. Application rates of chemical fertilizers and straw retention under different treatments.

Treatments	Rice Season		Wheat Season	
	Chemical Fertilizers N–P–K (kg·ha^{-1})	**Wheat Straw (t·ha^{-1})**	**Chemical Fertilizers N–P–K (kg·ha^{-1})**	**Rice Straw (t·ha^{-1})**
N1	240–15–60	-	200–30–30	-
WN1	240–15–60	5.50	200–30–30	-
RN1	240–15–60	-	200–30–30	10.0
WRN1	240–15–60	5.50	200–30–30	10.0
WRN2	300–15–60	5.50	250–30–30	10.0
WRN0	0–15–60	5.50	0–30–30	10.0

Note: N1, the recommended N fertilizer rates of 240 and 200 kg N·ha^{-1} with no straw retention for rice and wheat season, respectively; WN1, single-harvested wheat straw retention at a rate of 5.50 t·ha^{-1} (air dry base) before the rice season using N1's fertilizer rate; RN1, single-harvested rice straw retention at a rate of 10.0 t·ha^{-1} before the wheat season using N1's fertilizer rate; WRN1, double-season's retentions of harvested wheat and rice straw at rates of 5.50 t·ha^{-1} and 10.0 t·ha^{-1} using N1's fertilizer rate for rice and wheat season, respectively. WRN2, double-season's retentions of harvested wheat and rice straw at rates of 5.50 t·ha^{-1} and 10.0 t·ha^{-1} with N fertilizer rates of 300 and 250 kg N·ha^{-1} for rice and wheat season, respectively; WRN0, double-season's retentions of harvested wheat and rice straw at rates of 5.50 t·ha^{-1} and 10.0 t·ha^{-1} without any N fertilizer for rice and wheat season, respectively.

2.3. Gas Sampling and Flux Calculations

CH_4 and N_2O emission field measurements were conducted during the rice season from June to October 2013. A static chamber, composed of PVC, was used to simultaneously measure the CH_4 and N_2O fluxes. Each plot was equipped with a chamber either 0.50 m × 0.50 m × 0.50 m or 0.50 m × 0.50 m × 1.20 m (length × width × height), depending on the rice height. The chamber was placed on a fixed PVC frame in each plot. The frame's top edge had a 5.0 cm deep groove enabling it to be filled with water to seal the rim of the chamber. The chamber was equipped with a circulating fan to ensure a uniform gas mixing and was wrapped with a layer of insulating material to minimize the air temperature changes inside the chamber during closure [11,19].

Before the paddy fields were initially flooded, boardwalks were built from the ridge of the fields to randomly selected GHG measurement sites in order to reduce soil disturbance during flux measurements (Figure 3). Gas samples were obtained every two days during the two weeks after each fertilization and during the drainage period, and once a week during the remainder of the experiment. The sample was collected with syringe at 0, 10, 20, and 30 min after the chamber was closed, with 20 mL of gas extracted each time. While the gas samples were being extracted, the air temperature inside the chamber was simultaneously measured by a thermometer. Since the soil temperature during this period approximated the daily average, gas samples were collected from 08:00 to 10:00 [11].

Figure 3. Greenhouse gas (GHG) measurement sites in the paddy field during the rice growing season.

The gas sample's CH_4 and N_2O fluxes were simultaneously measured within 48 h by an Agilent 7890A gas chromatography system (Agilent Technologies, Palo Alto, CA, USA), equipped with a flame ionization detector (FID) for CH_4 detection and an electron capture detector (ECD) for N_2O detection. The FID and oven were maintained at 300 °C and 60 °C, respectively, and the carrier gas was 99.999% high-purity N_2, with a flow rate of 40 mL/min. The respective temperatures of the ECD and column were 300 °C and 60 °C, respectively, and the constituent gas was a 99.999% high-purity Ar–CH_4 gas mixture (95% Ar + 5% CH_4), with a flow rate of 40 mL/min.

The CH_4 and N_2O fluxes were calculated using the following equation [42]:

$$\mathrm{f} = \rho \times h \times \frac{dC}{dt} \times \frac{273}{273 + T} \quad (1)$$

where f is the gas flux ($mg \cdot m^{-2} \cdot h^{-1}$), ρ is the gas density of CH_4 or N_2O in the standard state ($mg \cdot cm^{-3}$), h is the chamber height (m), dC/dt is the CH_4 or N_2O gas accumulation rate in the chamber ($\mu g \cdot m^{-3} \cdot h^{-1}$), and T is the average air temperature inside the chamber (°C).

The seasonal cumulative CH_4 and N_2O emissions were calculated by linear interpolation of the daily fluxes between every two adjacent measurement intervals [8].

