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Effects of Straw Incorporation Years and Water-Saving Irrigation on Greenhouse Gas Emissions from Paddy Fields in Cold Region of Northeast China

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Abstract: Straw incorporation has a variety of impacts on greenhouse gas (GHG) emissions. However, few studies have focused on the effects of multi-year straw incorporation. In this study, a field experiment was established to study the effects of straw incorporation and water-saving irrigation on GHG emissions in the cold region of Northeast China. The following four treatments were included: (i) controlled irrigation (CI) with 1-year straw incorporation (C1), (ii) controlled irrigation with 5-year straw incorporation (C5), (iii) flooded irrigation (FI) with 1-year straw incorporation (F1), and (iv) flooded irrigation with 5-year straw incorporation (F5). The fluxes of N_2O, CO_2, and CH_4 were measured by the static chamber–gas chromatography method, and their global warming potential (*GWP*) and greenhouse gas intensity (*GHGI*) in units of CO_2-equivalent at the 100-year scale were calculated. The results showed that the 5-year straw incorporation reduced N_2O emissions but increased CH_4 emissions. Compared with C1 and F1, C5 and F5 reduced N_2O emissions by 73.1% and 44.9%, respectively, while increasing the CH_4 emissions by 101.7 and 195.8%, respectively. Under different irrigation regimes, CI reduced CH_4 emissions by 50.4–79.7% while increasing CO_2 emissions by 8.2–44.9% compared with FI. The contribution of N_2O and CO_2 emissions were relatively high at the mature and milk stages, respectively, with a range of 16–54% and 41–52% for the treatments. In contrast, CH_4 emissions were mainly manifested at the tillering stage, with a contribution of 36–58% for the treatments. Affected by higher CH_4 emissions in FI, the *GWP* of CI was 1.4–47.6% lower than FI. In addition, the yield of CI was 10.0–11.5% higher than FI, which resulted in a *GHGI* of 11.5–52.4% lower than FI, with C5 being the lowest. The irrigation regime of CI combined with 5-year straw incorporation was an effective agronomic measure to increase yield and reduce GHG emissions from paddy fields in the cold region of Northeast China.

Keywords: paddy fields; greenhouse gas; straw incorporation; irrigation regimes

1. Introduction

China, a significant rice-producing nation, contributed 19% and 28%, respectively, of the global rice planting area and yield in 2017 [1]. Widespread cultivation has brought a large amount of crop straw to China, which imposes additional costs and labor on farmers. According to studies, over 19% of agricultural straw was burned in Chinese fields [2], endangering both human and ecological health by destroying organic matter and emitting harmful gases such as CO, CO_2, CH_4, NO_X, and N_2O [3]. Thus, it is urgent to find a cleaner way to deal with crop straw in paddy fields. Moreover, straw incorporation enhanced soil physical and biochemical conditions as well as supplemented nutrients and organic carbon (C) [4], and it was also beneficial for soil C sequestration [5,6]. According to Lu et al., straw incorporation boosted the cropland's yearly C sequestration capacity in China from 9.76 Tg to 34.4 Tg [5]. Related studies have shown that soil C sequestration increased with the duration of cultivation and an increase in soil organic C also led to an increase in rice yield. For example, Huang et al. found that long-term continuous cultivation of rice elevated soil organic C in rice fields by 15–23%. A study by Arunrat et al. in Thailand showed that before soil organic C reached saturation, every increase in soil organic C content by 1 $g \cdot kg^{-1}$ increased rice yield by 302 $kg \cdot ha^{-1}$ [7,8]. Therefore, straw incorporation is strongly encouraged instead of straw burning to improve soil fertility and protect the deteriorating environment in China [9]. However, straw incorporation led to an increase in some GHG emissions. Thus, how to effectively balance GHG emissions and straw incorporation is a challenge.

Straw incorporation is an effective strategy to maintain soil fertility and crop yield [10]. According to studies, incorporating straw into 0–15 cm surface soil enhanced its nitrogen (N) concentration and postponed the soil's release of N during the early stages of rice growth [11]. In addition, straw incorporation ensured soil nutrient balance and increased soil organic matter and nutrient supply capacity [12]. Thus, straw incorporation improved the N supply–demand relationship between the crop and the soil, which promoted rice growth and increased yields [13]. Studies have found that incorporating straw into paddy fields boosted CO_2 and CH_4 emissions because it added another source of C to the soil [14]. However, there were different conclusions about the effects of straw incorporation on N_2O emissions [15–17]. For example, Wang et al. and Liu et al. found that straw incorporation reduced N_2O emissions by 1–15.2% [18,19], while Huang et al. and Zhang et al. found that straw incorporation increased or had no effect on N_2O emissions [20,21]. This might be connected to various soil types and field management techniques [22]. Due to the long duration of the decomposition process of straw, the effects of straw incorporation on the soil environment associated with GHG emissions would take some time to become apparent, especially in the cold region [23]. It has been demonstrated that throughout the long-term rice-growing season in Northeast China, straw incorporation served as a significant supply of carbon and nitrogen. However, most research on GHG emissions affected by straw incorporation was short-term [24,25]. Therefore, the effects of GHG emissions under multi-year straw incorporation need to be further explored.

Water-saving irrigation is seen as a management strategy for sustainable rice production and is consistent with the Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development. In China, water-saving irrigation techniques such as controlled irrigation (CI), shallow wet irrigation (SWI), intermittent irrigation (II), and rain-gathering irrigation (RGI) are frequently employed. According to field research conducted in China, CI had the highest average water-saving rate of 35.12% and the highest average pollutant-reduction rate of 54.97% among them [26]. For the generation and emissions of CH_4, soil water condition is to blame. Compared with traditional flooded irrigation (FI), water-saving irrigation showed great potential to mitigate CH_4 emissions [27]. The majority of water-saving irrigation practices included numerous drainage activities to reduce CH_4 production. The dry–wet cycles, however, may cause significant N_2O emissions [28]. If the paddy field is irrigated less frequently or has fewer precipitation events, an irrigation event in agricultural soils is more likely to cause a higher spike in CO_2 pulse. Typically, constantly flooded paddy fields have a higher global warming potential (*GWP*), and improved irrigation may help to lower CH_4 emissions and *GWP* [29].

