EFFECTS OF STRAW RETURNING AND WATER MANAGEMENT ON YIELD AND NON-CO_2 GREENHOUSE GAS EMISSIONS IN COLD BLACK SOIL PADDIES

XU, D.[1,2] – ZHANG, Z. X.[2,3*] – NIE, T. Z.[2]

[1]*College of Agriculture, Northeast Agricultural University, 150030 Harbin, China*

[2]*Key Laboratory of Efficient Use of Agricultural Water Resources, Ministry of Agriculture and Rural Affairs, Northeast Agricultural University, 150030 Harbin, China*

[3]*School of Water Conservancy and Civil Engineering, Heilongjiang University, 150030 Harbin, China*

[*]*Corresponding author*
e-mail: zhangzhongxue@163.com

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Abstract. In order to explore the effective management measures of increasing yield and reducing non-CO_2 greenhouse gas (CH_4 and N_2O) emission in the cold black soil paddy field, field experiments were carried out. This paper analyzed the impact of straw returning and different irrigation methods on rice field yield, greenhouse gas emissions, global warming potential (GWP) and greenhouse gas emission intensity (GHGI). The results showed that compared with the treatment without straw returning, the yield of straw returning treatment increased by 11.79% annually, CH_4 emissions increased by 62.71% annually, N_2O emissions decreased by 1.28% annually, GWP and GHGI increased by 60.90% and 45.58% annually, respectively. Compared with conventional flooding treatment, the yield of controlled irrigation treatment increased by 2.68% annually, the difference was not significant, CH_4 emissions decreased by 56.42% annually, N_2O emissions increased by 133.41%, GWP and GHGI decreased by 54.89% and 55.93% annually, respectively. Straw returning and controlled irrigation had significant interaction on GWP and GHGI, but not significant interaction on yield. The GHGI values of the four treatments were as follows: KFH0< KFHS< CFH0< CFHS. Therefore, controlled irrigation is an irrigation method with stable rice yield and good greenhouse gas emission reduction effect. Straw returning and controlled irrigation can achieve the double goals of increasing yield and reducing greenhouse gas emissions of rice fields in cold regions.
Keywords: *straw returning, controlled irrigation, GWP, GHGI, yield, CH_4, N_2O*

Introduction

CH_4 and N_2O oxide are important greenhouse gases that cause global warming, and the concentration of these two gases has continued to increase in the past hundred years, resulting in an intensification of the greenhouse effect. Agriculture is an important source of non-CO_2 greenhouse gas (CH_4 and N_2O) emissions. According to statistics, 52% of the world's methane and 84% of nitrous oxide come from agricultural activities (Smith et al., 2008). Rice is one of the main food crops, and China's rice planting area and yield account for 22% and 34% of the world, respectively (Liang et al., 2016). So, it is significant to study the reduction of non-CO_2 greenhouse gas emissions in rice fields and improve crop yields for the sustainable development of China's agriculture.

Northeast rice region is an important grain producing area in China, both its planting area and output are ranked first in the country (Dai, 2019), thus having a decisive role in ensuring national food security. In recent years, straw returning has become a protective tillage measure for black soil in cold land, which can improve soil fertility, improve the

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physical and chemical properties of farmland soil, and increase crop yield (Pei et al., 2014; Zeng et al., 2018). However, straw returning to the field improves the soil of the paddy field, which also affects the greenhouse gas emissions of the paddy field. A large number of studies have shown that straw returning significantly increases methane emissions from paddy fields, thereby increasing the integrated greenhouse effect of paddy fields (Jiang et al., 2003; Gong et al., 2015; Zhang et al., 2015). Water management is another agricultural measure that affects greenhouse gas emissions and yields in paddy fields, which is also an important factor influencing the effect of straw returning to the field (Wang et al., 2016; Nie et al., 2020). Faced with the relative shortage of water resources in northern China, rice water-saving irrigation technology has been widely promoted (Shi, 2007). Compared with conventional flooded irrigation of rice, water-saving irrigation can significantly reduce methane emissions in paddy fields. Due to the promotion of nitrification and denitrification reactions, it will stimulate the growth of nitrous oxide emissions, but generally reduce the combined greenhouse effect of rice fields (Li et al., 2006; Ahn et al., 2014). Although controlled irrigation has been proved to be a water-saving and emission-reducing cultivation method suitable for rice production in cold land (Sun et al., 2019), the results of controlled irrigation on rice yield are not yet uniform. Studies have shown that controlled irrigation can increase the effective tillering number and setting rate of rice, and then increase rice yield (Peng et al., 2000; Li et al., 2011). Other studies have shown that rice yields under controlled irrigation are not much different from conventional irrigation (Liu, 2012; Zhu et al., 2013). Other studies have shown that controlled irrigation technology needs to be combined with water-saving and drought-resistant varieties of rice to have yield advantages (Luo, 2010; Ding et al., 2021). Therefore, the coupling study of straw returning, and paddy water management is very necessary.

In the past, the study of rice yield and greenhouse gas emissions by straw returning was mostly focused on conventional flooded irrigation, and more on the impact of methane in rice fields. However, there are few reports on the impact of straw returning and controlled irrigation on rice yield and greenhouse gas emissions. Whether the greenhouse effect aggravated by straw returning can be compensated by controlled irrigation, and the yield of rice field under irrigation can be adjusted by straw returning to the field, so that the cold black soil rice field can have both yield and ecological environment benefits needs further studies. Therefore, this paper observes the effects of different water management and straw returning on paddy yield, paddy methane and nitrous oxide emissions, global warming potential (GWP) and GWP per unit yield through field experiments, in order to explore the coupling effect of straw returning and irrigation mode and provide a theoretical reference for the sustainable development of yield increase and greenhouse gas emission reduction in cold black soil paddy.