2.4. GWP and GHGI Estimates

GWP was used to assess the potential effects of GHGs on global warming. The GWP within a 100-year time frame was converted into CO_2 equivalent (CO_2-eq) emissions by multiplying the cumulative emissions of CH_4 and N_2O by 25 and 298, respectively [43].

$$\mathrm{GWP} = \mathrm{CH_4} \times 25 + \mathrm{N_2O} \times 298 \quad (2)$$

where GWP represents the potential effects of CH_4 and N_2O gases on global warming during the rice season (kg CO_2-eq$\cdot ha^{-1}$), CH_4 is the cumulative CH_4 emissions during the rice season (kg $CH_4 \cdot ha^{-1}$), and N_2O is the cumulative N_2O emissions during the rice season (kg $N_2O \cdot ha^{-1}$).

GHGI was used to evaluate the comprehensive influence of each treatment on the greenhouse effect. The GHGI was calculated by dividing the GWP by the rice grain yield [1].

2.5. Soil Analysis and Yield Measurement

Soil sample was collected from each plot from a 0–15 cm depth after the wheat harvest (late May 2013) and rice harvest (late October 2013), respectively. The soil organic C (SOC) concentration (g $C \cdot kg^{-1}$) was tested by the conventional $K_2Cr_2O_7$ oxidation method. Soil bulk density was measured using the cutting ring method. Next, the SOC density (SOCD, kg C·ha^{-1}) was calculated using the following equation [8,44]:

$$SOCD = SOC \times \rho \times H \times 10,000 \quad (3)$$

where SOCD refers to the soil organic C density (kg C·ha^{-1}) of the plough horizon (0–15 cm), SOC is the soil organic C (g C·kg^{-1}), ρ is the soil bulk density (kg·m^{-3}), and H is the depth of the plough horizon (0.15 m).

The rice grain yields (kg·ha^{-1}) were measured at physiological maturity. The rice grains were harvested manually from three m^2 areas in the middle of each plot. The grain samples were oven-dried at 70 °C to a constant weight to determine the dry matter content. Grain yield was adjusted to 14% moisture content.

2.6. Statistical Analysis

All statistical analyses were used with PASW Statistics 18 (IBM Corporation, Armonk, NY, USA). The effects of the straw retention modes and chemical N fertilizer rate on cumulative CH_4 and N_2O emissions, rice grain yields, GWP, and GHGI were assessed by one-way ANOVA, followed by a least significant difference test (LSD), in which $p < 0.05$ was considered statistically significant. All figures preparations were done using Origin Pro 8.0 (Origin Lab, Northampton, MA, USA).

3. Results

3.1. Rice Yield and Soil Properties

A significant difference in rice yield was found due to different straw retention modes (Figure 4a). Compared with the N1 treatment, the WRN1 and WN1 treatments significantly increased the rice yield ($p < 0.05$), while only a slight increase was observed from the RN1 treatment. Under both rice and wheat straw retentions, there was a significant difference in the rice yield in response to different chemical N fertilizer rates—the rice yield from the WRN1 treatment was 21.0% higher than that of the WRN2 treatment (Figure 4b).

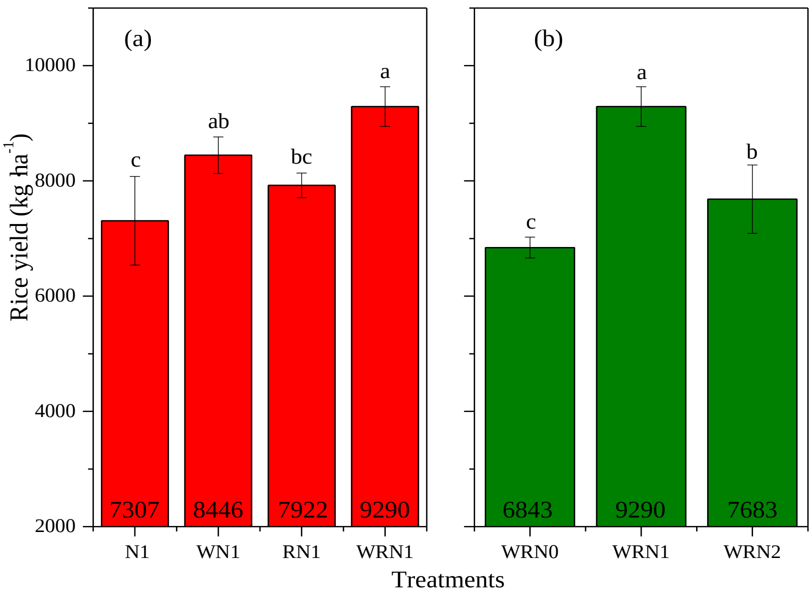

Figure 4. Rice yields under (**a**) different straw retention modes and (**b**) different chemical N fertilizer rates in 2013. Note: Treatments definitions are presented in the footnotes of Table 1. The vertical bars indicate standard errors. Different letters indicate significant differences at $p < 0.05$. The figures in the bar represent rice yields under different treatments.