The primary rice-producing region in China's cold region, Heilongjiang Province, has increased its rice-planting area by almost 3.4 times during the past 20 years [30]. Its rice-growing region has expanded more quickly than that of other Chinese provinces, significantly increasing agricultural water demand and worsening water problems. In addition, the over-exploitation of groundwater in some areas has created groundwater funnels. In the context of decreasing water resources and increasing straw, CI has been promoted and the promotion area of CI in Heilongjiang Province has reached more than 2 million hectares by 2020 [31]. However, with the increase in rice area, yield, and crop straw, the effects of water-saving irrigation and straw incorporation on GHG changes have become uncertain and complex.

In this study, we investigated the effects of different straw incorporation years and water management on the emissions of N_2O, CH_4, and CO_2 and the yield of paddy fields in the cold region of Northeast China through field in situ experiments. Furthermore, a comprehensive assessment of the impact of *GWP* and greenhouse gas intensity (*GHGI*) was carried out. This study aims to evaluate the ecological and environmental effects and water-saving effects of paddy fields and to provide the basis for water-saving and emission reductions of paddy fields in the cold region of Northeast China.

2. Materials and Methods

2.1. Experimental Site

This study was conducted at the National Irrigation Experiment Station in Heping Town, Qing'an County, Heilongjiang Province from May 2021 to September 2021. The experiment station (127°40′45″ E, 46°57′28″ N) is located in the middle and upper reaches of the Hulan River Basin in Northeast China. From rice transplanting to maturity, the total precipitation was 564 mm, the annual average temperature is 2.5 °C, the annual average water evaporation is 750 mm, the water–thermal growth period of the crop is 156–171 days, and the annual frost-free period is 128 days. The climate characteristics belong to the cold temperate continental monsoon climate. The soil type is Mollisols, which is classified as a soft soil (USDA classification) and is rich in organic matter [32]. It is the main soil type in the Songnen Plain, and rice has been planted in the experimental area for more than 20 years. The soil tillage thickness was 11.3 cm, and the thickness of the plow base layer was 10.5 cm. The soil is fertile, and the nutrient content is stable. Air temperature and precipitation data during the rice growth period are shown in Figure 1.

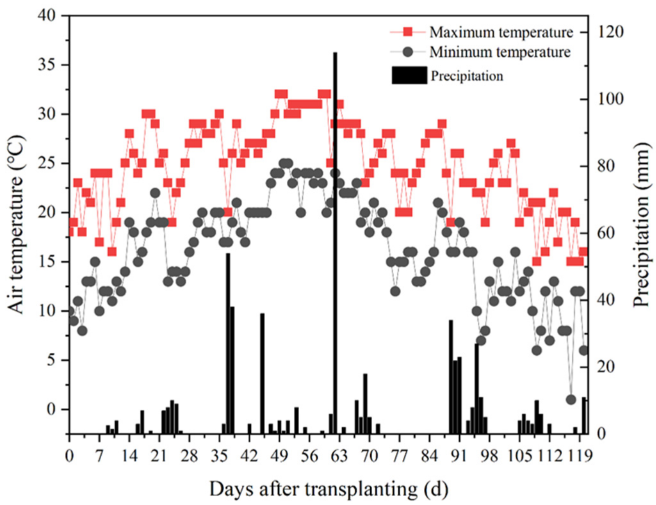

Figure 1. Air temperature and precipitation during rice growth period.

The pH of the soil was measured by a pH meter (PHS-3 C, INESA Scientific Instrument Co., Ltd., Shanghai, China). Soil total N was determined by an elemental analyzer (Thermo Fisher Scientific, Waltham, MA, USA), and the available P was measured by an injection pump analyzer (AA3, Seal Analytical GmbH, Norderstedt, Germany) [33]. The available K was measured by a photoelectric flame photometer [34]. The cation exchange capacity was measured by the ammonium acetate method following Wu et al. [35]. Total soil porosity was calculated by measuring the soil bulk density and particle density using a soil instrument (DIK-1150, Daiki Co., Ltd., Kyoto, Japan). The NH_4^+–N and NO_3^-–N contents were measured with an injection pump analyzer (AA3, Seal Analytical GmbH, Norderstedt, Germany) after the fresh soil samples were extracted with 2 M KCL. The measured physical and chemical properties of the soil were shown in Table 1.

Table 1. The properties of the soil.

Soil Properties	Values
pH	6.45
Total N ($g \cdot kg^{-1}$)	41.8
Available P ($mg \cdot kg^{-1}$)	36.22
Available K ($mg \cdot kg^{-1}$)	198.29
Cation exchange capacity (cmol kg^{-1})	32.45
Total porosity (%)	61.8
Soil texture	Sandy clay loam

2.2. Experimental Design

This study was conducted based on two different straw incorporation times (1 year and 5 consecutive years) in combination with two irrigation regimes (CI and FI). Among them, C5 and F5 treatments started in 2016 (rice straw was incorporated after harvest of 2015, 2016, 2017, 2018, and 2019, respectively), while C1 and F1 treatments started in 2020 (rice straw was incorporated after harvest of 2019). None of the treatments had a previous straw incorporation history before this study. The rice straw was all incorporated into the soil after the rice harvest of previous year (air-dried, 6×10^3 g ha^{-1}). The experimental treatments are shown in Table 2. In the controlled irrigation (C1 and C5), except that the field surface maintained a shallow water layer of 5–25 mm at the regreening stage of rice, no water layer was established at other growth stages [31]. The soil moisture content of the root layer was used as the control index to determine the irrigation time and quota, and the upper limit of irrigation was the soil-saturated moisture content. In the flooded irrigation (F1 and F5), there maintained a 3–5 mm water layer at the growth stage of rice in addition to appropriate drainage and drying at the late tillering stage to avoid ineffective tillers and natural drying at the mature stage [30]. Standards of experiment water control under flooded irrigation and controlled irrigation were shown in Figure 2.