Materials and methods

Overview of the test area

The test was conducted from May to October 2018 at the experimental station of Heilongjiang Rice Irrigation Test Center (125°44′ E, 45°58′ N), located in Ping'an Town, Qing'an County, Suihua City, Heilongjiang Province, China (*Fig. 1*). It is a typical cold black soil distribution area, belongs to cold temperate continental monsoon climate, four distinct seasons, and annual average precipitation of 580 mm. The average precipitation of rice during the growth stage is 509 mm, the frost-free stage is 130 days, and the

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effective accumulated temperature is 2300~2500 °C. The soil type is white slurry black soil, pH is 6.87, organic matter is 41.6 g·kg^{-1}, total nitrogen is 1.49 g·kg^{-1}, total phosphorus is 15.13 g·kg^{-1}, total potassium is 17.96 g·kg^{-1}, alkali-hydrolyzed nitrogen is 186.4 mg·kg^{-1}, effective phosphorus is 33.9 mg·kg^{-1}, effective potassium is 153.2 mg·kg^{-1}.Air temperature and precipitation data during the rice growth period are shown in *Figure 2*.

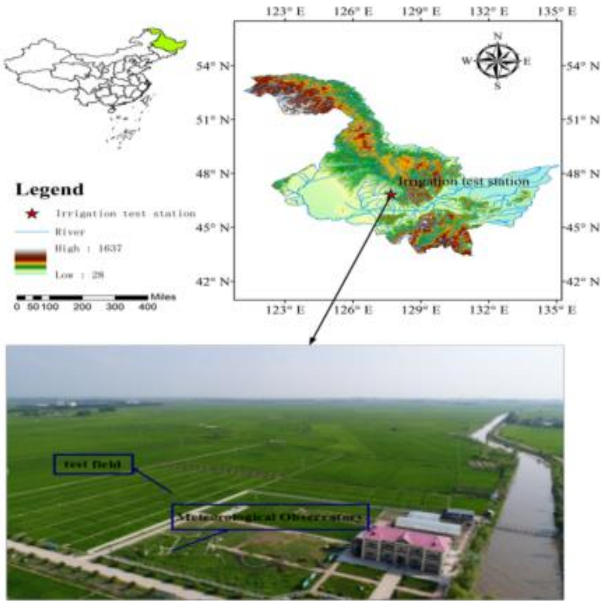

Figure 1. *Study area and experimental site*

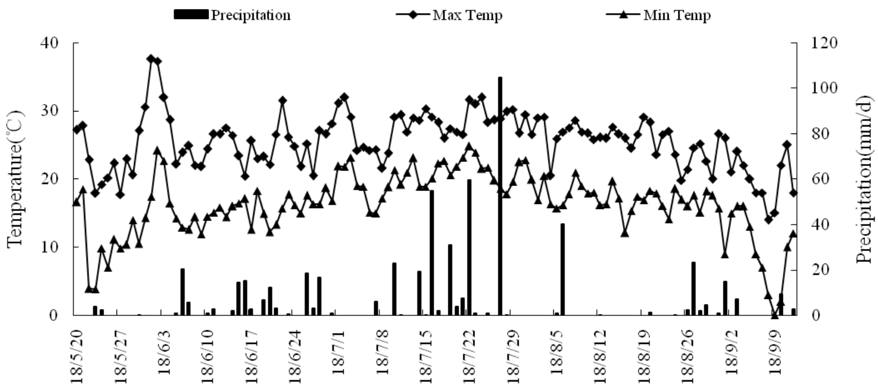

Figure 2. *Air temperature and precipitation*

Experimental design

Two factors were tested for straw returning and water management. The straw returning method adopts the two methods of full straw returning (HS) and non-returning (S0), and the amount of straw returning is at 6 t·hm^{-2}. Then, the rice straw is harvested autumn, the straw is crushed and cut into about 6~ 7 cm fragments and applied to the rice field. Finally, the crushed straw is pressed into 15~ 20 cm soil, it is tightly pressed and has no standing up. Water management adopts two methods: which is conventional

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flooded irrigation (CF) and controlled irrigation (KF), and the water management standards are shown in *Table 1*. Four treatments were formed between straw returning and irrigation mode: conventional flooded non-straw return (CFS0) was the control treatment, and full conventional flooded straw (CFHS) was returning to the field, controlled irrigation with non-straw returning (KFS0), full controlled flooded irrigation straw returning (KFHS). Each treatment was repeated 3 times, and there were 12 cells in total. The random block arrangement was designed. The area of each cell was 10 m×10 m, that is, 100 $m^{2.}$ The perimeter of the community is treated with water insulation, and the insulating materials are plastic board and cement. The square white steel base (50 cm× 50 cm) is embedded at 0.5 m from the ridge in the center of the community. The base is embedded into the soil at 5 cm deep as a sampling point for the placement of static boxes for manual sampling. Each district drains and irrigates separately, and the water intake is measured by water meter.