After a one-year rice–wheat cycle, SOC concentrations of wheat harvest soil (second season) were significantly higher under the straw retention treatments than those under the fertilizer treatment (Table 2). SOC concentrations in the WN1, RN1, and WRN1 treatments were 7.1%, 10.4%, and 11.5% higher than that in the N1 treatment ($p < 0.05$), respectively. There was no significant difference in SOC concentrations between the RN1 and WRN1 treatments, but both were significantly higher than the SOC concentration in the WN1 treatment. Straw retention increased the SOCD of the wheat season soil, and the SOCD in the WN1, RN1, and WRN1 treatments increased by 1.28%, 4.43%, and 2.48%, respectively, when compared with the N1 treatment. In this experiment, all the straw retention modes increased the C/N ratio in the wheat season soil, but the C/N ratio was particularly high under the RN1 and WRN1 treatments, with values of 10.19 and 10.17, respectively.

Table 2. Variation of soil C and N contents in the rice–wheat rotation system under different straw retention modes over 2–3 seasons.

Treatments	After Wheat Harvest (Second Season)			After Rice Harvest (Third Season)		
	SOC (g C·kg^{-1})	SOCD (kg C·ha^{-1})	C/N Ratio	SOC (g C·kg^{-1})	SOCD (kg C·ha^{-1})	C/N Ratio
N1	22.1±0.04 c	36761 ± 68 c	9.43 ± 0.25 b	20.9 ± 0.07 c	34834 ± 119 b	9.72 ± 0.08 c
WN1	23.6±0.43 b	37231 ± 671 bc	9.98 ± 0.48 ab	22.7 ± 0.14 b	35778 ± 217 a	10.47 ± 0.20 a
RN1	24.4±0.02 a	38391 ± 35 a	10.19 ± 0.24 a	22.6 ± 0.06 b	35656 ± 88 a	10.07 ± 0.04 b
WRN1	24.6±0.20 a	37672 ± 298 a	10.17 ± 0.15 a	23.4 ± 0.06 a	35823 ± 89 a	10.47 ± 0.13 a

Note: SOC: the total soil organic C concentration; SOCD: the soil organic C density; C/N ratio: a ratio of the mass of C to the mass of N in the soil. Different letters in the same column indicate a significant difference between the treatments at $p < 0.05$ according to the LSD test. Definitions of the treatments are given in the footnotes of Table 1.

As shown in Table 2, the SOC concentration, SOCD, and the C/N ratio in rice harvest soil (third season) were also higher in the straw retention treatments than those in the fertilizer-only treatment ($p < 0.05$). Compared with the wheat season soil, the SOC concentration and SOCD in the rice season soil decreased slightly, while the C/N ratio generally increased, excepting the RN1 treatment.

3.2. CH_4 Emission with Different Straw Retentions

As shown in Figure 5, during the rice season, the paddy field's CH_4 emission flux varied with different straw retention modes and changed regularly over time. The CH_4 emission flux of each treatment was relatively low during the 10 days after rice transplanting, and then subsequently increased gradually. The CH_4 emission flux peaks under different treatments all appeared in mid-to-late July, about 20 to 27 days after rice transplanting. The CH_4 emission flux peak was highest in the WRN1 treatment (55.6 mg·m^{-2}·h^{-1} on 15 July), followed by the RN1 treatment (23.4 mg·m^{-2}·h^{-1} on 20 July), and WN1 treatment (21.8 mg·m^{-2}·h^{-1} on 13 July). The N1 treatment exhibited the lowest CH_4 emission flux peak on 15 July (12.6 mg·m^{-2}·h^{-1}). During the drainage period, the CH_4 emission flux showed a rapid decline from 31 July to 8 August for all the investigated straw retention modes. After the drainage period, the paddy field was re-irrigated. A small peak in CH_4 emissions was observed during a later stage in the rice season in response to the application of PF and an increase in temperature. The CH_4 emission level remained low until the rice harvest.

In order to analyze the differences in GHG emissions under different straw retention modes, the rice season was divided into three stages: the BF stage, the TF stage, and the PF stage, which correspond to the three periods in which fertilizer was applied. The cumulative CH_4 emissions in the different rice growing stages were calculated and are shown in Table 3. The cumulative CH_4 emission values trended as follows: TF stage > PF stage > BF stage. CH_4 emissions in the TF stage of N1, WN1, RN1, and WRN1 treatments accounted for 77.2%, 54.2%, 87.5%, and 81.1%, respectively, of the total cumulative emissions during the rice season. These results indicated that CH_4 emissions from the paddy field mainly occurred in the TF stage. The cumulative CH_4 emissions of WN1, RN1, and WRN1 during the rice season were significantly higher than that of the N1 treatment. In summary, WRN1 > WN1 > RN1 > N1, with total emission values as follows: 270.4 > 248.3 > 112.3 > 64.5 kg·ha^{-1}, respectively ($p < 0.05$).