Table 2. Design of the experimental treatments.

Treatments	Irrigation Regimes	Years of Straw Incorporation
C1	Controlled irrigation	1 year
C5	Controlled irrigation	5 years
F1	Flooded irrigation	1 year
F5	Flooded irrigation	5 years

Each treatment was repeated 3 times for a total of 12 plots. The area of each plot was 100 m^2 (10 m $\times$ 10 m), using a random block arrangement. To prevent water and N exchange, each plot was separated by inserting plastic plates to a depth of 40 cm. According to the local fertilization standard, the N application rate was controlled at 110 $kg \cdot ha^{-1}$. Nitrogen fertilizer in the form of urea was applied in 3 growth stages: basal (45% fertilizer–N), tillering (20% fertilizer–N), and panicle (35% fertilizer–N) fertilizers. The basal fertilizer was applied one day before transplanting, the tillering fertilizer was applied 14 days after transplanting, and the panicle fertilizer was applied 50 days after transplanting. The phosphorus fertilizer (19.65 kg $P \cdot ha^{-1}$) and potassium fertilizer (66.38 kg $K \cdot ha^{-1}$) were used for each treatment. The phosphorus fertilizer was applied once before transplanting, and the potassium fertilizer was applied before transplanting and at an 8.5 leaf age of the rice with a ratio of 1:1. The study employed the variety "Suijing 18", which is a popular variety of rice in the local area, and the planting density was 30 cm $\times$ 10 cm with 3 plants per hill. According to the Irrigation Technology Manual for Water-Saving Control of Rice issued by the Heilongjiang Water Resources Department in 2020, each treatment was applied to weed control in the field before the re-greening stage as well as after the tillering stage.

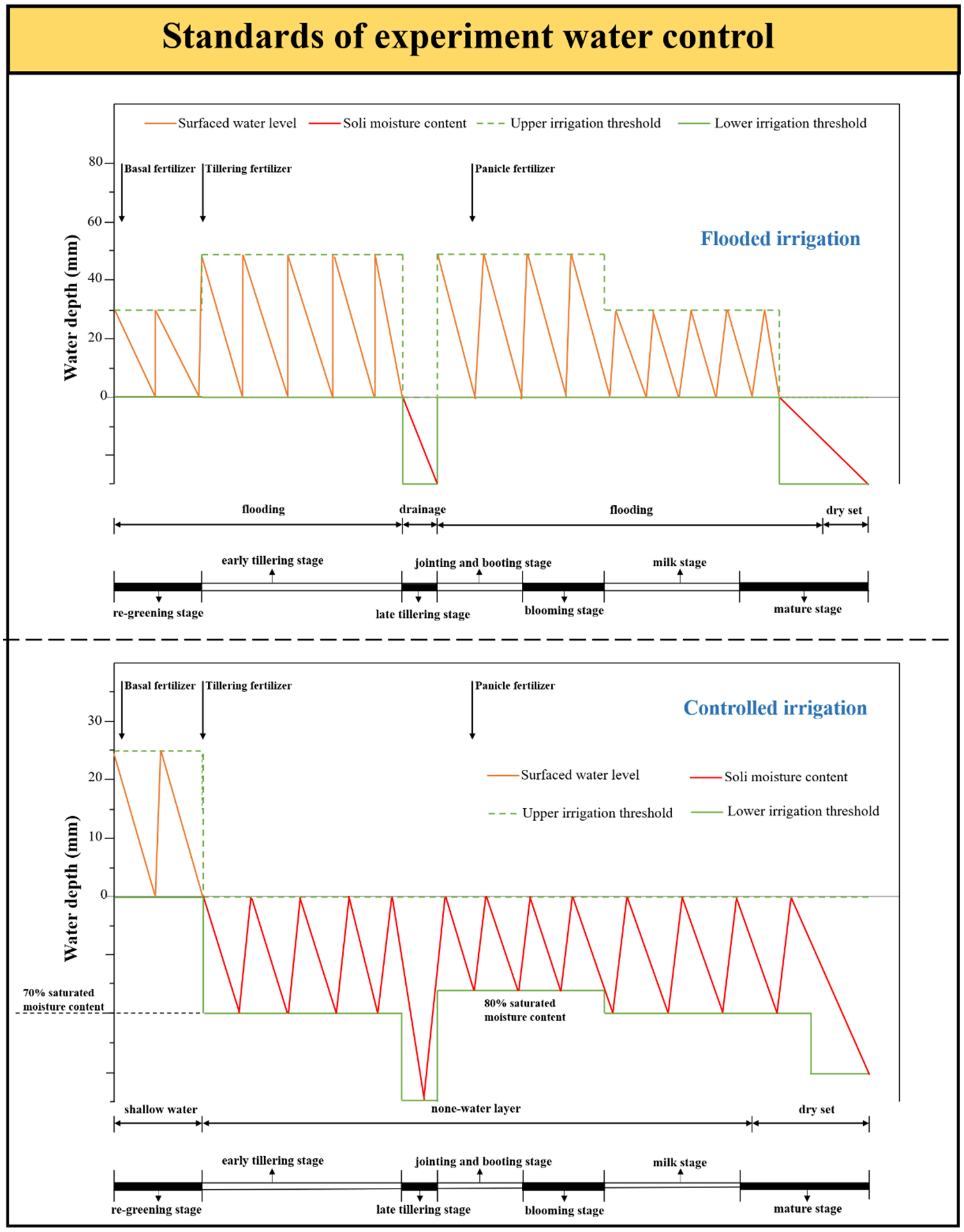

Figure 2. Standards of experiment water control under flooded irrigation and controlled irrigation.

2.3. Gas Sample Collection and Analysis

The greenhouse gases were measured by the static chamber–gas chromatography method. In each plot, the foundation frame made of stainless steel (with an area of 0.25 m × 0.25 m) was inserted into the soil at a depth of 20 cm. The chamber made of organic glass (0.25 m in length × 0.25 m in width × 1 m in height) was temporarily installed on the frame with a water seal and coated with tin paper on the outer layer for gas emission measurement. A circulating fan is installed at the top of each chamber to ensure complete gas mixing. Meteorological data were recorded by an automatic weather station near the study site.