Table 1. *Water management table of different irrigation modes*

Growth Stage	BBCH 14-19	BBCH 20-25	BBCH 26-27	BBCH 28-29	BBCH 30-49	BBCH 51-69	BBCH 71-85	BBCH 87-89
Control irrigation	0～30	0.7θs～0	0.7θs～0	Drying fields	0.8θs～0	0.8θs～0	0.7θs～0	Drop dry
Conventional flooding	0～30	0～50	0～50	Drying fields	0～50	0～50	0～50	Drop dry

Note: θs is the mass fraction of saturated moisture content of root layer soil, 85.5%. The data before "~" is the lower limit of moisture control, and the data after "~" is the upper limit of moisture control. The depth of the water layer on the field surface is mm. The growth stages is according to BBCH (Biologische Bundesanstalt, Bundessortenamt and Chemical industry) scale (Duman et al., 2019)：14-19 (green stage), 20-25(early tillering), 26-27 (middle tillering), 28-29 (late tillering), 30-49 (stem elongation and booting), 51-69 (inflorescence emergence and anthesis), 71-85 (fruit development and ripening) and 87-89 (yellow ripe) .The same below

The rice variety for test was the local main cultivar, Northern Oasis No. 2 Japonica rice, with a planting density of 30 cm × 10 cm, and three plants per hole. The fertilizers applied were urea (containing N at 46%), super phosphate (containing P_2O_5 at 12%), potassium chloride (containing K_2O at 60%), the application amount of N, P_2O_5, and K_2O is measured, respectively. each treatment of nitrogen fertilizer was applied to 110 k g·hm^{-2}, according to the base fertilizer, tillering fertilizer, regulating fertilizer. The ratio of ear fertilizer was 4.5 : 2 : 1.5 : 2 parts. Each treatment was administered P_2O_5 with 45 kg·hm^{-2}, and K_2O with 80 kg·hm^{-2}. Phosphorus fertilizer as base fertilizer once applied, potassium fertilizer as base fertilizer and 8.5 leaf age applied twice, the ratio before and after is 1:1. Rice was fertilized on May 12th and planted on May 20th, the growth stages were introduced in the corresponding *Table 2*. Other management measures such as weeding, and pest control are the same as local farming habits.

Table 2. *Time division of rice growth stages*

Growth Stage	BBCH 14-19	BBCH 20-25	BBCH 26-27	BBCH 28-29	BBCH 30-49	BBCH 51-69	BBCH 71-85	BBCH 87-89
Date	5.20~5.27	5.28~6.13	6.14~6.27	6.28~7.6	7.7~7. 24	7.25~8.6	8.7~8.21	8.22~9. 12
Number of days to last	8	17	14	9	18	13	15	21

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Observation indicators and methods

Yield

When rice matured, 10 representative rice plants were selected in each community. After drying, the seeds were examined, and the effective number of ears, the number of grains per ear, the setting rate, and the weight of 1,000 grains were investigated, and the theoretical yield of rice was calculated according to the density of rice population.

Gas sample collection and determination

Gas sampling adopts the static box method (Du et al., 2001). The sampling box is made of 5 mm thick transparent plexiglass, the outer surface of the box is pasted with thermal insulation material aluminum foil insulation, the cross-sectional size of the sampling box is 50 cm×50 cm, and the height of the box in the early stage of rice growth is 60 cm. The height of the box is increased to 110 cm after the BBCH 30-49 growth stage. A three-way valve gas collection hole is set 30 cm from the top on one side of the box to connect the three-way valve to facilitate gas collection. A built-in fan on the top of the sampling box and a temperature probe of a digital thermometer are installed to mix the gas in the box during sampling and prevent gas quality calculation errors caused by the temperature increase in the box during the sampling process. Before transplanting, the base is embedded in the soil, the base is level with the mud surface, and the sampling box is gently placed on the base of the return frame when sampling. The water injection in the base sink ensures that the gas inside and outside the box is isolated during sampling. Rice testing was initiated one week after transplanting, and the detection time was 10:00- 12:00 (Chen and Tu, 1995; Frei, 2007), with 3 repeated parallel acquisitions per treatment, on average weekly 1 time, until 1 week before harvest. When sampling, about 50 mL of gas was extracted from the box with a syringe, and samples were collected at 0, 5, 10, and 15 minutes, respectively. The gas inside the syringe is then immediately transferred to the aluminum foil sampling bag, which is brought back to the laboratory in time for determination.

Gas samples were determined by meteorological chromatograph (GC-2010Plus, Japan). CH_4 detector is FID (Flame Ionization Detector), detection temperature 200 °C, column temperature 60 °C, carrier gas is nitrogen. The N_2O detector is an ECD (Electron Capture Detector) with a detection temperature of 250°C and a column temperature of 60°C The carrier gas is a mixture of argon and methane. The gas emission flux is calculated as follows:

$$F = \rho \cdot h \cdot \frac{\mathrm{d}c}{\mathrm{d}t} \cdot \frac{273}{273+T} \quad \text{(Eq.1)}$$

where, F is the gas emission flux (mg·m^{-2}·h^{-1} or μ·g·m^{-2}·h^{-1}). ρ is the gas density (kg·m^{-3}) in the standard stage, h is the net height of the box (The distance from the top of the tank to the water surface, m). dc/dt is the concentration change rate of the gas in the sampling box (mL·m^{-3}·h^{-1}). 273 is the gaseous equation constant, which is the average temperature (T °C) in the sampling box during the sampling process. The gas emission flux was calculated according to the relationship curve between gas sample concentration and time, and the growing season emission was obtained by multiplying the average daily emission

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flux between the two sampling intervals and the number of days between sampling multiplied and accumulated (Tian et al., 2019).

Estimation of global warming potential and greenhouse gas emission intensity

In this study, GWP is used to represent the relative radiation effect of different greenhouse gases with the same mass on the enhancement of greenhouse effect. According to the combined greenhouse effect of CH_4 and N_2O per unit mass, it is 25 times and 298 times of CO_2 respectively on the 100-year scale (Metz et al., 2007). The CO_2 equivalent (E-CO_2) of CH_4 and N_2O emissions of each treatment is calculated, so as to obtain GWP ($kgCO_2\text{-}eq{\cdot}hm^{-2}$) of CH_4 and N_2O emissions of each treatment. The calculation formula is as follows:

$$GWP = 25 \times R_1 + 298 \times R_2 \quad \text{(Eq.2)}$$

where, R_1 and R_2 were the cumulative CH_4 and N_2O emissions ($kg{\cdot}hm^{-2}$) during the growing season, respectively.

