

# EFFECT OF DIFFERENT IRRIGATION AMOUNT AND STRAW RETURNING AMOUNT ON GLOBAL WARMING POTENTIAL OF PADDY IN COLD REGIONS

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**Abstract.** In order to explore the emission patterns and global warming potential (GWP) of CH<sub>4</sub> and N<sub>2</sub>O from cold rice fields, the cold rice fields in Heilongjiang Province, China were selected as the research objects. The artificial static box method was used to comprehensively observe the CH<sub>4</sub> and N<sub>2</sub>O gas emissions under three water management modes: controlled irrigation (CI), intermittent irrigation (II), and conventional flooding (CF), as well as three straw return management modes: no straw return amount (S0:0 t·hm<sup>-2</sup>), low straw return amount (S1:t·hm<sup>-2</sup>), and high straw return amount (S2:6t·hm<sup>-2</sup>). The results showed that both irrigation amount and straw returning amount promoted the comprehensive warming potential of CH<sub>4</sub> and N<sub>2</sub>O. The effects of irrigation amount and straw returning amount on warming potential were as follows: irrigation amount>straw returning amount. At the same time, irrigation amount and straw returning amount also promoted each other. Based on comprehensive analysis, the optimization mode of cold rice field management aimed at reducing the comprehensive warming potential of CH<sub>4</sub> and N<sub>2</sub>O in cold rice fields should adopt controlled irrigation (CI) and low straw return treatment (S1:3t·hm<sup>-2</sup>), which can facilitate the transformation of soil nutrients and effectively reduce the comprehensive warming potential of CH<sub>4</sub> and N<sub>2</sub>O.

**Keywords:** cold field rice paddy, CH<sub>4</sub> and N<sub>2</sub>O emissions, warming potential, water management, straw return to field

## Introduction

With the continuous development of society, the greenhouse effect is increasing. According to the scientific assessment report on climate change by the United Nations Intergovernmental Panel on Climate Change (IPCC), the temperature is expected to increase by 1.5-4.5°C by the end of the 21<sup>st</sup> century (William and Turner, 2024), which seriously affects the sustainable development of agriculture (Deng et al., 2008). CH<sub>4</sub> and N<sub>2</sub>O are both important greenhouse gases (GHGs) in the atmosphere, with a greenhouse potential 21 and 310 times higher than that of carbon dioxide (CO<sub>2</sub>), and contributing to the greenhouse effect with a contribution of 15% and 5% respectively (Irkowic et al., 1994). As one of the world's major agricultural countries, China ranks first in the world with 37.3% of the world's total rice production. Agricultural production is one of the major sources of anthropogenic GHG emissions, accounting for 14% of the total anthropogenic GHG emissions (Bouwman et al., 2002). Therefore, it is important to study

how to reduce the emissions of greenhouse gases CH<sub>4</sub> and nitrous oxide N<sub>2</sub>O from rice fields and reduce the GWP to mitigate the greenhouse effect.

Water management practices are one of the important factors affecting CH<sub>4</sub> and N<sub>2</sub>O emissions from paddy fields (Peng et al., 2012). It has been shown that compared with conventional irrigation, water-saving irrigation effectively reduces CH<sub>4</sub> emissions from paddy fields, and although N<sub>2</sub>O emissions increase to a certain extent, there is a significant suppression of overall greenhouse gas emissions (Zou et al., 2004). Similarly, straw return management practices have a crucial impact on CH<sub>4</sub> and N<sub>2</sub>O emissions from paddy fields (Zhang et al., 2021). For paddy fields where straw return is implemented, while improving soil water and fertilizer retention capacity, it also provides a large amount of organic matter metabolites for paddy CH<sub>4</sub> production, which promotes the production and emission of CH<sub>4</sub> from paddy fields (Ma et al., 2008). The interaction between water management practices and straw return management practices will indirectly affect the GWP of paddy fields (Yang et al., 2013). In this experiment, we observed CH<sub>4</sub> and N<sub>2</sub>O emissions from paddy fields in Heilongjiang Province, China, to investigate the coupling effect of irrigation volume and straw return volume on the combined GWP and emission pattern of CH<sub>4</sub> and N<sub>2</sub>O in paddy fields, and to search for the optimal water management and straw return management treatment scheme by combining paddy fields' agricultural yields and soil fertility, with a view to providing emission reduction and management technology for the greenhouse effect of paddy fields in the cold regions. In order to provide a basis for the study of greenhouse effect in paddy fields in cold regions and the technology of paddy field management.

