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Greenhouse Gas Emissions from Double-Season Rice Field under Different Tillage Practices and Fertilization Managements in Southeast China

Tong Yang †, Zhi Yang †, Chunchun Xu, Fengbo Li, Fuping Fang and Jinfei Feng *

China National Rice Research Institute, Hangzhou 310006, China
* Correspondence: fengjinfei@caas.cn; Tel.: +86-0571-63371009
† These authors contributed equally to this work.

Abstract: To better understand the effects of tillage practice and fertilization management on greenhouse gas emissions and yields, a four-year field experiment was conducted to assess the effects of tillage practices (rotary tillage (RT) and no tillage (NT)) on the emissions of methane (CH_4) and nitrous oxide (N_2O) and rice yield under four fertilization management strategies (no fertilizer without straw (CK), inorganic fertilizer without straw (F), inorganic fertilize with biochar (FB), and inorganic fertilizer with straw (FS)). The results showed that NT significantly reduced CH_4 emissions by 21.1% and 52.6% compared to RT in early and late rice, respectively. Conversely, NT led to a significant increase in N_2O emissions by 101.0%, 79.0%, and 220.8% during the early rice, late rice, and fallow periods. Nevertheless, global warming potential (GWP) and greenhouse gas intensity (GHGI) were significantly mitigated, respectively, by 36.4% and 35.9% in NT, compared to RT treatment. There were significant interactions between tillage practice and fertilization management. Compared with CK, the F and FB treatments significantly reduced the GWP, respectively, by 40.4% and 53.8%, as well as the GHGI, respectively, by 58.2% and 69.9% in the RT condition; however, no significant difference was found under the NT condition. In contrast, the FS treatment significantly increased GWP and GHGI in both the RT and NT conditions. Overall, FB treatment had the same significantly low GHGI rating, with a value of 0.44 kg CO_2-eq kg^{-1} yield $year^{-1}$ in RT and NT. Thus, the conversion of straw to biochar and its application to rice fields is a potentially sustainable agricultural strategy for mitigating GHG emissions and increasing yields. This study provides theoretical and practical support for double-season rice production in climate-smart agriculture.

Keywords: methane; nitrous oxide; no tillage; straw return; biochar; yield; greenhouse gas intensity

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1. Introduction

In recent years, global warming, caused by greenhouse gases (GHGs), has been gradually increasing, leading to increased attention on the resulting frequent occurrence of extreme weather events and environmental problems. Agricultural production is a main anthropogenic source of greenhouse gases, accounting for 50% and 60% of anthropogenic methane (CH_4) and nitrous oxide (N_2O), respectively [1]. Rice is one of the world's three staple crops, feeding nearly half of the world's population [2]. However, rice fields are also considered to be one of the largest sources of agricultural GHG emissions. The CH_4 and N_2O emissions from rice cultivation account for approximately 17.3% and 11.0%, respectively, of global agricultural emissions [3,4]. As the world's population continues to grow, an important challenge for future rice production is to increase crop yield while simultaneously reducing greenhouse gas emissions.

CH_4 and N_2O production in agricultural soils is based on complex microbial processes and is strongly influenced by agronomic measures such as tillage, fertilization, and irrigation, etc. [5–8]. Tillage performs an important role in the emissions of CH_4 and N_2O from soils. It can stimulate the decomposition of organic matter, alter soil physical structure, and influence the distribution of microbial communities, thereby impacting the utilization of available carbon and nitrogen in the soil, which are crucial substrates for CH_4 and N_2O production [9–11]. No tillage (NT), an agricultural conservation practice, enhances soil organic matter and nutrient levels by minimizing soil disturbance and preserving plant residues [12,13]. This practice can induce alterations in the soil's physical, chemical, and biological properties, in turn influencing the production and release of greenhouse gases [14]. However, the impact of NT on GHG emissions compared to conventional tillage (CT) remains unclear due to the substantial variations observed in different rice fields. Previous studies showed that NT either significantly reduced [15–17], increased [18], or did not affect [19,20] the CH_4 emissions from rice fields. Moreover, similar results in NT practice have been observed in response to N_2O emissions, with significant reductions [21], increases [15], and insignificant effects [16,18]. Therefore, further studies are needed to verify the effects of tillage on CH_4 and N_2O in rice fields.

Fertilization management is another important factor influencing CH_4 and N_2O emissions derived from soil [22]. It is widely accepted that nitrogen (N) fertilizer application is an important cause of N_2O emissions from agricultural fields [1]; however, the effect on CH_4 emissions is more complex, as it is influenced by a variety of factors including fertilizer type, application practice, and agricultural management [5,23]. Organic fertilizers (e.g., straw, manure, green manure, and biogas residue, etc.) are generally considered to contribute to soil CH_4 production and emission by supplying a large source of carbon [24–27]; meanwhile, the effects of inorganic fertilizers vary with positive, negative, or negligible impacts due to the intricate underlying mechanisms [23,28–30]. In recent years, the addition of biochar has been recommended as an effective agricultural practice for crop production because of its advantageous ability to improve soil structure, enhance soil carbon sequestration, and maintain water and fertility [31–33]. However, the impact of biochar on CH_4 and N_2O emissions remains uncertain. Some studies have found that biochar can enhance CH_4 emission [34,35] and N_2O emission [25,36] in rice fields. Conversely, other studies have reported a significant decrease in CH_4 emission [37,38] and N_2O emission [39,40] with biochar amendment. Recent meta-analyses have indicated that the effect of fertilization management strategies (e.g., straw return, biochar amendment) on GHG emissions was highly influenced by tillage practices [6,26,41]. However, most current in situ field studies have focused on individual aspects of either tillage or fertilization, and there is a lack of research on their interaction, particularly in double-season rice fields.