Greenhouse gas intensity (GHGI) is a comprehensive evaluation index, which evaluates the greenhouse effect and coordinates the environmental and economic benefits. The value is the ratio of greenhouse gas emission equivalents to the economic output of crops:

$$GHGI = GWP/Y \quad \text{(Eq.3)}$$

where, the formula Y is the annual yield of rice ($kg{\cdot}hm^{-2}$).

Data processing and analysis

Microsoft Excel 2013 software was used for data processing, and SAS 9.4 statistical software was used for Two-way ANOVA and method-based LSD_α difference significance test. (P<0.05).

Results and analysis

Analysis of differences in production and greenhouse gas emissions

Yield

Irrigation treatment had no significant effect on annual yields in paddy fields (*Table 3*). KFH0 treatment increased the annual yield of CFH0 treatment by 1.75%, and KFHS treatment was higher than CFHS. The annual yield of treatment increased by 3.53% (*Fig. 3*). Compared with conventional flood irrigation, controlled irrigation increased the yield of rice, but there was no significant difference. Straw returning significantly affected the annual yield of paddy fields (P<0.05). The annual yield of CFHS treatment increased by 10.82% compared with CFH0 treatment, and KFHS treatment was higher KFH0 treatment annual production increased by 12.75% (*Fig. 3*). The annual yield of paddy fields showed no significant difference in the interaction between irrigation methods and straw returning.

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Table 3. *Two-way ANOVA analysis of yield and greenhouse gas emissions by irrigation methods and straw returning to rice fields (F-value)*

Source of difference	Annual production	Anniversary CH_4 emissions	Anniversary N_2O emissions	GWP	GHGI	$F_{0.05}$	$F_{0.01}$
Irrigation methods	0.589ns	144.719**	296.271**	138.972**	250.554**	5.317	11.259
Return the straw to the field	10.401*	53.39**	2.367ns	52.920**	55.187**	5.317	11.259
Irrigation× return of straw to the field	0.085ns	13.759**	0.285ns	14.767**	18.781**	5.317	11.259

Note: ** indicates a significant difference at the 0.01 level, * indicates a significant difference at the 0.05 level, and ns indicates that the difference is not significant

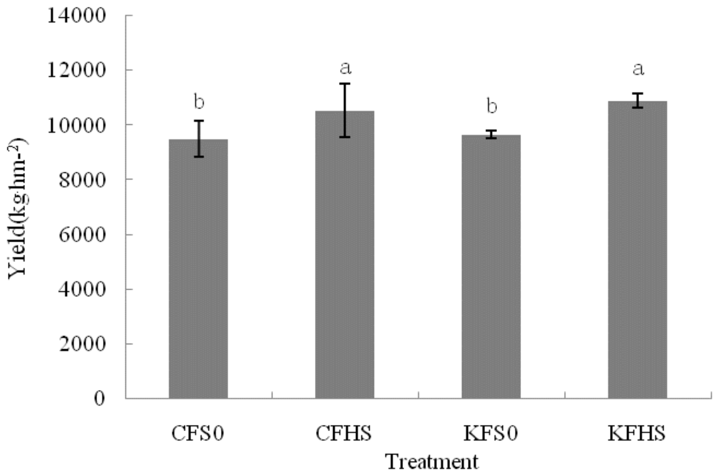

Figure 3. *Effects of water management and straw returning on paddy yield. The vertical bars represent the standard deviations of the means, n=3. Different lowercase letters indicate significant differences in yield among different treatments (P<0.05)*

Methane emissions

Irrigation had significant effect on CH_4 emission in rice growing season (*Table 3*). Compared with CFHS treatment, CH_4 emissions in the growing season decreased by 58.66% under KFHS treatment. Compared with CFH0 treatment, KFH0 treatment reduced CH_4 emission in growing season by 52.63%. Compared with conventional inundation treatment, controlled irrigation significantly reduced the CH_4 emission in the growing season by 56.42% on average (*Fig. 4*). CH_4 emission was mainly concentrated at BBCH 20-25 and BBCH 26-27 growth stage and kept at a low level in other growth stages. The emission of CH_4 in conventional inundated paddy field was also concentrated in BBCH 20-29 growth stage, and the emission peaks were about 10 days later than that of controlled irrigation, both of which occurred in the BBCH 26-27 growth stage. When rice entered the BBCH 30-49 growth stage, the CH_4 emission flux decreased slowly, but still maintained a high level until the end of the BBCH 51-69 growth stage. The CH_4 emission flux decreased to a very low level at BBCH 71-85 growth stage and BBCH

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87-89 growth stage (*Fig. 5*). The methane emission rate was significantly increased by straw returning (P<0.01). Under conventional inundation treatment, the emission of CH_4 in growing season increased by 69.67% with CFHS compared with that with CFH0. In controlled irrigation treatment, the CH_4 emissions of KFHS increased by 48.03% compared with that of KFH0 treatment. The average CH_4 emission during the growing season increased by 62.71% compared with that with non-straw returning. The CH_4 emissions in the growing season of paddy field showed a significant difference (P<0.01) in the interaction effect between irrigation and straw returning. The CH_4 emissions in the growing season of paddy field were reduced by 29.86% compared with CFH0 treatment.