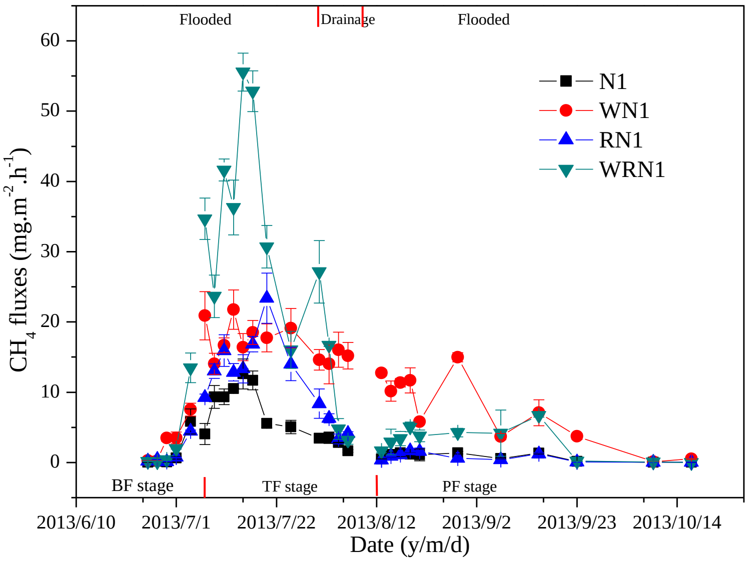

Figure 5. Dynamics of CH_4 flux during the rice season under different straw retention modes in 2013. Note: The following are all phases that take place during the rice season: BF stage: the basal fertilizer stage occurs from basal fertilizer application to tillering fertilizer application; TF stage: the tillering fertilizer stage occurs from tillering fertilizer application to panicle fertilizer application; PF stage: the panicle fertilizer stage occurs from panicle fertilizer application to rice harvest; Drainage (drainage period) refers to a period of drainage from 31 July to 8 August; Flooded refers to typical periods of continuous flooding. Treatment definitions are presented in the footnotes of Table 1. The vertical bars indicate standard errors.

Table 3. CH_4 and N_2O accumulated emissions during different rice growing stages under different treatments in 2013.

Factor	Treatments	CH_4 Accumulated Emission (kg·ha^{-1})				N_2O Accumulated Emission (kg·ha^{-1})			
		BF Stage	TF Stage	PF Stage	Rice Season	BF Stage	TF Stage	PF Stage	Rice Season
Straw retention modes	N1	3.39	49.8	11.32	64.5 d	0.30	0.11	0.36	0.77 a
	WN1	7.59	134.7	106.01	248.3 b	0.08	0.17	0.24	0.49 b
	RN1	2.91	98.3	11.13	112.3 c	0.10	0.22	0.28	0.60 a
	WRN1	7.99	219.3	43.07	270.4 a	0.13	0.04	0.18	0.35 b
Chemical N rates	WRN0	7.94	176.0	40.45	224.4 c	0.07	0.04	0.14	0.25 c
	WRN1	7.99	219.3	43.07	270.4 b	0.13	0.04	0.18	0.35 b
	WRN2	15.18	256.9	50.12	322.2 a	0.25	0.17	0.14	0.55 a

Note: Treatment definitions are presented in the footnotes of Table 1. Definitions of BF stage, TF stage, and PF stage are presented in the footnotes of Figure 5. Different letters within the same column with different straw retention modes or N rates indicate a significant difference at $p < 0.05$ according to the LSD test.

3.3. N_2O Emission with Different Straw Retentions

As shown in Figure 6, relative to the N1 treatment, the rice paddy field's N_2O fluxes were all low under the different straw retention modes. Furthermore, the N_2O emissions first increased and then decreased, exhibiting obvious fluctuating behavior. During the rice season, N_2O emission fluxes depicted four peaks, which appeared in the BF, TF, and PF stages, as well as the drainage period. The maximum peak value (0.32 mg·m^{-2}·h^{-1}) was observed in the BF stage during the N1 treatment, and the minimum peak value (0.02 mg·m^{-2}·h^{-1}) occurred in the drainage period during the WN1 treatment. The total N_2O cumulative emissions of the different straw retention modes during the rice season trended as follows: N1 (0.77) > RN1 (0.60) > WN1 (0.49) > WRN1 (0.35 kg·ha^{-1}). Thus, while straw retention was able to reduce N_2O emissions from the paddy field, the WN1 and WRN1 treatments had a stronger reduction effect on N_2O emissions than the RN1 treatment. In addition, the N_2O emission flux peak occurred only one time after each fertilization, indicating that N_2O emission was significantly affected by chemical N fertilizer application. While an N_2O emission flux peak was observed during the drainage period, this incident was attributed to the paddy field water being drained, which changed the paddy soil's anaerobic environment to promote N_2O production and emission.