## Materials and methods

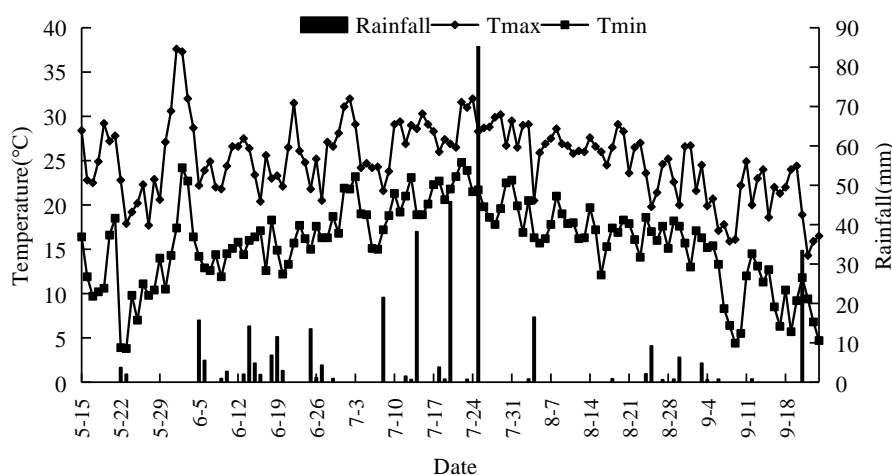
### *Overview of the test area*

The experiment was conducted at Qing'an Irrigation Experiment Station in Heilongjiang Province, which is located in Heping Town, Qing'an County, with the geographic coordinates of 125°44'E and 45°43'N. It is a typical cold black soil distribution area (Zhang et al., 2018). The average multi-year temperature is 2~3°C, the average multi-year precipitation is 580 mm, and the average multi-year water surface evaporation is 700~800 mm. The crop hydrothermal growing period is 156~171 d, the annual frost-free period is 128 d, and the effective cumulative temperature is 2532°C (Li et al., 2023). Climatic characteristics of the cold temperate continental monsoon climate, the four seasons of the year, windy and arid in the spring; warm and rainy in the summer; cool and moderate in the fall; cold and dry in the winter (Cao et al., 2022). The soil type is white slurry soil type rice soil with 61.8% porosity. Rice was sown on May 25, 2018, and harvested on October 10, 2018. The variation of maximum air temperature, minimum air temperature, and rainfall in the experimental area during the reproductive period of rice in 2018 is shown in *Figure 1*.

### *Test protocol*

Three water management modes were used in the experiment, i.e. controlled irrigation (CI), intermittent irrigation (II) and conventional flood irrigation (CF), and the water management of the different irrigation modes is shown in *Table 1*. The experiment also used three straw return management modes, and the straw returned to the field was taken as the amount of no straw returned to the field (S0: 0 t·hm<sup>-2</sup>), the amount of low amount

of straw returned to the field (S1: 3 t·hm<sup>-2</sup>), and the amount of high amount of straw returned to the field (S2: 6 t·hm<sup>-2</sup>), and the amount of high amount of straw returned to the field (S2: 6 t·hm<sup>-2</sup>). Rice straw was selected after harvesting in the fall, and the rice straw was cut into about 6~7 cm pieces and applied to the paddy field, and then the crushed straw was pressed into 15~20 cm of soil by tilling operation, so as to make the tilling tight and no standing ridges. The experimental treatment program is shown in Table 2, with three replications for each treatment and a total of 18 plots, each with an area of 100 m<sup>2</sup> (i.e. 10 m×10 m). The plots were surrounded by seepage barrier treatment, and the seepage barrier materials were plastic sheets and cement ridges. Each plot was drained and irrigated separately, and the water intake was measured by water meter.