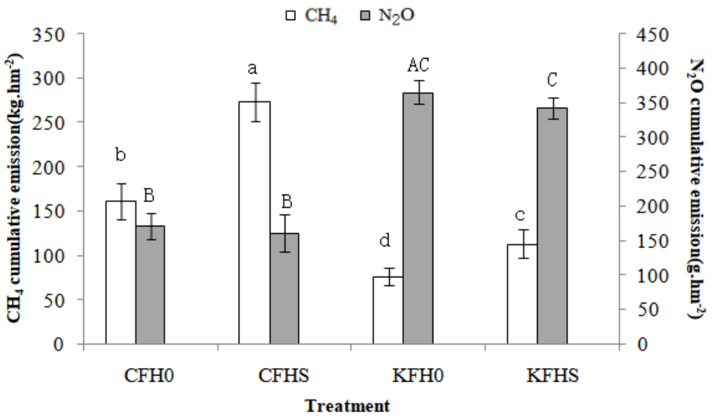

Figure 4. *CH_4 and N_2O cumulative emissions of each treatment during rice growth period.The vertical bars represent the standard deviations of the means. n=3Different lowercase letters indicate significant differences in CH_4 cumulative emissions among different treatments(P<0.05).Different capital letters indicate significant differences in N_2O cumulative emissions among different treatments(P<0.05)*

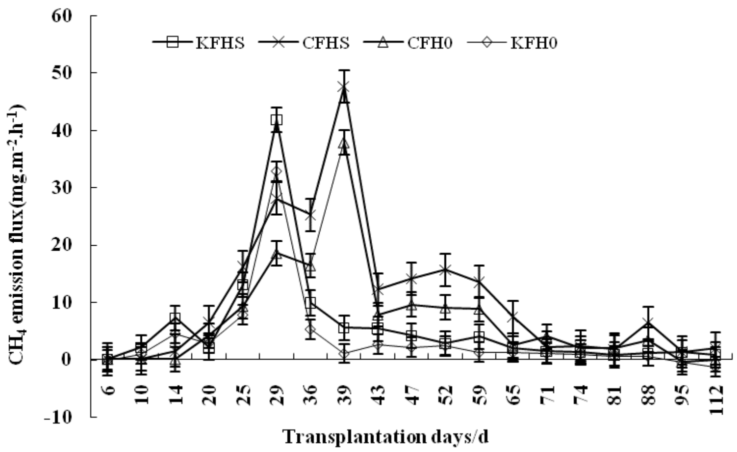

Figure 5. *Changes of CH_4 emission flux in paddy fields under different water management and straw returning modes. The vertical bars represent the standard deviations of the means, n=3*

Nitrous oxide emissions

Irrigation had significant effect on N_2O emission in rice growing season (*Table 3*). Under straw returning, N_2O emission in growing season increased 135.88% by KFHS

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compared with CFHS treatment. Compared with CFH0 treatment, N_2O emission in growing season increased by 131.10% under KFH0 treatment when non-straw was returning to the field. Compared with conventional irrigation treatment, controlled irrigation significantly increased the emission of N_2O in the growing season by 133.41% on average (*Fig. 4*). Under controlled irrigation mode, the N_2O emission fluxes in the paddy field showed a multi-peak phenomenon of alternating increase and decrease in each growth stage, and the emission fluxes in the BBCH 14-19 growth stage were very small. After tillering, the tillering fertilizer and the short-term unsaturated stage of soil resulted in the growth of N_2O emission flux, and the first emission peak appeared. Subsequently, under the combined action of fertilization in the early stage and multiple desiccating, the N_2O emission flux reached the second peak in the whole growth stage at the BBCH 28-29 growth stage. At BBCH 30-49 growth stage, the N_2O emission flux of the paddy field decreased significantly, and two small peaks appeared in BBCH 51-69 growth stage and BBCH 71-85 growth stage, respectively, due to the application of ear fertilizer and grain fertilizer. Under the conventional inundation mode, the N_2O emission flux of the paddy field showed a double-peak stage during the whole growth stage. The drying of the paddy field in BBCH 28-29 growth stage made the N_2O emission flux reach the highest peak during the whole growth stage. The natural drying of the paddy water layer after the BBCH 87-89 growth stage resulted in the second small peak of N_2O emission flux, while the N_2O emission flux in other growth stages was very small (*Fig. 6*). Straw returning reduced N_2O emission, but the difference was not significant, and there was also no significant difference in N_2O emissions during the growing season of paddy field in the interaction effect between irrigation and straw returning (*Table 3*).

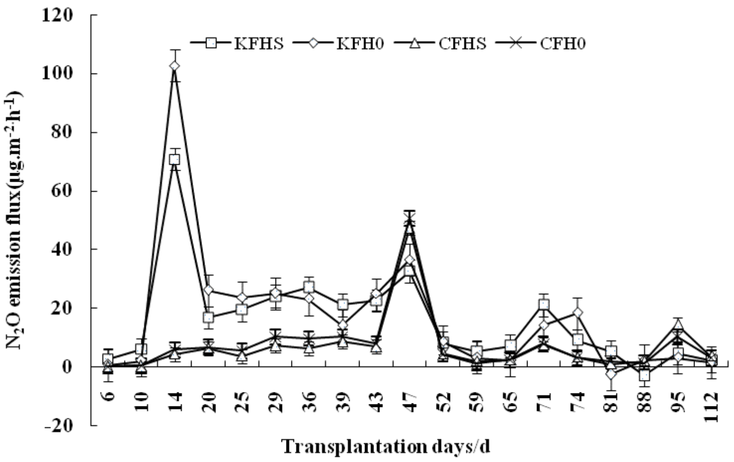

Figure 6. *Changes in emission flux of N_2O in paddy fields under different water management and straw returning modes. The vertical bars represent the standard deviations of the means, n=3*