China is the world's largest rice-cultivating nation, accounting for 19.1% of the global rice cultivation area [4]. The double-season rice cropping system is a primary method of rice production, covering 40.1% of the total cultivation area [42]. Compared with other rice production patterns, such as rice-upland rotation and single-season rice, double-season rice exhibited the highest CH_4 and N_2O emissions [24]. In this study, it was hypothesized that adopting the appropriate tillage practice and fertilization management strategy can maintain high yields while reducing greenhouse gas emissions, thus achieving a sustainable and clean production of double-season rice. Hence, we conducted a four-year split-plot-designed experiment with tillage as the main plot and fertilization as the subplot and aimed to: (1) monitor and analyze the variations of CH_4 and N_2O emissions under different tillage practices and fertilization management strategies and (2) propose optimal combinations of tillage practices and fertilization management strategies to maintain a high rice yield while minimizing greenhouse gas emissions.

2. Materials and Methods

2.1. Experimental Site

The experiment was initiated in 2017 at the experimental field of China International Rice Research Institute (CNRRI), Zhejiang Province, China (30°05′ N, 119°55′ E). The region has a subtropical monsoon climate with a mean annual rainfall of 1454 mm and an average temperature of 17.8 °C. The daily mean air temperature and precipitation in the experimental site from April 2017 to April 2021 are shown in Figure 1. Before the experiment, the soil type in the site was submerged paddy soil with a pH (1:2.5H_2O) of 5.82, a SOC of 17.85 g kg^{-1}, a total N of 1.79 g kg^{-1}, a total P of 0.43 g kg^{-1}, and a total K of 15.76 g kg^{-1}.

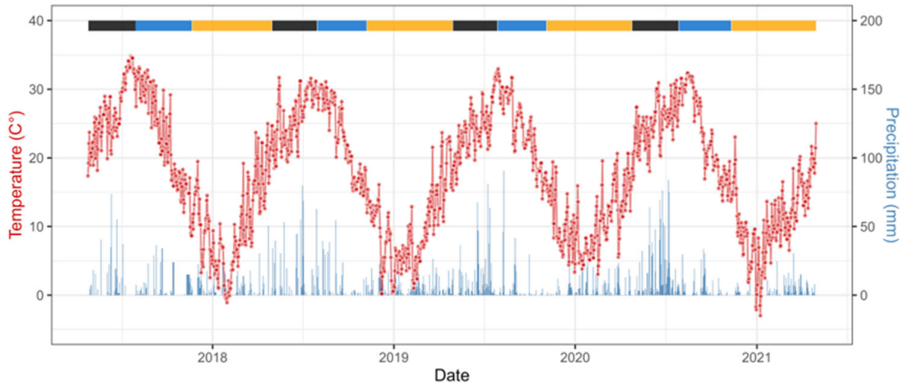

Figure 1. Daily mean air temperature and precipitation in the experimental site from April 2017 to April 2021. At the top of the figure, black bar indicates the growing season of early rice, blue bar indicates the growing season of late rice, and orange bar indicates the fallow period.

2.2. Experimental Design and Field Management

In this double-season rice field experiment, the treatments were adopted by a split-plot design with eight treatments (Figure 2a). The main plot consisted of two types of tillage: rotary tillage (RT) and no tillage (NT); the subplot consisted of four fertilization management strategies: no fertilizer without straw (CK), inorganic fertilizer without straw (F), inorganic fertilize with biochar (FB), and inorganic fertilizer with straw (FS). Each treatment had three replicated plots with a 28 m^2 area (4 m by 7 m); between plots, the ridges (30 cm wide and 30 cm high) were covered by plastic films in order to prevent the exchange of water and fertilizer.

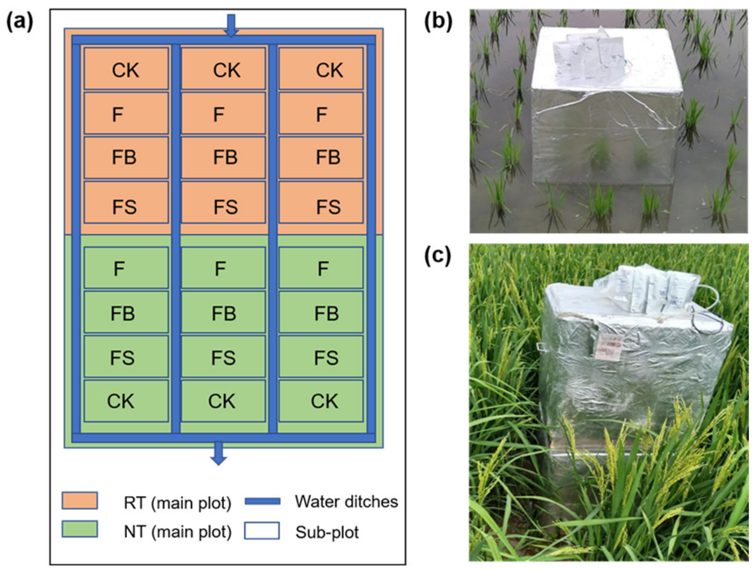

Figure 2. Schematic diagram of the plot layout (**a**), sampling in tillering stage (**b**), and sampling in the heading stage with height-raising devices (**c**).