**Figure 1.** The variations of the maximum air temperature, the minimum air temperature and the rainfall during the growth period of rice

**Table 1.** Moisture management table

Irrigation methods	Rejuvenation	Tillering at the beginning	Tillers flourish	Tillers	Joint pregnancy spike	Pumping ears bloom	Milk ripening	Yellow ripe
Control irrigation	0~30	0.7 $\theta$ s~0	0.7 $\theta$ s~0	Drying fields	0.8 $\theta$ s~0	0.8 $\theta$ s ~0	0.7 $\theta$ s ~0	Naturally drying
Intermittent irrigation	0~30	0~40	0~40	Drying fields	0~30	0~40	0~40	Naturally drying
Conventional flooding	0~30	0~50	0~50	Drying fields	0~50	0~50	0~50	Naturally drying

Note:  $\theta$ s is the mass fraction of soil saturated moisture content in the root layer. The data before "~" is the lower limit of moisture control, and the upper limit of moisture control after the data bit after "~". Field surface water layer depth unit: mm

The rice variety for test was "Sui-Japonica 18", the planting density was 30 cm×10 cm, 3 plants per hole. The fertilizers were urea (N46%), calcium superphosphate (P<sub>2</sub>O<sub>5</sub>12%) and potassium chloride (K<sub>2</sub>O60%). Nitrogen fertilizer of each treatment was applied according to the ratio of base fertilizer: tiller fertilizer: flower-promoting fertilizer: flower-preserving fertilizer as 4.5:2:1.5:2, P<sub>2</sub>O<sub>5</sub>45 kg·hm<sup>-2</sup>, K<sub>2</sub>O 80 kg·hm<sup>-2</sup> were applied

to each treatment; potash fertilizer was applied twice at the age of basal fertilizer and 8.5 leaf age (the stage of young spikes' differentiation), with the proportion of before and after being 1:1, and phosphorus fertilizer was applied as a basal fertilizer at one time.

**Table 2.** Field experimental treatment settings

Dispose	Handling codenames	Processing name	The amount of straw returning to the field
1	CIS0	Control irrigation, straw-free returning to the field	0 t·hm <sup>-2</sup>
2	CIS1	Control irrigation, low amount of straw returning to the field	3 t·hm <sup>-2</sup>
3	CIS2	Control irrigation, high amounts of straw returning to the field	6 t·hm <sup>-2</sup>
4	CFS0	Conventional flooding irrigation, no straw returning to the field	0 t·hm <sup>-2</sup>
5	CFS1	Conventional flooding irrigation, low-amount straw returning	3 t·hm <sup>-2</sup>
6	CFS2	Conventional flooding irrigation and high-amount straw returning	6 t·hm <sup>-2</sup>
7	IIS0	Intermittent irrigation, straw-free returning to the field	0 t·hm <sup>-2</sup>
8	IIS1	Intermittent irrigation, low-amount straw returning	3 t·hm <sup>-2</sup>
9	IIS2	Intermittent irrigation, high amount of straw returning to the field	6 t·hm <sup>-2</sup>