Global warming potential

The results of CH_4 and N_2O in the growing season of paddy fields showed that irrigation had a significant effect on GWP (*Table 3*). As shown in *Figure 7,* under straw returning, KFHS reduced GWP by 57.46% compared with CFHS treatment. When returning straw to the field, KFH0 reduced GWP by 50.55% compared with CFH0. Compared with conventional flood irrigation treatment, the GWP of controlled irrigation

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treatment decreased significantly, with an average decrease of 54.89%. The effect of straw returning on GWP was also very significant (*P*<0.01). The GWP of straw returning increased significantly, and the GWP of KFHS was increased compared with that of KFH0 under controlled irrigation 45.11%. Under conventional flood irrigation, CFHS increased by 68.71% compared with CFH0 treatment GWP. Compared with non-returning treatment, straw returning increased GWP by an average of 60.90%. GWP is mainly determined by CH_4 emissions from paddy fields (*Fig. 8*), and the contribution of the four treatment CH_4 emissions to GWP is expressed as KFH0<KFHS<CFH0<CFHS. The interaction effect of irrigation mode and straw returning had a significant effect on GWP (*P*<0.01), and KFHS was more CFH0 than the control The average annual GWP decreased by 28.25%.

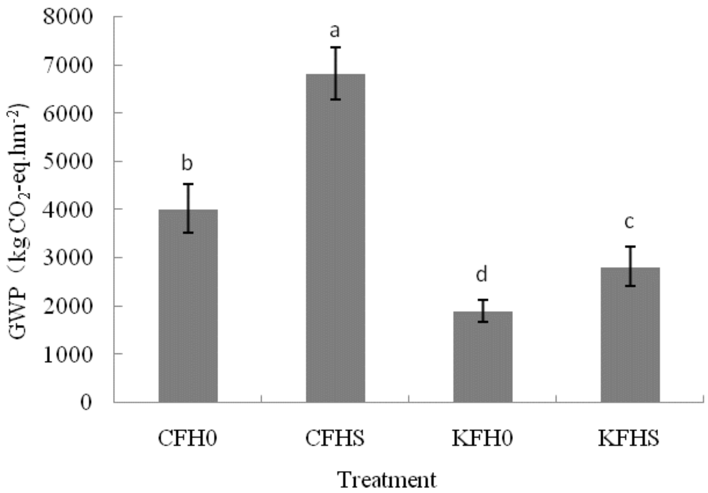

Figure 7. *Effects of different water management and straw returning modes on GWP in paddy field. The vertical bars represent the standard deviations of the means, n=3.Different lowercase letters indicate significant differences in GWP among different treatments (P<0.05)*

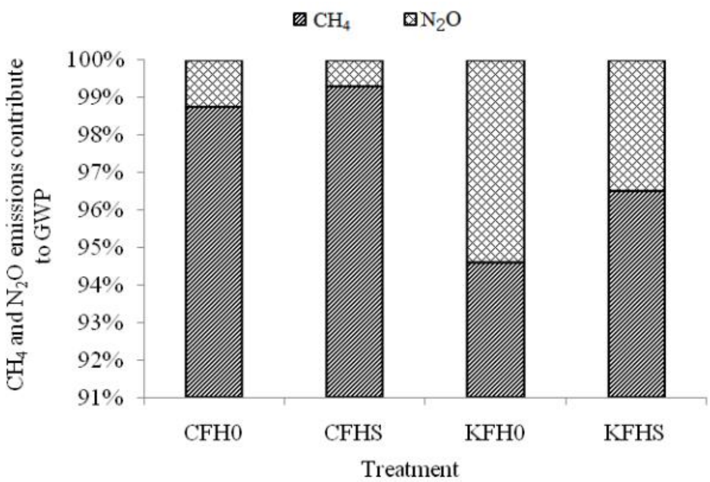

Figure 8. *Contributions of CH_4 and N_2O to GWP under different water management and straw returning modes*

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Greenhouse gas emission intensity

The results showed that the water management model had a significant effect on greenhouse gas emission intensity (GHGI) (*Table 3*), and the GHGI of controlled irrigation was significantly reduced, compared with flooded irrigation the average reduction was 55.93%. Straw returning significantly increased GHGI (P<0.01), and straw returning increased GHGI in paddy fields by an average of 44.58% compared with no treatment. The interaction effect of irrigation mode and straw returning had a significant effect on the annual mean GHGI (P<0.01), and the annual average GHGI of the four treatments was as follows: KFH0<KFHS<CFH0< CFHS, there was no significant difference between KFH0 and KFHS (*Table 4*).

Table 4. *Rice yield and greenhouse gas emissions under different irrigation methods and straw returning*

Dispose	CH_4 emission equivalent (kg·CO_2·hm^{-2})	N_2O emission equivalent (kg·CO_2· hm^{-2})	GWP (kg· CO_2· hm^{-2})	GWP emission reductions (kg·CO_2· hm^{-2})	yield (kg· hm^{-2})	GHGI (kg · kg^{-1})
CFH0	4022.08± 505.34b	51.03± 5.69b	4073.08± 501.70b	0b	9502.80± 664.42b	0.43± 0.04b
CFHS	6824.17± 544.08a	47.76± 7.98b	6871.92± 547.90a	2798.81± 269.82a	10530.67± 969.25a	0.65± 0.036a
KFH0	1905.77± 237.41d	108.75± 5.13a	2014.52± 238.98d	-2058.59± 711.50d	9669.49± 131.24b	0.21± 0.03c
KFHS	2820.92± 410.56c	102.01± 2.13a	2922.92± 412.41c	-1150.19± 89.44c	10902.10± 275.18a	0.27± 0.031c