In NT, the soil was always protected from disturbance. For RT, the soil in the plots was separately tilled with a rotary tiller to a depth of about 20~25 cm. In F treatment, the inorganic fertilizers were urea (N), calcium superphosphate (P), and potassium chloride (K). The inorganic fertilizer was applied at rates of 120 kg N ha^{-1}, 65 kg P_2O_5 ha^{-1}, and 90 kg K_2O ha^{-1} in the early rice season, and rates of 150 kg N ha^{-1}, 75 kg P_2O_5 ha^{-1}, and

112.5 kg K_2O ha^{-1} in the late rice season. The P and K fertilizers were applied only as basal fertilizer, while the N fertilizer was split into basal fertilizer (60%), tillering fertilizer (25%), and panicle fertilizer (15%). The application rates and methods of the inorganic fertilizers (urea (N), calcium superphosphate (P), and potassium chloride (K)) were consistent with those employed by local farmers. In the FB treatment, biochar was applied at a rate of 10.8 t ha^{-1} before the early rice season in 2017. For the FS treatment, the rice straw of every plot was collected and fragmented into 5 cm pieces and then returned to each plot after harvest with an amount of 5.17 and 5.82 t ha^{-1}, respectively, for the early and late rice seasons. The straw of other treatments was removed, meaning that the rice residue left in the field was less than 1 cm. In the RT treatment, the basal fertilizer, straw fragments, and biochar were uniformly mixed into the soil using rototilling, while, under the NT treatment, they were spread evenly on the ground surface.

The early rice (Zhongjiazao 17, an inbred variety) was transplanted between 27 April and 3 May in 2017–2020 at a spacing of 16 cm × 25 cm, and the late rice (Tianyouhuazhan, a hybrid variety) was transplanted between 31 July and 3 August at a spacing of 20 cm × 30 cm. All agricultural practices were carried out according to local farmers' tradition, with mid-season aeration and late-season drainage in every growing season. During the fallow period, from November to April, the fields were uncultivated and maintained drainage.

2.3. Measurements of CH_4 and N_2O Fluxes

The fluxes of CH_4 and N_2O were monitored continuously in the double-season rice field using a static chamber technique. The chamber was made of stainless steel (dimensions: 50 cm × 50 cm × 50 cm) and covered with insulated and reflective materials to avoid external temperature and solar interference (Figure 2b). Stainless steel bases for chambers were immediately fixed in the plots after the rice transplant and kept immobile until the next transplant. The removable steel foot-bridges were used to collect samples in order to avoid disturbing the soil in plots. Moreover, from the heading stage to harvest, a height-raising device was used to increase the height of the chamber (50 cm × 50 cm × 100 cm) to collect the gases in order to avoid damaging the rice plants (Figure 2c).

Gas samples were collected once a week during the growth period and once every two weeks during the fallow period between 8:00 AM and 10:00 AM; moreover, they were collected every other day for the first week after fertilizer addition. However, in the fallow periods of 2019–2020 and 2020–2021, the collecting cycle was not fixed due to the occurrence of COVID-19, with an average cycle of 21 and 25 days. The sampling time was 30 min for each plot, and a total of four samples were collected at 0, 10, 20, and 30 min using an automatic GHG sampler. The gas samples were analyzed using gas chromatography (GC 2010, Shimadzu, Kyoto, Japan), and the flux (F) of CH_4 and N_2O was calculated using the following equation [43]:

$$F = \rho \times V/A \times dc/dt \times 273/(273 + T) \tag{1}$$

where F is the flux of CH_4 or N_2O ($mg \cdot m^{-2} \cdot h^{-1}$), ρ is the density of CH_4 (0.714 $kg \cdot m^{-3}$) or N_2O (1.964 $kg \cdot m^{-3}$), V and A are the volume (m^3) and area (m^2) of the static chamber, respectively, dc/dt is the change of CH_4 or N_2O concentration in the sampling chamber in unit time ($\mu L \cdot L^{-1} \cdot h^{-1}$), and T is the air temperature in the chamber (°C). The cumulative emission was estimated by averaging the flux between the two samplings and multiplying by the time interval.

2.4. Data Calculation and Statistical Analysis

The global warming potential (GWP) and greenhouse gas intensity (GHGI) were calculated using the following equations [20,44]:

$$GWP = 27 \times CH_4\ (kg\ CH_4\ ha^{-1}) + 273 \times N_2O\ (kg\ N_2O\ ha^{-1}) \tag{2}$$

$$GHGI = GWP/Yield\ (kg\ CO_2\ eq\ kg^{-1}\ grain\ yield) \quad (3)$$

In Equation (2) the numbers 27 and 273 are the conversion factors for CH_4 and N_2O to CO_2, respectively [1]. The data were statistically analyzed using R software (4.2.2). Two-factor analysis of variance (ANOVA) was used to test the effect of tillage and fertilization and their interactions. The Tukey HSD test was used to compare the mean differences among treatments. All graphs were plotted using the ggplot2 package (3.4.1).

3. Results

3.1. CH_4 Emissions

The seasonal patterns of the CH_4 fluxes were similar among the different tillage practices or different fertilization management strategies in the double-season rice field from 2017 to 2021 (Figure 3). The fluxes of CH_4 ranged from −1.81 to 37.10 mg m^{-2} h^{-1} with an average of 3.07 mg m^{-2} h^{-1} during the early rice season, from −0.42 to 213.6 mg m^{-2} h^{-1} with an average of 13.22 mg m^{-2} h^{-1} during the late rice season, and from −1.23 to 1.15 mg m^{-2} h^{-1} with an average of 0.03 mg m^{-2} h^{-1} during the fallow period over the four years. The peak CH_4 emissions of all treatments occurred in the early stage of the late rice growing season, achieving the highest value of 213.6 mg m^{-2} h^{-1} of RT-FS.