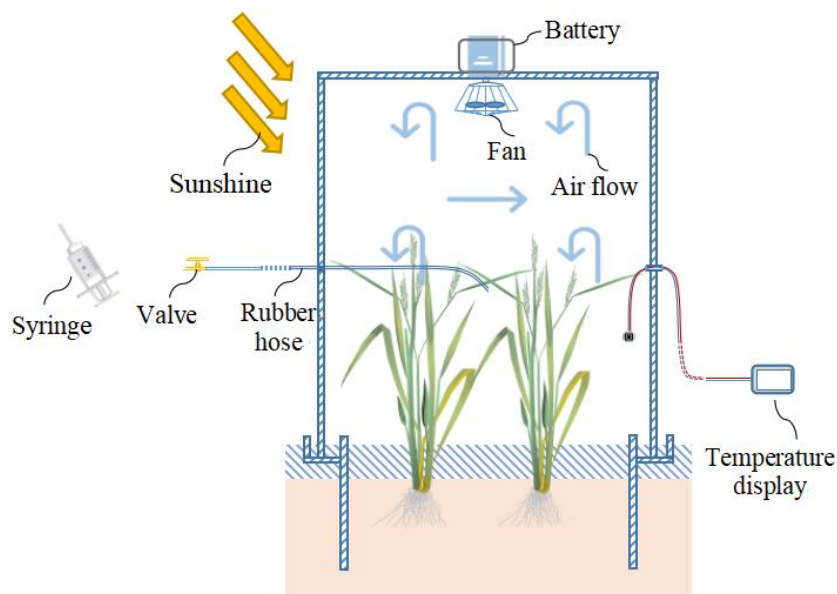
### Observation indicators and observation methods

Field gas sampling is divided into time periods according to the growth period, and the moment when the gas sample is collected is selected at the time when the gas emission best represents the average gas emission of the day. The collection time is flexibly arranged between 10:00 and 14:00.

The CH<sub>4</sub> gas emission flux was located and observed by manual static box method. The static box is made of transparent polymethyl methacrylate, as shown in *Figure 2*. The polymethyl methacrylate is 0.005 m thick, which includes the housing and stainless steel base. When CH<sub>4</sub> gas is collected, an opaque static box is used. A sealing groove 0.03 m wide and 0.05 m deep is left at the top of the stainless-steel base for sealing the box during gas collection, and water is injected into the sealing groove of the stainless-steel base to avoid the exchange of gas in the box with the outside world. A micro electric fan is installed on the top of the box, two small holes are opened on the top, and the gas collection pipe is punched from the side of the box to enter, and the length of the gas collection pipe entering the box is 0.2 m. The gas sample is drawn using a 60 ml sampler and the gas is transferred to the gas bag. During sample collection, to reduce the temperature variation of the gas in the chamber due to solar illumination, the outer layer of the chamber is covered with tin foil for thermal insulation.

When sampling, the sampling box is sealed and placed on the sampling point, and it is stationary for 2~ 3 min to make the gas in the box mix evenly. After the sampling starts, record the time and the temperature in the sampling box at the same time. Samples were collected at 0, 10, 20, and 30 minutes. The sampling also records the depth of the water layer on the field surface, the temperature of the ground and the weather conditions. Gas sample collection and measurement from harvest to soil freezing, gas collection time is

10:00~ 14:00 daily. Diurnal sampling is performed by every 3 h at 7 d. The gas recovery method is the same as above. Gas sample collection and measurement during the period of soil melting to field preparation: the gas collection time is 10:00~14:00 every day.



**Figure 2.** Schematic diagram of static box

Gas sample determination: The collected gas samples must be brought back to the laboratory in time for laboratory testing, and their concentration shall be detected by gas chromatography (Figure 3). Before testing, this paper selects the appropriate gas chromatograph and configures the various chromatographic conditions. The gas concentration was determined by manual injection by gas chromatography, the CH<sub>4</sub> detector was FID (Agilent 7890A, produced by Agilent Corporation of the United States), the detection temperature was 200 °C, the column temperature was 60 °C, the carrier gas was 99.99% high-purity N<sub>2</sub>, and the flow rate was 30 ml·min<sup>-1</sup>. The standard gas is supplied by Dalian Date Gas Co., Ltd.