Note: GWP emission reduction is the GWP reduction of each treatment compared with the control treatment of CFH0. Different letters in the same column indicate significant differences between treatments (P<0.05)

Discussion

Effects of water management and straw returning on yield in cold paddy fields

Rice is a semi-aquatic plant suitable for growth and development in aqueous or humid conditions. The amount and mode of water supply determine the aeration and nutrient supply of the soil, which in turn affects the rice yield (Cai and Li, 2008). The results of this study showed that the yield of controlled irrigation treatment increased by an average of 2.68% compared with conventional flooded irrigation treatment, but the yield difference was not significant (*Table 3*), which was similar to the research of Zhang et al. (2018) and Zhu et al. (2013). The results are consistent and based on controlling irrigation to meet the basic water requirements of rice, stable yields can be obtained while reducing the amount of irrigation.

After straw returning to the field, it can provide a large number of nutrients such as nitrogen, phosphorus and potassium for the soil, and the number of soil microorganisms is also increased, the physical and chemical properties are improved, which is conducive to the growth of crops, and the most direct effect is reflected in the yield growth (Yang et al., 2010). The results of this study showed that under both irrigation conditions, straw returning to the field had a significant effect on the yield of paddy field, with an average yield growth of 11.79%, which was consistent with most previous research results. Gong et al. (2015) believes that rice yield increases with the growth of straw returning to field

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in cold land rice fields, and the yield of rice returning to the field has always been higher than that of non-returning treatment for many years. Liu et al. (2017) showed that straw returning in rice fields for consecutive 4 years showed that straw returning could increase the yield and soil organic matter level of rice after straw returning, and the yield increase rate of rice increased with the growth of straw returning.

This study also found that KFHS treatment was the highest among the four treatments, and the yield of KFHS treatment increased by 14.73% compared with the control CFH0 treatment, indicating that the combined regulation and yield increase effect of straw returning, and controlled irrigation was better than that of straw returning or single cultivation measures of controlled irrigation. The reason for this, Zhang et al. (2018) believe that the control of irrigation soil permeability is better, the dissolved oxygen capacity of the root area is enhanced, which can make rice maintain high root vitality, which is conducive to promoting the efficient absorption and utilization of water and nutrients, and then improving the unit utilization rate. Du et al. (2015) believes that after transplanting rice with 2- 3 leaf ages, controlled irrigation ensures its normal physiological water storage and also increases oxygenation, promote the effect of rooting, especially in the case of full straw returning. It is more necessary to increase oxygen in the open field to reduce the toxicity of seedlings during the straw rot. Therefore, the improvement of soil fertility by straw returning and the regulation of soil permeability by controlled irrigation may be the main reason for the large growth in yield.

Effects of water management and straw returning on CH_4 emissions in cold paddy fields

The results of this study showed that straw returning significantly promoted the seasonal CH_4 emissions of paddy fields, and the average increase in CH_4 seasonal emissions in paddy fields was 77.58% compared with non-returning treatment. The reason for this is generally believed to be that straw input reduces the soil redox potential while providing sufficient effective carbon and energy for methanogenic bacteria (Ma et al., 2008; Hou et al., 2013; Yan et al., 2020). Naser et al. 's experiment in Hokkaido, Japan showed that rice straw returning increased the CH_4 emission flux in the paddy field, and there was a significant positive correlation between the CH_4 emission flux and straw returning amount. The rice-wheat rotation experiment conducted by Zhang et al. (2015) found that the 1-year and 5-year straw returning treatment increased CH_4 and CO_2 emission flux compared with the control treatment.

Water management has a decisive impact on the process of CH_4 discharge in the paddy field. The results of this study showed that controlled irrigation had a significant inhibitory effect on methane discharge in the paddy field, and seasonal CH_4 discharge was reduced by 56.41% on average under controlled irrigation treatment compared with conventional irrigation treatment. The reason is that when go into the BBCH 28-29 growth stage under controlled irrigation mode, the field surface no longer establishes an aquifer, and the relative moisture content of the soil is used as the upper and lower limits of irrigation, and the soil is in alternation of dry and wet, even the relative moisture content of the soil upper limit of irrigation, the soil surface is in a stage of contact with the atmosphere, so the controlled irrigation seriously destroys the formation of the conventional flooding mode. In an anaerobic environment, the production of CH_4 is greatly reduced. In addition, the growth oxygen required by methane oxidizing bacteria in the soil further oxidizes and depletes CH_4 in the environment, resulting in lower CH_4 emissions from controlled irrigated rice fields (Li et al., 2007; Nie et al., 2023).

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It was also found that the combined control of straw returning and controlled irrigation significantly reduced the seasonal CH_4 emissions in the paddy field, and the seasonal CH_4 emissions in the paddy field under KFHS treatment were 29.88% lower than those under CFH0 control treatment. The reason may be that the aerenchyma of rice under controlled irrigation is less developed than that under conventional inundation, which limits the transport and discharge of CH_4 (Kludze et al., 2011). In addition, controlled irrigation can promote the aerobic decomposition of straw organic matter and reduce the conversion of decomposition products to CH_4, thus significantly reducing CH_4 emission (Ma et al., 2010).