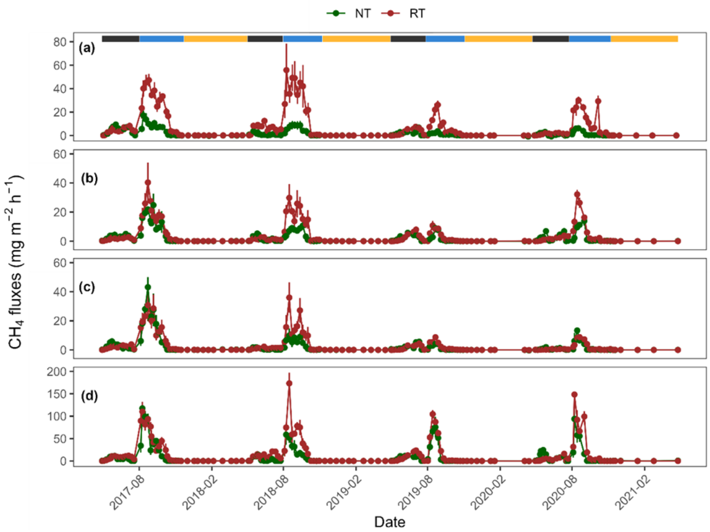

Figure 3. CH_4 fluxes of different tillage practices in the double-season rice field combined with CK (**a**), F (**b**), FB (**c**), and FS (**d**) from April 2017 to April 2021. At the top of the figure, black bar indicates the growing season of early rice, blue bar indicates the growing season of late rice, and orange bar indicates the fallow period. Error bars represent standard error (n = 3).

Tillage and fertilization significantly affected CH_4 emissions, and they had significant interactions in the early and late rice seasons (Table 1). The four-year average cumulative CH_4 emission of NT significantly decreased by 21.1% and 52.6%, respectively, in the early and late rice seasons compared with RT. Fertilization management strategies had a consistent effect on CH_4 emission in both early and late rice seasons (Table 1). Compared to CK, the FS significantly enhanced CH_4 emission during the early rice, late rice, and fallow stages, with an annual increase of 165.5%. In contrast, the F and FB treatments significantly mitigated CH_4 emissions, with decreases of 32.2% and 44.5%, respectively. Interestingly, the inhibition of CH_4 by F and FB occurred only under RT conditions but not NT. This suggested that the change in tillage practice significantly affected the effect of fertilization.

Table 1. Responses of the cumulative emission of CH_4 to different tillage practices and fertilization management strategies over the four-year experimental period.

Factors	Treatment	CH_4 (kg ha^{-1})			
		Early Rice	**Late Rice**	**Fallow**	**Total**
Tillage (T)	RT	75.9 ± 22.6 a	433.3 ± 173.6 a	1.4 ± 0.3 a	510.6 ± 206.5 a
	NT	59.9 ± 33.0 b	205.6 ± 109.7 b	1.1 ± 0.8 a	267.0 ± 131.9 b
Fertilization (F)					
	CK	60.9 ± 11.4 b	256.5 ± 114.8 b	0.7 ± 0.5 b	318.1 ± 126.3 b
	F	43.0 ± 5.4 bc	171.5 ± 38.6 c	1.3 ± 0.4 ab	215.8 ± 36.7 c
	FB	26.8 ± 3.1 c	148.7 ± 27.9 c	0.9 ± 0.3 b	176.5 ± 29.7 c
	FS	140.9 ± 19.4 a	701.7 ± 132.6 a	2.1 ± 0.8 a	844.7 ± 150.2 a
Tillage (T) × Fertilization (F)					
	RT-CK	77.2 ± 7.5 c	433.1 ± 41.3 b	1.5 ± 0.1 ab	511.7 ± 48.4 b
	RT-F	38.4 ± 6.3 d	231.3 ± 12.2 c	1.6 ± 0.4 ab	271.4 ± 16.1 c
	RT-FB	25.9 ± 3.1 d	177.5 ± 27.1 cd	1.0 ± 0.2 bc	204.4 ± 30.3 cd
	RT-FS	162.2 ± 14.4 a	891.1 ± 72.2 a	1.5 ± 0.4 ab	1054.8 ± 86.7 a
	NT-CK	44.6 ± 2.2 d	80.0 ± 8.3 d	0.0 ± 0.4 c	124.5 ± 7.6 d
	NT-F	47.5 ± 3.4 d	111.7 ± 1.1 d	1.0 ± 0.3 bc	160.2 ± 4.0 cd
	NT-FB	27.7 ± 3.8 d	120 ± 19.5 cd	0.8 ± 0.5 bc	148.5 ± 22.5 cd
	NT-FS	119.6 ± 16.7 b	512.2 ± 53.1 b	2.7 ± 1.0 a	634.6 ± 68.5 b
F values					
T		6.62 *	74.71 ***	0.635	58.24 ***
F		65.82 **	96.9 ***	3.666 *	91.15 ***
T × F		4.13 *	9.55 ***	3.055	8.55 **

Mean ± SE; different letters indicate significant difference at $p < 0.05$. *, **, and *** mean significance at the 0.05, 0.01, and 0.001 levels, respectively.

3.2. N_2O Emissions

Different from CH_4 fluxes, the fluxes of N_2O demonstrated an unpredictable seasonal pattern; moreover, its peak emissions occurred in the early rice season, late rice season, or fallow period throughout the four years (Figure 4). Fluxes of N_2O ranged from −28.5 to 2547.1 µg m^{-2} h^{-1} with an average of 60.1 µg m^{-2} h^{-1} during the early rice season, from −88.2 to 1725.1 µg m^{-2} h^{-1} with an average of 56.0 µg m^{-2} h^{-1} during the late rice season, and from −78.8 to 1266.2 µg m^{-2} h^{-1} with an average of 42.9 µg m^{-2} h^{-1} during the fallow period over the four years. The highest fluxes of N_2O occurred mainly in the mid-season or late drainage period of early and late rice.

Tillage, fertilization, and their interactions all had significant effects on N_2O emissions (Table 2). For the four-year average, N_2O emissions from NT were significantly higher by 101.0%, 79.0%, and 220.8% in early rice, late rice, and fallow period, respectively, compared to CT. Inorganic fertilization application significantly improved the N_2O emission in all three periods, with an annual increase of 240.6%. Compared with the F treatment, biochar amendment significantly increased N_2O emission during the early rice season under NT conditions but not under RT conditions. The combination of NT and FS produced the highest N_2O emission, with an annual emission of 14.51 kg ha^{-1}.