Gas sampling was conducted from 10:00 to 12:00 a.m. during the whole growing season of rice from 25 May to 22 September 2021, and gas samples were collected about once a week. Sampling was postponed on cloudy or rainy days. Four gas samples were taken from each chamber every 10 min (0, 10, 20, and 30 min after the chamber was closed) using a 60 mL plastic syringe. After each sampling, the static chamber was removed from the experimental plot, and then each sample was transferred to a 12 mL vacuum bottle with a butyl rubber match vacuumized in advance for laboratory analysis within 24 h. The concentrations of CH_4, N_2O, and CO_2 in samples were detected at 250 °C using a gas chromatograph (SHIMADZU GC-2010 plus, Kyoto, Japan) equipped with a hydrogen flame ionization detector (FID), and an electron capture detector (ECD) for detecting N_2O at 350 °C. In GHG analysis, N_2 is used as carrier gas and the mixture of CO_2 and N_2 (10% CO_2 in N_2) is used as supplementary gas [36,37]. The annual total GHG emissions were accumulated in the order of the average emissions of each two adjacent measurement intervals, and the average emissions and standard error of each treatment were calculated from the three repetitions.

The fluxes of N_2O, CO_2, and CH_4 were calculated with the following formula [15]:

$$F = \rho h \cdot \frac{dC}{dt} \cdot \frac{273}{273 + T} \tag{1}$$

where F is the N_2O flux (ug·m^{-2}·h^{-1}) or CO_2 (mg·m^{-2}·h^{-1}) or CH_4 flux (mg·m^{-2}·h^{-1}); $\frac{dC}{dt}$ is the slope of the curve of gas concentration versus time; h is the effective height of the chamber (m); ρ is gas density at the standard state (kg·m^{-3}); and T is the average temperature inside the chamber (°C).

Cumulative GHG emissions were calculated with the following formula [38]:

$$f_{\text{GHG}} = \sum_i^n \left[\frac{(F_i + F_{i-1})}{2} \times d \times 24 \times 10^{-2} \right] \tag{2}$$

where f_{GHG} is cumulative emissions of N_2O, CO_2, and CH_4 between the ith and $i-1$th intervals (kg·ha^{-1}); F_i and F_{i-1} are the ith and $i-1$th measured GHG fluxes, respectively; d is days between two adjacent samplings; n is total samplings observed times.

The *GWP* and *GHGI* were used to assess the GHG effects. Taking 100 years as the time scale, the *GWP* of CH_4 and N_2O gas per unit mass was 28 and 265 times that of CO_2, respectively [39]. The *GWP* was calculated with the following formula [15]:

$$GWP = f_{CO_2} + (28 \times f_{CH_4}) + (265 \times f_{N_2O}) \tag{3}$$

where f is the cumulative emissions of different *GHG* from the paddy field ecosystem during the whole growth period of rice.

The *GHGI* was calculated with the following formula [40]:

$$GHGI = \frac{GWP}{yield} \tag{4}$$

2.4. Grain Yield

In the mature stage, a 1 m^2 block of evenly grown rice plants from each plot was collected for yield measurement. Rice yield per unit area was calculated according to 14.5% moisture content.

2.5. Data Analysis

The experimental data were subjected to Duncan test and ANOVA, with LSD test for evaluating the significance of treatment differences at $p \leq 0.05$. All statistical calculations were performed using SPSS 26.0 (SPSS Inc., Chicago, IL, USA), and Origin 2021 software was used to draw pictures.

3. Results

3.1. N_2O Flux

The interaction of straw incorporation and irrigation regimes on cumulative emissions of N_2O was significant ($p < 0.001$) (Table 3). As shown in Figure 3, the N_2O flux changes in the four treatments exhibited different characteristics throughout the experimental period. The flux variation ranges of C1, C5, F1, and F5 were -9.0 ± 2.1–208.3 ± 32.1 $\mu g \cdot m^{-2} \cdot h^{-1}$. After rice entered the mature stage, the N_2O fluxes of C1 and F1 peaked at 117.5 ± 13.1 $\mu g \cdot m^{-2} \cdot h^{-1}$ and 208.3 ± 29.4 $\mu g \cdot m^{-2} \cdot h^{-1}$, respectively. Different from C1 and F1, the variation of N_2O fluxes in C5 and F5 was smaller in the rice growth period. The seasonally averaged N_2O fluxes of C1, C5, F1 and F5 decreased in the following order: C1 > F1 > F5 > C5, which were 1.4 ± 0.1, 1.4 ± 0.4, 0.8 ± 0.2, and 0.4 ± 0.2 $\mu g \cdot m^{-2} \cdot d^{-1}$, respectively ($p < 0.05$). In addition, the N_2O fluxes of both C1 and F1 increased after the application of tillering fertilizer, with C1 increasing significantly; however, no significant N_2O fluxes increasing of C5 and F5 were observed. Moreover, a small N_2O flux peak of each treatment occurred after the application of panicle fertilizer.