Effects of water management and straw returning on N_2O emissions in cold paddy fields

N_2O is the product of nitrification and denitrification in soil. The results of this study showed that the seasonal N_2O emissions of straw returning treatment decreased by 1.28% on average compared with non-returning treatment, but the difference was not significant. This is similar to previous research results (Jiang et al., 2003; Xia et al., 2018), that is, straw returning to the field can reduce N_2O emission in the paddy field. Xia et al. (2018) conducted a meta-analysis of related articles around the world, and the results showed that straw returning could reduce N_2O emission by 17.3% in paddy fields. The reason may be that straw returning promoted microbial fixation of soil nitrogen and reduced effective N for nitrification and denitrification (Xia et al., 2018). At present, the research conclusions on the effect of straw returning on N_2O emission in paddy fields are not consistent. On the other hand, some studies believe that straw returning will increase N_2O emission in paddy fields (Toma and Hatano, 2007; Li et al., 2011). Huang et al. (2004) suggested that the nitrogen source in straw and fertilizer may participate in the nitrification reaction and promote the production and emission of N_2O. The difference of the above two research results may be related to the influence of straw returning method, returning time, soil type, fertilizer application and other factors. Therefore, the effect of straw returning on N_2O emission in paddy field needs further study.

N_2O emissions in Paddy soil were mainly concentrated in the alternating dry and wet stages with severe water changes, so water management had a significant impact on N_2O emissions. The results of this study showed that controlled irrigation significantly increased the seasonal emission of N_2O compared with conventional flooded irrigation, and the seasonal emission increased by an average of 133.41%. In conventional flooded irrigation, except for the large emission of N_2O in the drying stage at the BBCH 28-29 growth stage, the anaerobic environment formed by the flooding stage in the remaining growth stage caused the N_2O produced by the denitrification process. Most of it is reduced to N_2O, so the emission of N_2O is not large throughout the growth stage. The controlled irrigation soil is in a stage of alternating dry and wet most of the time, the soil moisture changes drastically, and the good aeration condition makes the oxygen sufficient to promote the digestion process. Denitrification occurs when the soil is wet, and N_2O is produced faster than reduction, resulting in N_2O accumulation and merging massive emissions (Zhang et al., 2011).

This study also found that although KFHS treatment significantly increased N_2O seasonal emissions by 99.9% compared to control treatment CFH0, KFHS treatment and KFHS treatment did not have a significant 99.9% growth in N_2O seasonal emissions compared to the control treatment CFH0. The seasonal emission of N_2O treated by KFH0

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was basically comparable, indicating that water management was the main factor affecting N_2O emissions from paddy fields compared with straw returning.

Effects of water management and straw returning on GWP and GHGI in cold paddy fields

The emission of CH_4 and N_2O in the paddy field fluctuates each other (Zhang et al., 2018). The results of this study showed that the yield of straw returning to the field was significantly higher than that with non-straw returning to the field, while the comprehensive GWP was increased by 60.90% on average. The combined GWP of controlled irrigation treatment was significantly lower than that of conventional flooding irrigation treatment by 54.89%. At the same time, straw returning, and controlled irrigation had significant interaction effect on GWP of paddy field. Compared with CFH0, KFHS reduced seasonal CH_4 emissions by 29.88%. At the same time, seasonal N_2O emissions from rice fields nearly doubled, resulting in a 28.25 percent reduction in GWP. The results showed that combined control of straw returning, and controlled irrigation could significantly reduce GWP in paddy fields. The water management model of controlled irrigation can not only offset the greenhouse effect caused by the growth of CH_4 emission caused by straw returning, but also further reduce the GWP of paddy fields. This is with Xu et al. (2004) to carry out wet irrigation under no-till conditions on rice fields CH_4 and N_2O The results of the impact tests were similar.

In this study, it was also found that the effects of water management and straw returning on GHGI and GWP were basically consistent, and the interaction between straw returning and controlled irrigation on GHGI was significant, which was compared with the control treatment Compared to CFH0, KFHS treated GHGI by 37.51%. Among the four treatments, although KFH0 treated GHGI the least, KFHS treated the second, KFH0 and KFHS were treated. The difference in GHGI results was not significant, and the KFHS treatment was significantly higher than the KFH0 treatment in terms of yield, so KFHS was considered comprehensively. Treatment is a farmland measure to achieve the dual benefits of increasing yield and reducing greenhouse gas emissions in cold black soil paddies.

Conclusion

(1) Under the same irrigation method, straw returning significantly increased the yield paddy fields, with an average annual yield of 11.79%. Straw returning significantly increased CH_4 emissions from paddy fields and slightly reduced N_2O emissions, among which CH_4 seasonal emissions increased by 62.71% per year. N_2O Seasonal emission decreased by 1.28% on average. The GWP and GHGI of CH_4 and N_2O increased by 60.90% and 45.58%, respectively, compared with non-returning treatment.

(2) There was no significant difference between the yield of paddy under controlled irrigation and conventional irrigation, and the average annual yield increased by 2.68%, basically achieving stable yield. Controlled irrigation significantly reduced CH_4 emissions in paddy fields, but at the same time N_2O emissions increased significantly, among which CH_4 seasonal emissions were reduced by 56.42% per year. N_2O seasonal emission of increased by 133.41% on average, and the GWP and GHGI decreased due to the control of irrigation finally. Compared with the conventional irrigation treatment, they decreased by 54.89% and 55.93% respectively. Controlled irrigation is an irrigation method with stable rice yields and good greenhouse gas emission reduction effects.

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(3) Straw returning and controlled irrigation had significant interaction on GWP and GHGI but had no significant interaction on yield. Compared with CFH0, the GWP and GHGI of KFHS treatment decreased by 28.25% and 37.51% respectively. and with the highest yield. Considering the factors of yield and greenhouse effect, the combined control of straw returning with controlled irrigation can achieve the dual goals of increasing paddy output and reducing greenhouse gas emission in cold region.

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