3.3. Grain Yields

The impacts of tillage and fertilization on yields showed variations across different years, with no significant interaction observed between tillage and fertilization (Table 3). The NT significantly reduced annual yield by 17.1% and 13.3% during the initial 2 years (2017 and 2018), while there was no significant decrease in rice yield in NT during the final 2 years (2019 and 2020). On average, NT decreased the rice yield by 8.4% compared with RT over the four cropping years. Inorganic fertilization application significantly increased the rice yield across the four years; however, no significant difference was found between the F and FS treatments. However, the biochar amendment significantly increased the annual yield both under RT and NT conditions, with values of 8.7% and 6.9%, respectively, compared with the F treatment.

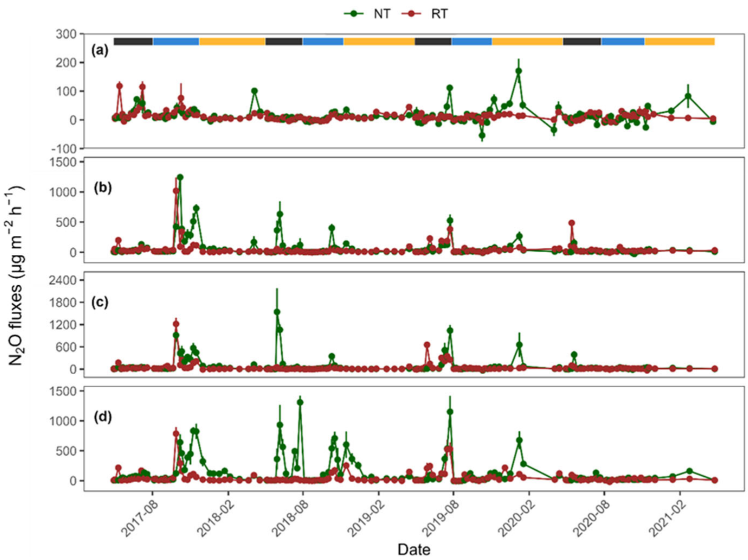

Figure 4. N_2O fluxes of different tillage practices in the double-season rice field combined with CK (**a**), F (**b**), FB (**c**), and FS (**d**) from April 2017 to April 2021. At the top of the figure, black bar indicates the growing season of early rice, blue bar indicates the growing season of late rice, and orange bar indicates the fallow period. Error bars represent standard error (n = 3).

Table 2. Responses of cumulative emission of N_2O to different tillage practices and fertilization management strategies over the four-year experimental period.

Factors	**Treatment**	**N_2O (kg ha^{-1})**			
		Early Rice	**Late Rice**	**Fallow**	**Total**
Tillage (T)	RT	1.05 ± 0.24 b	1.43 ± 0.40 b	1.01 ± 0.32 b	3.50 ± 0.85 b
	NT	2.11 ± 0.75 a	2.56 ± 0.85 a	3.24 ± 1.40 a	7.92 ± 2.72 a
Fertilization (F)					
	CK	0.49 ± 0.07 c	0.32 ± 0.04 c	0.84 ± 0.26 c	1.65 ± 0.31 c
	F	1.40 ± 0.24 b	2.39 ± 0.47 b	1.83 ± 0.45 b	5.62 ± 1.01 b
	FB	2.03 ± 0.58 a	2.43 ± 0.42 b	1.42 ± 0.55 b	5.88 ± 1.41 b
	FS	2.41 ± 0.75 a	2.86 ± 0.71 a	4.42 ± 1.72 a	9.68 ± 3.11 a
Tillage (T) × Fertilization (F)					
	RT-CK	0.40 ± 0.01 d	0.38 ± 0.01 d	0.49 ± 0.02 d	1.27 ± 0.03 d
	RT-F	1.23 ± 0.07 bc	1.71 ± 0.16 c	1.15 ± 0.14 cd	4.09 ± 0.32 c
	RT-FB	1.25 ± 0.14 bc	1.89 ± 0.29 c	0.63 ± 0.07 d	3.77 ± 0.47 c
	RT-FS	1.32 ± 0.11 bc	1.77 ± 0.11 c	1.77 ± 0.21 bc	4.85 ± 0.21 c
	NT-CK	0.58 ± 0.06 cd	0.27 ± 0.02 d	1.18 ± 0.24 cd	2.03 ± 0.30 d
	NT-F	1.56 ± 0.34 b	3.07 ± 0.25 b	2.52 ± 0.10 b	7.14 ± 0.36 b
	NT-FB	2.81 ± 0.46 a	2.97 ± 0.27 b	2.21 ± 0.36 b	7.98 ± 0.55 b
	NT-FS	3.50 ± 0.46 a	3.95 ± 0.23 a	7.07 ± 0.55 a	14.51 ± 0.87 a
F values					
T		30.76 ***	65.31 ***	139.81 ***	189.71 ***
F		19.32 ***	66.53 ***	69.99 ***	104.63 ***
T × F		6.39 **	11.61 ***	30.24 ***	34.57 ***

Mean ± SE; different letters indicate significant difference at $p < 0.05$. ** and *** mean significance at the 0.01 and 0.001 levels, respectively.

3.4. GWP and GHGI

Global warming potential (GWP) and greenhouse gas intensity (GHGI) were significantly affected by tillage, fertilization, and their interactions across this four-year experiment (Table 4). NT significantly decreased the annual GWP and GHGI by 36.4% and 35.9%, respectively, compared with the RT treatment. Regarding the different fertilization management strategies, the F and FB treatments only significantly decreased GWP and GHGI under RT conditions compared with the CK treatment. However, the GWP and

GHGI of the FS treatment were significantly high in two tillage practices, with values of 29,806.4 kg CO_2-eq ha^{-1} and 2.16 kg CO_2-eq kg^{-1} in RT and 21,095.1 kg CO_2-eq ha^{-1} and 1.58 kg CO_2-eq kg^{-1} in NT.