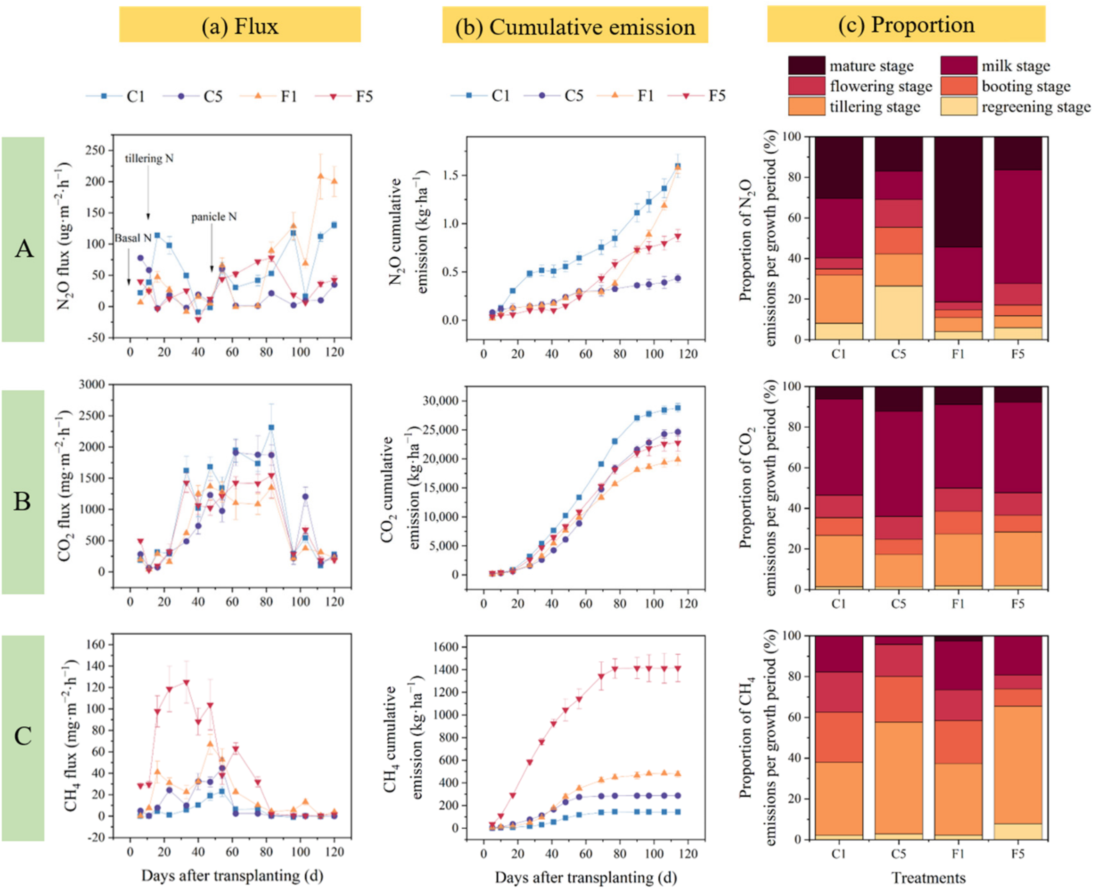

Figure 3. Fluxes, cumulative emissions, and emission percentages in each growth period of N_2O, CO_2, and CH_4. Column (**a**) shows the flux changes in the three GHGs. Column (**b**) shows the cumulative emissions changes for the three GHGs. Column (**c**) shows the percentages of the three GHG emissions in each growth period of rice. Row A, from left to right, represents the N_2O flux change, the cumulative emission change, and the emission percentage of rice in each growth period. Row B from left to right represents the change in CO_2 flux, the change in cumulative emission, and the emission percentage of rice in each growth period. Row C from left to right represents the CH_4 flux change, the cumulative emission change, and the emission percentage of rice in each growth period. The black arrow indicates the application of N fertilizer. C1: controlled irrigation with 1-year straw incorporation. C5: controlled irrigation with 5-year straw incorporation. F1: flooded irrigation with 1-year straw incorporation. F5: flooded irrigation with 5-year straw incorporation.

Table 3. Significance, values, and degrees of freedom for two-way ANOVA.

Factor	*df*	N_2O (kg·ha^{-1})		CO_2 (kg·ha^{-1})		CH_4 (kg·ha^{-1})	
		F	Significance	F	Significance	F	Significance
Y	1	2742.21	<0.001	1.39	0.273	24.33	<0.001
I	1	136.86	<0.001	110.41	<0.001	44.48	<0.001
Y × I	1	159.45	<0.001	47.21	<0.001	13.03	0.007
Error	8						

Note: Y represents the year of straw incorporation, I represents the irrigation regime, *df* represents the degree of freedom, and F represents the statistic value of the F test in the analysis of variance.

In general, the cumulative N_2O emissions of C1 were consistently higher. At 77 days after rice transplanting, the cumulative N_2O emissions of C1 were 160%, 122%, and 46% higher than those from C5, F1, and F5, respectively. From 80 days after rice transplanting to the end of the rice growth period, the significant increase in the N_2O flux of F1 led to a rapid increase in its cumulative emissions. During this period, the cumulative N_2O emissions of F1 accounted for 47% of the total emissions. By calculating the percentage of N_2O emissions at each growth stage in the total cumulative emissions, C1 treatment had a large contribution rate at tillering stage, milk stage, and mature stage, which were 23.8%, 29.4%, and 30.3%, respectively. F1 and F5 contributed more to the milk stage and mature stage, with F1 accounting for 26% and 48%, F5 accounting for 56.0% and 16.4%, respectively. Unlike the other treatments, the percentage of N_2O emissions of C5 differed less among the growth stages. Its N_2O emissions were greatest at the re-greening stage, accounting for 26.4% of the total N_2O emissions. Overall, the 5-year straw incorporation effectively reduced the cumulative N_2O emissions by 44.9–73.1% compared with 1-year straw incorporation.