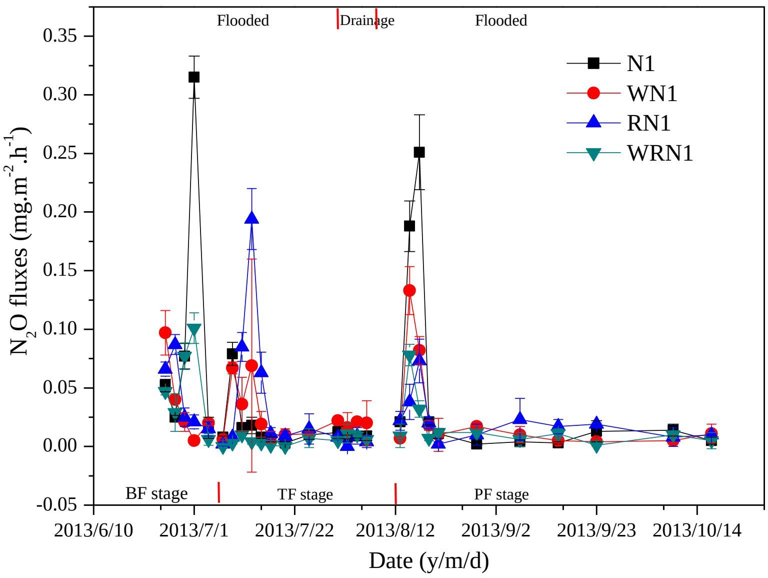

Figure 6. Dynamics of N_2O flux during the rice season under different straw retention modes in 2013. Note: Treatments definitions are presented in the footnotes of Table 1, and definitions of the BF stage, the TF stage, the PF stage, drainage, and flooded are presented in the footnotes of Figure 5. The vertical bars indicate standard errors.

The calculated cumulative N_2O emissions in different rice growing stages are presented in Table 3. The cumulative N_2O emission was highest during the PF stage, which accounted for 46.8%, 49.0%, 46.7%, and 51.4% of the total emissions for the N1, WN1, RN1, and WRN1 treatments, respectively. During the PF stage, N_2O emissions from the WN1 and WRN1 treatments were slightly higher than those of the N1 and RN1 treatments, indicating that N_2O emissions from rice fields treated with WN1 and WRN1 were more likely to occur in the rice season's late growing stage. In other words, wheat straw retention delayed the release of N_2O from the paddy field during the rice season.

3.4. *CH_4 and N_2O Emissions with Different N Fertilizer Rates*

CH_4 and N_2O emissions fluxes from the rice field with double-season's straw retentions under different chemical N application rates are presented in Figure 7. The CH_4 emission flux peaks during the rice season all occurred in the middle of July (Figure 7a). There was a significant difference in the CH_4 emission flux peaks in response to the different N fertilizer rates. The WRN2 treatment facilitated the highest peak value of 83.2 mg·m^{-2}·h^{-1}, the WRN1 treatment resulted in a peak value of 52.8 mg·m^{-2}·h^{-1}, and the WRN0 treatment produced the lowest peak value of 39.7 mg·m^{-2}·h^{-1}. There was also a significant difference in the cumulative CH_4 emissions among the different N fertilizer treatments (Table 3). The total CH_4 emissions during the rice season were 322.2, 270.4, and 224.4 kg·ha^{-1} for the WRN2, WRN1, and WRN0 treatments, respectively. Compared with the WRN1 treatment, CH_4 emissions from the WRN2 treatment increased by 19.2% ($p < 0.05$). These results suggest that during the rice season, CH_4 emissions in a paddy field with double-season's straw retentions significantly increased with conventional N application when compared with the recommended N application.

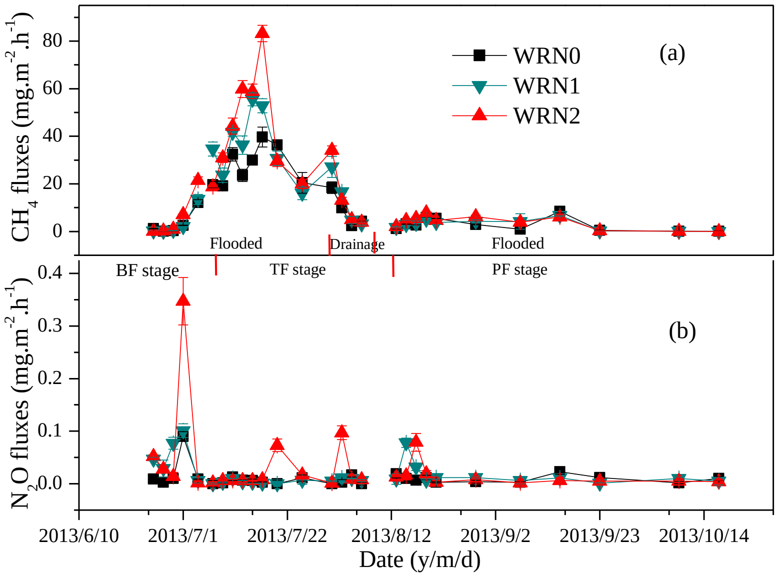

Figure 7. Dynamics of (**a**) CH_4 and (**b**) N_2O emissions during the rice season under double-season's straw retentions with different chemical N fertilizer rates in 2013. Note: Treatments definitions are presented in the footnotes of Table 1 and definitions of the BF stage, the TF stage, the PF stage, drainage, and flooded are presented in the footnotes of Figure 5. The vertical bars indicate standard errors.