Table 3. Responses of rice yield to different tillage practices and fertilization management strategies from 2017 to 2020.

Factors	Treatment	Yield (t ha^{-1})				
		2017	2018	2019	2020	2017–2020
Tillage (T)	RT	14.0 ± 1.1 a	10.5 ± 0.9 a	15.3 ± 1.4 a	12.5 ± 2.0 a	13.1 ± 1.3 a
	NT	11.6 ± 1.1 b	9.1 ± 1.1 b	15.1 ± 1.9 a	12.3 ± 2.0 a	12.0 ± 1.5 b
Fertilization (F)						
	CK	9.9 ± 0.9 b	7.3 ± 0.9 b	11.1 ± 0.9 c	6.8 ± 0.4 d	8.8 ± 0.6 c
	F	14.0 ± 0.9 a	10.5 ± 0.4 a	15.6 ± 0.7 b	13.5 ± 0.3 c	13.4 ± 0.4 b
	FB	13.8 ± 0.9 a	10.8 ± 0.9 a	18.3 ± 0.4 a	15.0 ± 0.2 a	14.5 ± 0.4 a
	FS	13.5 ± 0.8 a	10.5 ± 0.4 a	15.9 ± 0.7 b	14.3 ± 0.3 b	13.5 ± 0.3 b
Tillage (T) × Fertilization (F)						
RT	CK	11.1 ± 0.5 c	8.5 ± 0.7 c	11.9 ± 0.9 d	7.0 ± 0.3 c	9.6 ± 0.3 d
	F	15.4 ± 0.4 a	10.9 ± 0.3 ab	15.3 ± 0.6 c	13.6 ± 0.4 b	13.8 ± 0.4 bc
	FB	15.0 ± 0.5 a	12.0 ± 0.7 a	18.0 ± 0.5 ab	15.1 ± 0.3 a	15.0 ± 0.3 a
	FS	14.5 ± 0.6 a	10.5 ± 0.5 b	16.0 ± 0.5 bc	14.2 ± 0.3 ab	13.8 ± 0.2 bc
NT	CK	8.7 ± 0.5 d	6.2 ± 0.4 d	10.3 ± 0.7 d	6.6 ± 0.5 c	7.9 ± 0.2 e
	F	12.6 ± 0.3 b	10.1 ± 0.4 b	15.8 ± 0.9 c	13.4 ± 0.1 b	13.0 ± 0.4 c
	FB	12.0 ± 0.6 b	9.7 ± 0.2 bc	18.5 ± 0.5 a	14.9 ± 0.1 a	13.9 ± 0.1 b
	FS	12.5 ± 0.3 bc	10.6 ± 0.3 b	15.8 ± 0.9 c	14.4 ± 0.4 ab	13.3 ± 0.4 bc
F values						
T		51.65 ***	16.96 ***	0.226	0.312	24.70 ***
F		33.53 ***	25.56 ***	36.19 ***	280.72 ***	152.43 ***
T × F		0.304	3.401	1.058	0.329	1.644

Mean ± SE; different letters indicate significant difference at $p < 0.05$. *** mean significance at the 0.001 level, respectively.

Table 4. Responses of global warming potential (GWP) and greenhouse gas intensity (GHGI) to different tillage practices and fertilization management strategies over the four-year experimental period.

Factors	Treatment	GWP (Kg CO_2-eq ha^{-1})	Ratios of GWP (%)		GHGI (Kg CO_2-eq kg^{-1})
			CH_4	N_2O	
Tillage (T)	RT	14,740.4 ± 5638.0 a	90.9 ± 3.8 a	9.1 ± 3.8 b	1.17 ± 0.43 a
	NT	9369.0 ± 4195.9 b	74.9 ± 5.8 b	25.1 ± 5.8 a	0.75 ± 0.29 b
Fertilization (F)					
	CK	9039.5 ± 3344.7 b	91.6 ± 4.1 a	8.4 ± 4.1 b	0.98 ± 0.31 b
	F	7359.6 ± 750.4 bc	77.8 ± 5.8 b	22.2 ± 5.8 a	0.55 ± 0.05 c
	FB	6369 ± 648.3 c	73.9 ± 7.0 b	26.1 ± 7.0 b	0.44 ± 0.05 c
	FS	25,450.7 ± 3296.7 a	88.2 ± 4.9 a	11.8 ± 4.9 a	1.87 ± 0.22 a
Tillage (T) × Fertilization (F)					
RT	CK	14,162.2 ± 1306.1 c	97.5 ± 0.2 a	2.5 ± 0.2 c	1.46 ± 0.10 b
	F	8443.9 ± 481.2 d	86.8 ± 0.9 b	13.2 ± 0.9 b	0.61 ± 0.05 c
	FB	6549.4 ± 787.5 de	83.7 ± 3.2 b	16.3 ± 3.2 b	0.44 ± 0.06 c
	FS	29,806.4 ± 2290.2 a	95.5 ± 0.5 a	4.5 ± 0.5 c	2.16 ± 0.15 a
NT	CK	3916.8 ± 138.8 e	85.7 ± 2.6 b	14.3 ± 2.6 b	0.49 ± 0.02 c
	F	6275.4 ± 20.4 de	68.9 ± 1.6 c	31.1 ± 1.6 a	0.48 ± 0.01 c
	FB	6188.7 ± 631.0 de	64.1 ± 4.1 c	35.9 ± 4.1 a	0.44 ± 0.05 c
	FS	21,095.1 ± 1718.8 b	80.9 ± 2.3 b	19.1 ± 2.3 b	1.58 ± 0.11 b
F values					
T		41.31 ***	95.28 ***	95.28 ***	52.66 ***
F		115.94 ***	26.12 ***	26.12 ***	127.69 ***
T × F		8.39 **	1.129	1.129	14.92 ***

Mean ± SE; different letters indicate significant difference at $p < 0.05$. ** and *** mean significance at the 0.01 and 0.001 levels, respectively.