3.2. CO_2 Flux

As shown in Table 3, the effects of straw incorporation year on cumulative CO_2 emissions were not significant (p = 0.273), while the effect was highly significant under the interaction of straw incorporation year and irrigation regimes ($p < 0.001$). During the first 30 days after rice transplanting, the CO_2 fluxes of the four treatments did not change significantly. Before entering the mature stage (90 days after transplanting), the CO_2 fluxes of the treatments showed an increasing trend, with maximum fluxes of 1348.6 ± 150.7–2309.8 ± 295.3 mg·m^{-2}·h^{-1} (Figure 3). After entering the mature stage, the CO_2 fluxes of the four treatments decreased sharply and then stabilized at a lower level until the end of the rice growth period. The average CO_2 fluxes of C1, C5, F1 and F5 were 25,271.5 ± 1004.2, 21,632.4 ± 1142.5, 17,442.1 ± 977.2 and 19,999.3 ± 1155.3 mg·m^{-2}·d^{-1} ($p < 0.05$), respectively. The cumulative CO_2 emissions of C1 and C5 were 44.9% and 8.2% higher than those of F1 and F5, respectively ($p < 0.05$), indicating that CI promoted CO_2 emissions compared to FI. After the tillering stage, C1, C5, F1, and F5 contributed 73.3%, 82.8%, 72.7%, and 71.6% of the cumulative CO_2 emissions, respectively. Throughout the whole growth period, the contribution rate of CO_2 emissions of each treatment was the largest in the milk stage, and the contribution rates of C1, C5, F1, and F5 were 47%, 52%, 41%, and 44%, respectively. Followed by tillering stage, and the contribution rate of each treatment decreased in the following order: F5 > F1 > C1 > C5, which were 27%, 26%, 25%, and 16%, respectively. The contribution of CO_2 emissions at the flowering stage was the same for all treatments at 11%. In addition, the CO_2 emissions at the booting and mature stages were relatively small for each treatment, contributing only 6–12% ($p < 0.05$).

3.3. CH_4 Flux

The effects of straw incorporation year and irrigation regimes on cumulative CH_4 emissions were highly significant ($p < 0.001$) (Table 3). After rice transplanting, the CH_4 fluxes of C1, C5, and F1 increased steadily and reached the peak about 48 days after transplanting, which were 23.1 ± 6.2, 44.8 ± 8.5, and 67.0 ± 13.7 mg·m^{-2}·h^{-1}, respectively ($p < 0.05$). However, the change range of F5 was significantly higher compared with the other treatments. During the tillering stage, the CH_4 fluxes of F5 increased sharply and reached the peak value of 125.1 ± 16.5 mg·m^{-2}·h^{-1} 27 days after transplanting. After entering the booting stage (50 days after transplanting), the CH_4 fluxes of each treatment began to decrease. At the end of the milk stage, the CH_4 fluxes of each treatment were stable at a low level until the end of the rice growth period. The seasonal average CH_4 fluxes of C1, C5, F1, and F5 treatments were 5.1 ± 2.1, 10.8 ± 3.4, 21.0 ± 5.6, and 48.7 ± 9.1 mg·m^{-2}·h^{-1}, respectively ($p < 0.05$).

Table 4 emissions of each treatment decreased in the following order: F5 > F1 > C5 > C1, with the range of 142.72–1414.60 kg·ha^{-1}. The cumulative CH_4 emissions of C1 decreased by 70.2% compared to F1. Similarly, the cumulative CH_4 emissions of C5 decreased by 79.7% compared to F5, which demonstrated that CI was effective in reducing CH_4 emissions regardless of whether the straw was incorporated in 1 or 5 consecutive years. From the perspective of the emission ratio in the growth period, the CH_4 emissions of each treatment accounted for the largest proportion in the tillering stage, and the least in the mature stage. After rice transplanting, the largest proportion of CH_4 emissions was 7.9% for F5 at the re-greening stage. While the proportion of CH_4 emissions of C1, C5, and F1 was relatively close, 2.8%, 2.1%, and 2.3%, respectively. In the tillering stage, the CH_4 emission contribution rates of C5 and F5 were relatively high, which were 57.6% and 54.8%, respectively, while those of C1 and F1 were 36.0% and 35.1%, respectively. The proportion of CH_4 emissions in each treatment at the booting stage decreased in the following order: C1 > C5 > F1 > F5, which were 24.8%, 22.4%, 21.0%, and 8.4%, respectively. In the same order as the booting stage, the proportion of CH_4 emissions at the flowering stage was 19.9%, 15.7%, 15.1%, and 6.9%, respectively. The CH_4 emissions of C5 at the mature stage were much smaller than those of other treatments, accounting for only 3.9%. At the mature stage, the emissions of F1 accounted for 2.6% of the total growth period, and the emissions of other treatments accounted for a particularly small proportion, approaching 0 ($p < 0.05$).

Table 4. Global warming potential and greenhouse gas intensity in each treatment.

Treatments	N_2O Emissions (kg·ha^{-1})	CO_2 Emissions (kg·ha^{-1})	CH_4 Emissions (kg·ha^{-1})	*GWP* by N_2O (kg CO_2-eq·ha^{-1})	*GWP* by CO_2 (kg CO_2-eq·ha^{-1})	*GWP* by CH_4 (kg CO_2-eq·ha^{-1})	Total *GWP* (kg CO_2-eq·ha^{-1})	Grain Yield (kg·ha^{-1})	*GHGI* by N_2O (kg CO_2-eq·kg^{-1})	*GHGI* by CO_2 (kg CO_2-eq·kg^{-1})	*GHGI* by CH_4 (kg CO_2-eq·kg^{-1})	*GHGI* (kg CO_2-eq·kg^{-1})
C1	1.60a	28,809.50a	142.72b	423.14a	28,809.50a	3996.08d	33,228.72b	9024b	0.05a	3.19a	0.44d	3.68b
C5	0.43a	24,660.97b	287.84b	115.27c	24,660.97b	8059.55c	32,835.78b	9423a	0.01c	2.62b	0.86c	3.48b
F1	1.58a	19,883.99d	478.18b	418.32a	19,883.99d	13,389.05b	33,691.35b	8094d	0.05a	2.46c	1.65b	4.16b
F5	0.87a	22,799.16c	1414.60a	231.50b	22,799.16c	39,608.78a	62,639.44a	8567c	0.03b	2.66b	4.62a	7.31a

Note: *GWP*: global warming potential, *GHGI*: greenhouse gas intensity, C1: controlled irrigation with 1-year straw incorporation; C5: controlled irrigation with 5-year straw incorporation, F1: flooded irrigation with 1-year straw incorporation, F5: flooded irrigation with 5-year straw incorporation; lowercase letters indicate that the difference between treatments was significant ($p < 0.05$).