The highest N_2O emission flux peak value under the different N rates was only 0.35 $mg{\cdot}m^{-2}{\cdot}h^{-1}$, which was significantly lower than the CH_4 emission flux peak value (Figure 7b). The total N_2O emissions from WRN0, WRN1, and WRN2 treatments during the rice season were 0.25, 0.35, and 0.55 $kg{\cdot}ha^{-1}$, respectively. Moreover, as shown in Table 3, there were significant differences in the cumulative N_2O emissions among the different N application rates ($p < 0.05$). Compared with the WRN0 treatment, the total N_2O emissions of the WRN1 and WRN2 treatments increased by 0.10 and 0.30 $kg{\cdot}ha^{-1}$, respectively, which indicates that chemical N fertilizer application significantly increased N_2O emissions of the paddy field with double-season's straw retentions. Relative to the WRN1 treatment, the total N_2O emissions of WRN2 increased by 36.4%, suggesting that N_2O emission from the paddy field increased in response to a higher N fertilizer application rate.

3.5. GWP and GHGI with Different Straw Retentions and N Fertilizer Rates

In this work, the cumulative CH_4 emissions under the WN1, RN1, and WRN1 treatments were 3.85, 1.74, and 4.19 times higher than that of the N1 treatment, respectively; while the cumulative N_2O emissions were 0.64, 0.78, and 0.46 times lower than that of the N1 treatment, respectively. Thus, straw retention increased CH_4 emissions and reduced N_2O emissions of the paddy field during the rice season. In contrast, the paddy field's CH_4 and N_2O emissions increased as a function of increasing chemical N fertilizer application. Under the WRN2 treatment, the cumulative emissions of CH_4 and N_2O increased by 19.2% and 57.1%, respectively, relative to the WRN1 treatment (Table 3).

The GWP values for the CH_4 and N_2O emissions were calculated for all six treatments, and the results are presented in Table 4. CH_4 accounted for 87.5%–98.5% of the total GWP under the different evaluated treatments. The contribution of CH_4 to total GWP during the rice season was significantly higher than that of N_2O. Thus, CH_4 was the main contributor to the greenhouse effect during the rice season. Straw retention and N fertilizer application significantly increased the total GWP of CH_4 and N_2O in the rice field ($p < 0.05$). Under different straw retention modes, the total GWP was highest in the WRN1 treatment, which was not significantly different from the WN1 treatment but was significantly higher than the RN1 treatment. Furthermore, the total GWP values of the WRN1, WN1, and RN1 treatments were 3.73, 3.45, and 1.62 times higher than that of the N1 treatment, respectively. The GWP values under different N fertilizer rates are accordingly ordered WRN2 > WRN1 > WRN0, and the total GWP value of the WRN1 treatment decreased by 16.5% relative to the WRN2 treatment.

Table 4. Effects of straw retention modes and N fertilizer rates on global warming potential (GWP) and greenhouse gas intensity (GHGI) during the rice season.

Factor	Treatments	GWP (kg CO_2-eq·ha^{-1})			GHGI (kg CO_2·kg^{-1}grain)
		CH_4	N_2O	CH_4+N_2O	
Straw retention modes	N1	1612.5 d	229.5 a	1842 c	0.25 c
	WN1	6207.5 b	146.0 b	6354 a	0.75 a
	RN1	2807.5 c	178.8 a	2986 b	0.38 b
	WRN1	6760.0 a	104.3 b	6864 a	0.74 a
Chemical N rates	WRN0	5610.0 c	74.5 c	5685 c	0.83 b
	WRN1	6760.0 b	104.3 b	6864 b	0.74 c
	WRN2	8055.0 a	163.9 a	8219 a	1.07 a

Note: The GWP of CH_4 and N_2O within a 100-year time frame were converted into their CO_2 equivalent (CO_2-eq) emissions by multiplying their cumulative emissions by 25 and 298, respectively [43]. GHGI was calculated by dividing the GWP by the rice yield. Treatment definitions are presented in the footnotes of Table 1. Different letters in the same column with different straw retention modes or N rates indicate a significant difference between the treatments at $p < 0.05$ according to the LSD test.

Each treatment's GHGI was calculated by dividing its GWP by the rice yield (Table 4). The GHGI under different straw retention modes demonstrated the following trend: WN1 ≥ WRN1 > RN1 > N1 and was ordered as follows under different N fertilizer rates: WRN2 > WRN0 > WRN1. The GHGI values under the WN1, WRN1, and RN1 treatments were 3.00, 2.96, and 1.52 times higher than that of the N1 treatment, respectively. Compared with the WRN2 treatment, the GHGI of the WRN1 treatment decreased by 30.1%, indicating that the WRN1 treatment effectively reduced the GHGI during the rice season.