4. Discussion

4.1. Effects of Tillage and Fertilization on CH_4 Emissions

In this study, the late rice season dominated the CH_4 emission across the four years, accounting for 64.3% to 86.8% of annual emissions (Table 1), which was consistent with previous findings [20,45,46]. In the late rice season, the high temperature (mean temperature of 29.1 °C), flooded environment, and abundant root residues left by early rice provided an abundant substrate and a suitable environment for CH_4 production and thus stimulated the emission of CH_4 [21,46,47]. The NT practice significantly reduced CH_4 by 21.1% in early rice and 52.6% in late rice; moreover, annual emissions of up to 47.7% were averaged over the four years, which is similar to the results of previous studies [15–17,46]. The reduction in CH_4 by NT may be a combination of multiple effects, including soil physical structure, substrates, and biological community. Compared with RT, NT can avoid the mixing of soils and weaken the decomposition of organic matter, which in turn significantly reduces the substrates for CH_4 production. A previous study has shown that NT significantly decreased the soil's DOC content compared to tillage in a double-season rice field [17]. Otherwise, the NT practice altered the physical and profile structure of soils, which had important effects on CH_4 production and oxidation. On the one hand, NT significantly reduced CH_4 content in the middle or deep layer of the soils [10]; on the other hand, the no-till strategy significantly promoted soil porosity, which may promote more CH_4 oxidation [17,21,48].

It was observed that the F treatment significantly reduced CH_4 emissions under RT conditions but not under NT conditions (Table 1). It has been shown that the effect of inorganic fertilizer on CH_4 depends on the trade-off between the effects of CH_4 production and oxidation [5,23]. Ammonium nitrogen fertilizer could promote CH_4 production through more root exudates and residues by promoting rice growth [49], or could mitigate CH_4 emissions by promoting CH_4 oxidation [50]. We suggested that, compared with NT, RT promoted the growth and distribution of rice roots in soils for the F treatment, which further promoted the radial oxygen loss capacity of rice roots and increased the CH_4 oxidation in the soil. Biochar amendment reduced CH_4 emissions by 24.7% and 7.3% under RT and NT conditions, respectively, compared to the F treatment; however, the differences were not significant ($p > 0.05$). The mitigation of biochar on CH_4 emission may be mainly due to the increased CH_4 oxidation in soils, as biochar can stimulate methanotrophic activity through increasing pH and aeration [25,38]. The straw return was definitively expected to enhance CH_4 emissions from rice fields due to the high input of stable organic matter and the reduction in soil Eh [25,51]. However, it was observed that the enhancing effect of straw return on CH_4 emission can be dramatically weakened under NT conditions. Compared to RT, NT maintained the straw in the surface layer of the soil, which significantly reduced the decomposition rate of the straw [52] and soil microbial respiration [53] and thus limited the substrates for CH_4 production. Our study demonstrated that tillage practices and fertilizer management have a significant interactive effect on CH_4 emissions in double-season rice fields, and this needs to be considered carefully in production practices to determine the optional combination of CH_4 reduction.

4.2. Effects of Tillage and Fertilization on N_2O Emissions

In this study, the peaks of N_2O emission occurred in the drainage period of early or late rice and the fallow seasons, which is consistent with the observations of previous studies [27,54,55]. The results can be explained in two ways. Firstly, during the gradual drying of the soil after drainage, both nitrification [56] and denitrification [54] were significantly enhanced, thereby highly promoting N_2O production. Secondly, the drying of the soil led to increased soil fissures, creating the "highway" channels for N_2O emissions within the underground soils [54,57]. However, the N_2O emission showed great variability under different tillage practices and fertilization management strategies (Table 2). The NT treatment significantly increased N_2O emissions in early rice, late rice, and fallow periods and was accompanied by an annual 126.3% increase compared to RT. Due to a lack of soil disturbance, soils in the NT treatment can exhibit significant stratification with large differences between layers [58,59]. Since inorganic fertilizer could only be thrown on the soil surface, this led to higher NH_4^+ and NO_3^- concentrations at the soil–water interface. This might stimulate N_2O production and contribute to a high N_2O concentration in surface soil or water by facilitating both nitrification and denitrification [10,60]. In addition, due to increased soil compactness, soil bulk density, and reduced field water holding capacity [61], the soil dried more rapidly during drainage, further accelerating the breakout of N_2O in the NT treatment.

The effect of the fertilization management strategies on N_2O emissions was significantly influenced by tillage practices (Table 2). Inorganic fertilizer application significantly increased N_2O emissions under both NT and RT conditions due to enhanced microbial nitrification and denitrification from the additional N source [22]. Surprisingly, the amendment of biochar and straw return significantly increased N_2O emissions under NT conditions but not under RT conditions. NT probably increases N losses from leaching and runoff from rice fields compared to conventional tillage [62,63]. Due to its porous structure and strong adsorption capacity, biochar can improve nutrient retention and reduce nutrient leaching [64,65]. Therefore, it was suggested that biochar amendment in NT might promote N_2O production and emission by providing more N sources compared with the F treatment. As for the increase in N_2O emission derived from the straw return, we supposed that there are two reasons. First, similar to biochar amendment, the straw cover on the soil surface reduced the leaching and runoff losses of N [66,67]. Second, the decomposition of crop straw directly supplies substrate carbon (C) and nitrogen (N) for nitrification and denitrification, potentially enhancing soil N_2O production [8].