3.4. GWP, Yield, and GHGI

The total *GWP* of each treatment decreased in the following order: F5 > C1 > F1 > C5. Among the four treatments, the *GWP* of F5 was much larger than the other treatments, which directly led to a larger *GHGI* (Table 4). As shown in Figure 4, CO_2 and CH_4 were the main contributors to the total *GWP* of each treatment. The contribution of CO_2 emissions from C1, C5, and F1 to the total *GWP* was 86.7%, 75.1%, and 59.2%, respectively. In F5, the contribution of CH_4 emissions to total *GWP* was 63.23%. Although N_2O had a stronger greenhouse effect than CH_4, its contribution to total *GWP* in the four treatments was very small, only accounting for 0.35–1.27%. In general, the *GWP* of each treatment was mainly caused by CO_2, while the contribution of CH_4 emissions to the total *GWP* increased after 5-year straw incorporation, especially under FI treatments. In terms of yield, the treatments decreased in the following order: C5 > C1 > F5 > F1 (Table 4). CI significantly increased yield by 10.0–11.5% compared to FI ($p < 0.05$). In addition, the yields of C5 and F5 were 4.4% and 5.8% higher than those of C1 and F1, respectively, indicating that the 5-year straw incorporation also had a promoting effect on the yield. The *GHGI* is an important indicator for evaluating GHGs per unit of rice yield. Affected by a large amount of CH_4 emissions, the *GHGI* of F5 was much higher than those of other treatments, which were 75.7%, 98.6%, and 110.1% higher than F1, C1, and C5, respectively. Although the *GWP* of C1 and C5 were very close, the higher yields of C5 make its *GHGI* lower than C1 by 5.4%. Overall, C5 has the highest yield with the lowest *GWP* and *GHGI*.

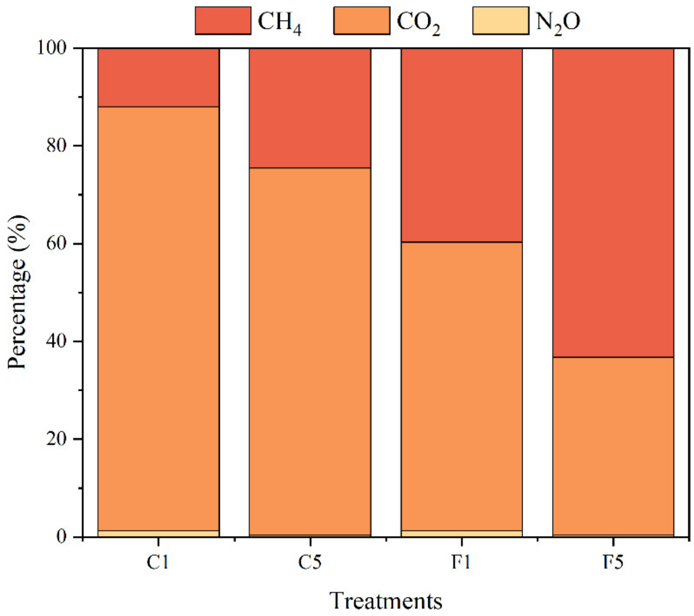

Figure 4. *GWP* percentage of N_2O, CO_2, and CH_4 in each treatment. C1: controlled irrigation with 1-year straw incorporation. C5: controlled irrigation with 5-year straw incorporation. F1: flooded irrigation with 1-year straw incorporation. F5: flooded irrigation with 5-year straw incorporation.

4. Discussion

After straw incorporation, straw undergoes a long and complex decomposition process through the activity of soil microorganisms and enzymes. Microbial decomposition of organic matter is regulated by the chemical composition of the straw and by moisture and temperature, as well as by microbial activity and nutrient availability in the surrounding soil environment [41,42]. Most studies found that a large amount of organic C in straw provided a C source for the production of CH_4 [18,43], which was an important factor in the fact that straw incorporation significantly increased CH_4 emissions compared to treatments without straw [44]. In a 5-year straw incorporation experiment, it was found that the decomposition of straw occurred mainly in the first three years, with a "slow release" of C and N from the straw that lasted 1–2 years. The main reason for this is that the low temperatures in Northeastern China severely inhibit straw decomposition. Therefore, the C replenishment from straw to paddy fields is a slow-growing process, especially if the straw is continuously incorporated into the field for many years [12]. Our study showed that 5-year straw incorporation still increased CH_4 emissions compared with 1-year straw incorporation and this phenomenon varies in different irrigation regimes. Water management is considered to be an important way to reduce CH_4 emissions, and CI, as a water-saving irrigation regime, has a significant impact on CH_4 emissions [31,32]. After transplanting, the water in the paddy field was effectively managed under CI during all growth stages except for the re-greening stage, and no water layer was formed [24]. Compared with FI, soil aeration was greatly increased in CI, which promoted the formation of an aerobic environment [45]. The environment effectively promoted the oxidation of CH_4 and inhibited the activity of methanogens, thereby reducing the CH_4 emissions [17]. Previous studies have shown that the frequency of alternating wet and dry soils determined the mitigation potential of CH_4 [46], which was consistent with the results of this study. In this study, more frequent dry–wet alternation in the CI treatment resulted in relatively low CH_4 fluxes throughout the growth period, which suggested that effective water management reduced

CH_4 emissions from the paddy fields. Methane emissions decreased with the reduction of water-filled pore space, while excess water content inhibited CH_4 oxidation and promoted CH_4 emissions [47].