4. Discussion

4.1. Effects of Straw Retention and N Fertilizer Application on Rice Yields

Nitrogen is the most limiting nutrient in rice production [45] as it directly determines the grain yield [46]. While too little N will inhibit output, N fertilizer application can increase rice yield. The results obtained in this experiment validated that premise. The rice yields significantly increased under the treatment with straw retention and N fertilizer application relative to the rice yield with no N fertilizer. However, the WRN2 treatment exhibited an N fertilizer rate 25.0% higher than that of the WRN1 treatment, yet the rice yield decreased by 17.3%. Apparently, there is an optimal N fertilizer range in which the rice yield increases as the N fertilizer rate increases [47]. When the amount of N fertilizer exceeds the maximum application rate of the optimal range, grain yield decreases in response to the increase of lodging, pests and diseases of rice [48,49] and negative environmental effects, such as water and soil pollution [50]. Wang et al. [47] showed that the optimum N application range was 225–270 kg N·ha^{-1} for rice in this region. In this study, the WRN2 treatment's N fertilizer application rate was excessive, so the rice yield from this treatment was lower than that of the WRN1 treatment. In this experiment, all the different straw retention modes showed an increased rice yield under the optimal N fertilizer application rate. In essence, straw retention can increase SOC content, improve soil nutrients, and enhance the rice-growing environment [9,10,51,52]. Straw retention coupled with the optimal N application rate increases rice yield by increasing the number of effective panicles per unit area and the number of grains per panicle [53].

4.2. Effect of Straw Retention on CH_4 Emission

Rice fields are primary sources of atmospheric CH_4. Organic materials, such as plant and animal residue, transform the paddy soil into CH_4-producing precursors via microorganisms; then CH_4-producing bacteria generate CH_4 under anaerobic and waterlogged conditions. In the process of being released into the atmosphere, a certain percentage of CH_4 is oxidized. Eventually, about 10%–50% of CH_4 emissions are released into the atmosphere [54,55]. Straw return increased CH_4 emissions from the paddy field, which has two possible explanations: (1) straw return provided a rich precursor for CH_4 production in the paddy soil; and (2) during flooded irrigation, the oxygen-consuming decomposition of organic matter formed a strong reducing environment, which was beneficial to the growth of methanogens [11,34,35,38]. In this study, the paddy field's CH_4 emissions under straw retention were significantly higher than that under the single fertilizer treatment. Moreover, the cumulative CH_4 emission was highest under double-season's straw retentions, intermediate under single wheat straw retention, and lowest under single rice straw retention. In addition, the cumulative CH_4 emission values of the WRN1, WN1, and RN1 treatments were 4.19, 3.85, and 1.74 times higher than that of the N1 treatment, respectively. We surmise that this phenomenon is mainly due to an increase in the paddy field's SOC in response to different straw retention treatments. In this experiment, because the amount of rice straw retention (10.0 t·ha^{-1}) was greater than the amount of wheat straw retention (5.50 t·ha^{-1}), after a year of rice–wheat cycle, the SOCD of the wheat harvest soil subjected to RN1 and WN1 treatments was 38,391 and 37,231 kg C·ha^{-1}, respectively. With respect to the rice harvest soil (third season), the decomposition of embedded rice straw in the RN1 treatment mainly occurred in the previous wheat season [56], while the WN1 treatment brought about 2431 kg C·ha^{-1} by wheat straw retention, resulting in a higher SOCD from the WN1 treatment than the RN1 treatment. Therefore, during the rice season, the paddy field's SOCD was largest under the double-season's straw retentions mode, intermediate under the wheat straw retention mode, and smallest under the rice straw retention mode.

4.3. Effect of Straw Retention on N_2O Emission

N_2O in the rice field was mainly produced by the nitrification and denitrification of mineral N in the soil. As a byproduct of nitrification and denitrification, part of the N_2O was converted to N_2 by N_2O reductase in the soil's strong reducing environment. The paddy field was flooded for a long time during the rice season, which caused the soil to become strongly reducing, and therefore not conducive to N_2O production. As such, the field in this region had a low N_2O emission flux during the rice season.