4.3. The Balance of Yield and GHG Emissions

Due to the different demands between CH_4 and N_2O production on soil moisture and redox potential [68–70], CH_4 and N_2O fluxes often exhibited opposite variation characteristics in double-season rice fields [18,25,30,45,46]. Thus, a consideration of the trade-offs between CH_4 and N_2O in terms of GWP was needed to estimate the impact of different tillage practices and fertilization management strategies on GHG emissions. In the present study, we observed a considerable variation in the mean annual GWP across the range of 6118.7 kg CO_2-eq ha^{-1} $year^{-1}$ (NT-CK) to 29,806.4 kg CO_2-eq ha^{-1} $year^{-1}$ (RT-FS). Tillage practice had a significant effect on GWP emission, and a 36.4% decrease in annual GWP in NT was found compared to RT, which was higher than previous studies, with values of 25.9% [46], 16.6% [21], and 13.1% [71]. Although the F treatment significantly increased N_2O emissions compared to the CK treatment, it also resulted in a remarkable 40.4% reduction in GWP under RT conditions, primarily due to a significant decrease in CH_4 emissions [30]. The straw return significantly increased the GWP both in RT and NT, which was due to its promoting effect on CH_4 and N_2O emissions [71].

The purpose of agricultural production is to produce more food to support the demands of a growing population. Thus, we should focus more on the yield of rice while considering greenhouse gas emission reduction. Our results showed that NT reduced rice yield in the first two years; however, there was no significant difference in the second two years of the four-year experiment (Table 3), and the response of NT to the yield appeared to be related to a time effect. Previous studies [63,72] have reported that rice yields gradually improved with increasing years of NT compared with tillage (when the duration $\geq$ 3 years), which may be attributed to the improvement of soil properties and microbial communities [73]. Compared to F, straw return slightly increased rice yield, albeit not significantly. Ref. [74] also reported that, in the initial three years, straw return did not significantly affect the crop yield, and that the adverse effects of straw on crop yield may be balanced by the duration of straw incorporation [25]. In contrast, the addition of biochar significantly increased rice yield by 8.7% and 6.9%, respectively, under RT and NT, which was slightly lower than that recorded in the two newest meta-analysis studies in rice fields, with values of 11.3% [41] and 10.7% [75]. The increased yield induced by biochar can be primarily attributed to its beneficial effects on soil fertility, including enhanced soil structure [76], reduced nitrogen (N) loss [64,65], and an increased abundance and activity of microbial communities [77].

When the yield-scaled GHG emissions are comprehensively considered, NT significantly reduced GHGI by 35.9% compared with RT. This suggests that NT was more effective in mitigating the trade-offs between GHGs emission and enhancing crop yield. Among fertilization management strategies, FB had the same significantly low value of 0.44 kg CO_2-eq kg^{-1} yield $year^{-1}$ in RT and NT, while FS had a significantly high value of 2.16 and 1.58 kg CO_2-eq kg^{-1} yield $year^{-1}$, respectively, in RT and NT. Therefore, we suggest that converting straw into biochar and then returning it to the field can both improve yields and reduce greenhouse gas emissions.

However, despite its effectiveness in increasing rice yields and reducing GHGs emissions, biochar addition is difficult for farmers and cultivators to consider due to its high price cost. In our cost–benefit analysis in the present study, it was found that the economic benefits of biochar addition were 27.2% and 16.1% lower than the farmer's conventional approach (RT-FS) under RT and NT conditions, respectively (Table S1). When the biochar cost inputs are not considered, it was found that, compared to RT-FS, the biochar addition could increase the direct benefit by 2868 and 4564 CNY ha^{-1} $year^{-1}$, respectively, in RT and NT (Table S2). But, compared to the biochar cost of 28,080 CNY ha^{-1}, RT-FB and NT-FB will take nearly 10 and 6 years to compensate for the biochar input cost. Yet, when the carbon offsets of the biochar addition were taken into account, the total benefits reached 4247 and 5965 CNY ha^{-1} $year^{-1}$, respectively (Table S2). On this basis, it would take 7 and 5 years, respectively, for the economic benefits of biochar to be sufficient to exceed its price input. Thus, we recommend that carbon offsets from rice paddies should be incorporated into the carbon trading market in order to increase the willingness of farmers and cultivators to promote the implementation of emission reduction measures in rice paddies.

5. Conclusions

In this four-year field study, we observed that no tillage (NT) significantly reduced CH_4 emissions compared to rotary tillage (RT) while promoting N_2O emissions. Rice yields from NT were lower than RT in the first two years but equal to RT from the third year onward. Overall, the NT significantly reduced GHG emissions in both area- and yield-scales compared to RT. Significant effects of tillage practices and fertilization management strategies were found on the interactions of GHG emissions and rice yield. The application of inorganic fertilizer significantly reduced area- and yield-scaled GHG emissions under RT conditions but not under NT conditions. The straw return performed the highest GWP and GHGI in both RT and NT conditions; thus, to reduce GHG emissions, the direct use of straw return is not recommended. In contrast, biochar addition treatment was able to significantly increase rice yield while reducing GHG emissions, thus obtaining the lowest GHGI. Therefore, the conversion of straw to biochar and its subsequent application to rice fields may be an effective measure to mitigate GHG emissions and increase rice yields. It is important to note that the high cost of biochar is a significant barrier limiting its application among farmers and cultivators. We recommend that rice paddy carbon offsets be included in the carbon trading market to financially compensate biochar for its role in reducing greenhouse gas emissions, thereby increasing farmers' willingness to adopt rice paddy mitigation agricultural practices.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13071887/s1, Table S1: Effects of different tillage practices and fertilization management strategies on the annual economic input, income, and benefit of rice production over the four-year experimental period.; Table S2: The annual economic benefit of biochar application compared to local farmers' production over the four-year experimental period.

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