A significant increase in N_2O flux was observed for three to four days after the three N fertilizer applications for the C1 and F1 treatments, but not for C5 and F5, which may have been influenced by the multi-year straw incorporation. There were different conclusions about the effects of straw incorporation on N_2O emissions [9]. Most studies have shown that straw incorporation leads to an increase in N_2O emissions compared to paddy fields without straw incorporation [14]. However, the effects of continuous multi-years of straw incorporation on N_2O emissions from paddy fields were still unclear. Studies have found that straw incorporation changed the C-N balance in the soil and affected the activities of soil microorganisms, which in turn affected N_2O emissions [9]. The C/N ratio of rice straw is generally 50–60, while the C/N ratio of organic matter for microbial decomposition is between 20 and 30, therefore, straw incorporation increased the C/N ratio in the soil environment [48]. Higher C/N in straw enhanced soil N fixation and reduced N_2O emissions, as N_2O is a product of soil nitrification–denitrification [49]. This study showed that 5-year straw incorporation inhibited N_2O emissions under both irrigation regimes. In the early stages of rice growth, the paddy fields in each treatment retained an aqueous layer and the soil had strong reducing conditions, which promoted denitrification and reduced N_2O production [50]. The alternating wet and dry conditions give the soil good permeability and favor nitrification-denitrification. In addition, studies have shown that there was a trade-off relationship between N_2O and CH_4 emissions in paddy fields [18,51]. In this experiment, CH_4 fluxes showed high levels around 40 days after rice transplanting, while N_2O fluxes decreased significantly. In terms of flux trend, the CH_4 fluxes generally showed a decreasing trend, while N_2O fluxes showed a slowly increasing trend, which was particularly evident in F1 and C1.

Affected by straw incorporation, soil CO_2 emission rate showed a process of "rapid rise-stable-higher value-continuous decline" over time, which was related to the depletion of easily decomposable organic matter in the soil and the growth of microbial groups. The CO_2 emission rate decreased rapidly from a higher emission rate after straw incorporation, because the straw was easily decomposed into short-chain organic substances (monosaccharides, starches, simple proteins, etc.), after incorporating into the soil and was depleted. The higher value around 30 days after transplanting is related to the growth of microbial taxa that decompose long-chain or cyclic organic matter, while the continued reduction of decomposable organic matter thereafter leads to a further attenuation of the CO_2 emission rate [52]. As one of the important factors of soil respiration, temperature affects soil CO_2 emissions by affecting soil microorganisms, root biomass, and rhizosphere activities [53]. Studies have shown that soil respiration was directly proportional to soil temperature and organic C content. Affected by temperature, all treatments in this study reached a peak in early August (about 80 days after transplanting), and the CO_2 emissions of rice at the mature stage accounted for the largest proportion [54,55]. Compared with other GHG experiments in Southern China, CH_4 and CO_2 emissions were greater in our experiments. Among them, CH_4 emissions were on average about 30% higher and CO_2 emissions were on average about 300% higher. In contrast, the differences in N_2O fluxes were not significant [56,57]. Studies have shown that the organic C content in Mollisols was about twice as high as in other regions in China, and the high organic C content makes it a major source of C emissions [58]. In addition, microorganisms play a dominant role in soil C sequestration. Compared to other paddy soils, Mollisols have high microbial content, complex structure, and high organic matter content. These characteristics make it a stronger "microbial C pump". Mollisols are mainly distributed at high latitudes, where lower temperatures expose the soil to freeze–thaw cycles, which destroy macromolecular organic matter in the soil and increase the availability of organic matter to microorganisms [59].

Normally, farmers always worried that the lack of water in paddy fields would affect crop yield, prompting FI to become a universal irrigation regime. However, in this study, the yields of C1 and C5 increased by 11.5% and 10.0%, respectively, compared to F1 and F5 through rational field water management practices. This was mainly due to the effective control of inefficient tillering at the tillering stage by CI, which reduced the loss of N [32]. In addition, the year of straw incorporation also affected the paddy yield. Under the same irrigation regime, the yield of C5 increased by 4.4% compared to C1 and the yield of F5 increased by 5.8% compared to F1. This was because the soil organic C content increased with planting time, and the increase in soil organic C content would further contribute to the increase in rice yield [7]. Moreover, CI sometimes was more favorable for weed growth and enrichment compared to FI, which might also help to increase soil organic C and nutrients, leading to an increase in rice yield [60,61]. From a water resource perspective, FI needs to maintain a continuous water layer in the field, which increases water waste due to evaporation, surface runoff, and deep infiltration [62,63]. In contrast, CI has good water conservation effects from tillering to maturity, it improved water use efficiency and N fertilizer utilization in paddy fields in the early growth stage and reduces N leakage losses in the late growth stage of rice. For example, Chen et al. showed that CI promoted straw N sequestration and reduced straw N losses while improving plant utilization of straw N [64]. Since fertilizer application contributed significantly to GHGs emissions and reactive N, less N loss under CI treatment and higher N fertilizer utilization efficiency effectively reduced farmers' labor costs and fertilizer application, which effectively reduced graywater production during rice production [59,65,66]. The promotion of CI effectively solved the water shortage problem of rice cultivation in the cold region without affecting crop yield, while effectively reducing the *GWP* and *GHGI* produced by N_2O and CH_4 in paddy fields. Heilongjiang Province of China is a typical rice-planting area in cold regions, according to Heilongjiang Statistical Yearbook 2016, the rice-planting area in Heilongjiang Province is about 3.81×10^6 ha^{-1} [67]. If the irrigation regime of CI was used instead of FI, it was estimated that the annual *GWP* would be reduced by about 0.18×10^{10}–11.4×10^{10} kg CO_2-eq during the rice growth period. Therefore, promoting CI in the cold region of China is a key measure to reduce GHGs, alleviate water shortage, and ensure rice yield.

5. Conclusions

Straw incorporation years and irrigation regimes had significant effects on GHG emissions from paddy fields. Five-year straw incorporation slightly increased crop yield by 4.42–5.84% and significantly reduced cumulative N_2O emissions by 44.9–73.1% from paddy fields; however, it increased the cumulative emissions of CH_4. FI greatly promoted the CH_4 emissions by 235.0–391.5%, which further lead to the far greater *GWP* and *GHGI* of F5 than other treatments. Conversely, although CI partially increased CO_2 emissions, CI had lower *GWP* and *GHGI*. Among them, C5 had the lowest *GWP* and *GHGI*, with *GWP* 1.2%, 2.5%, and 47.6% lower than C1, F1, and F5, respectively, while *GHGI* was 5.4%, 16.3%, and 52.4% lower than C1, F1, and F5, respectively. Our study indicates that controlled irrigation has high GHG reduction potential under continuous multi-year straw incorporation, which provides a basis for GHG emissions from paddy fields in the cold region of Northeast China.

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