In recent years, studies investigating whether straw retention can promote or inhibit N_2O emission in rice fields have been carried out. Some studies found that straw retention provided rich C and N reactive substrates for soil nitrification and denitrification, which significantly increased the rice field's N_2O emission during the rice season [35,36]. However, our study showed that straw retention reduced the rice field's N_2O emission. Although straw returned to the field released a certain amount of mineral N during the decomposition process, the high C/N ratio of crop straw resulted in the external N consumption [57]; thus, large amounts of soil mineral N were immobilized in the decomposition process. Therefore, the nitrification and denitrification reaction substrate decreased to some extent [11]. In addition, the produced N_2O could be easily converted to N_2 by denitrification in a strong reducing environment [8]. In this study, the cumulative N_2O emissions of the WRN1, WN1, and RN1 treatments reduced by 54.4%, 36.4%, and 22.1%, respectively, compared with the N1 treatment. N_2O emissions from the WRN1 treatment were lower than those of the WN1 and RN1 treatments because the amount of straw returned in the WRN1 treatment was maximized. The amount of straw returned for a one-year cropping cycle was higher in the RN1 treatment than the WN1 treatment, but the cumulative N_2O emissions of the RN1 treatment was lower than that of the WN1 treatment. This phenomenon is explained by the fact that the rice straw decomposition of the RN1 treatment mainly occurred in the previous wheat season. After decomposing for one wheat season, the residual rate for the embedded rice straw was 40% [56] (about 4.00 t·ha^{-1}) under the RN1 treatment, which was less than the amount of wheat straw returned under the WN1 treatment (5.50 t·ha^{-1}). This result indicates that the rice field's N_2O emissions are negatively correlated with the amount of straw retention.

4.4. Effects of N Fertilizer Application on CH_4 and N_2O Emissions

Generally, straw retention with N fertilizer application increases the rice field's CH_4 emission [1,22–25]. This occurs because the N fertilizer application provides substrates for methanogens by increasing root secretions and litter [24,58]. In addition, Cai et al. [27] surmised that chemical N (urea) hydrolysis released NH_4^+, after which the NH_4^+ stimulated CH_4 emission. In this experiment, the paddy field's CH_4 emission increased as a function of increasing chemical N fertilizer application. This result is consistent with the previous research results on paddy fields. The respective cumulative CH_4 emissions of the WRN2 and WRN1 treatments were 1.44 and 1.20 times higher than that of the WRN0 treatment. Compared with the recommended N fertilizer treatment, the conventional N fertilizer treatment significantly increased the cumulative CH_4 emission by 19.2%. Essentially, the soil's NH_4^+ concentration was higher under the conventional N application rate than under the recommended N application rate. When the NH_4^+ concentration was high, NH_4^+ could inhibit CH_4 oxidation and methanotroph growth by competing with CH_4 for enzyme (CH_4 monooxygenase) reaction sites, leading to an increase in the field's CH_4 emissions [26,59].

N_2O emissions from the rice fields with straw retention were reported to decrease during the rice season [33,34,39]. However, chemical N fertilizer application under straw retention could increase N_2O emissions [1]. In this work, under the condition of double-season's straw retentions, the cumulative N_2O emission from the rice field treated with the conventional N fertilizer rate increased by 36.4% relative to the paddy field treated with the recommended N fertilizer rate. Essentially, the conventional N fertilizer treatment enhanced the NH_4^+ and NO_3^- concentrations in the paddy soil compared with the recommended N fertilizer treatment, which provided more NH_4^+ and NO_3^- reaction substrates for the nitrification–denitrification process, and ultimately promoted N_2O production [60,61]. Therefore, excessive application of N fertilizer is an important cause of increasing the paddy field's N_2O emission. Cai et al. [27] and Ma et al. [62] also reached a similar conclusion based on their evaluation of a paddy field in China.

5. Conclusions

This study demonstrated the effects of straw retention and N fertilizer on rice yield, CH_4 and N_2O emissions, GWP, and GHGI of a rice–wheat cropping system during the rice season in the lower Yangtze River region, China. Our results showed that CH_4 emissions were mainly concentrated in the TF stage of rice season, which was the main contributor of GHGs from the paddy field, while N_2O was mainly in the PF stage. Straw retention enhanced CH_4 emissions and reduced N_2O emissions, however, N fertilizer application increased both CH_4 and N_2O emissions. All the three straw retention modes investigated herein significantly enhanced greenhouse effect, and the single rice straw retention mode made the smallest contribution to the GWP and GHGI. The recommended N fertilizer rate not only maintained high rice yield but also significantly reduced GWP and GHGI relative to the conventional N rate under the condition of double-season's straw retentions. Therefore, with the development of full mechanized straw retention, we propose this region adopt the "rice straw retention + recommended N fertilizer" model for the rice–wheat cropping system. Wheat straw should be removed from the field by a straw pickup baler and used for various alternative purposes, which both resolves the environmental problems associated with wheat straw burning and increases the farmer's revenue. In addition, water management measures, such as intermittent drainage and controlled irrigation, should be applied during the TF stage of rice season to reduce CH_4 emissions. Nevertheless, it is necessary to consider minimizing N_2O emissions by optimizing these measures.

Due to limited data, this study did not analyze the CH_4 and N_2O emissions and wheat yield during the wheat season, which should be considered in evaluating the effects of straw retention and

N fertilizer application on CH_4 and N_2O emissions in paddy fields in a yearly rice–wheat cropping system. In the future, year-round GHG emissions and crop yields should be investigated in this system. Additionally, the single rice straw retention mode may lead to a reduction in wheat production, but this risk can be mitigated by agronomic measures such as post-sowing soil compaction.

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