**Figure 3.** Gas chromatograph

### Calculation method and result analysis method

The GWP of the integrated of cold land rice fields is the sum of the same mass of CH<sub>4</sub> gases emitted from the rice field N<sub>2</sub>O. The relative radiation effect of gases on the greenhouse effect enhancement is expressed in terms of Take 100 amps as the time scale. The GWP per unit mass of CH<sub>4</sub> gas is 21 times that of CO<sub>2</sub>, Unit mass N<sub>2</sub>O The GWP of the gas is 310 times that of CO<sub>2</sub> (Randall, 2007).

The CH<sub>4</sub> and N<sub>2</sub>O emission of Rice Fields calculation formula is as follows (Guo et al., 2015).

$$F = \rho \cdot h \cdot \frac{dC}{dt} \cdot \frac{273}{273+t} \cdot \frac{p}{p_0} \quad (\text{Eq.1})$$

Among them, *F* presents CH<sub>4</sub> emission flux [mg/(m<sup>2</sup>·h)] and N<sub>2</sub>O emission flux [ug/(m<sup>2</sup>·h)]. *ρ* indicates CH<sub>4</sub> and N<sub>2</sub>O density in standard state (0.714 kg/m<sup>3</sup> and 1.964 kg/m<sup>3</sup>). *h* means the effective height of the box (m). *dC/dt* is the change rate of CH<sub>4</sub> concentration in the sampling box [ml/(m<sup>3</sup>·h)] during the sampling process N<sub>2</sub>O concentration rate of change [ul/(m<sup>3</sup>·h)]. *t* means the average temperature in the sampling box (°C). *p* presents air pressure in the sampling box; *p*<sub>0</sub> indicates the standard atmospheric pressure.

The test data were statistically analyzed by SPSS software, and the result analysis was carried out by diameter analysis and correlation analysis, and the test data were shown in Table 3.

**Table 3.** Greenhouse gas emissions

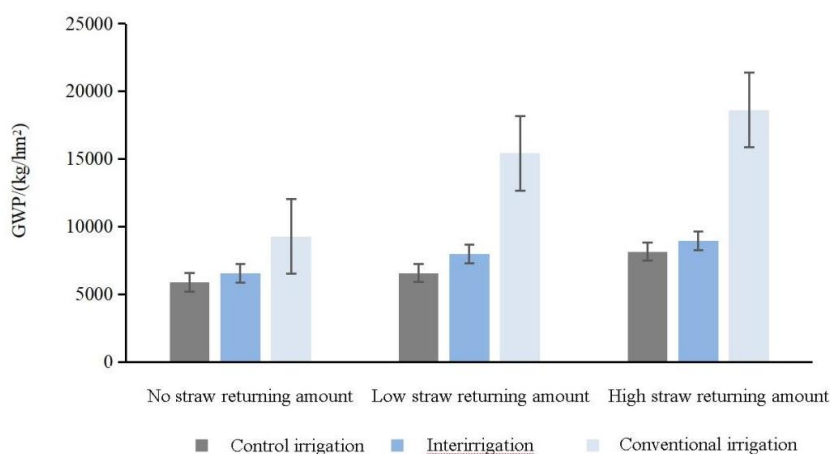
Dispose	Irrigation amount/ (m <sup>3</sup> /hm <sup>2</sup> ).	Amount of straw returning to the field/ (t/hm <sup>2</sup> ).	CH <sub>4</sub> emissions/ (kg/hm <sup>2</sup> )	N <sub>2</sub> O emissions/ (kg/hm <sup>2</sup> )	Global warming potential (GWP)/(kg/hm <sup>2</sup> )
CIS0	3500	0	272.2	0.56	5899.68
CIS1	3500	3	304.98	0.58	6584.628
CIS2	3500	6	378.6	0.64	8149.527
CFS0	5000	0	438.3	0.27	9286.9584
CFS1	5000	3	729.6	0.33	15422.412
CFS2	5000	6	882	0.34	18626.942
IIS0	4000	0	307.2	0.33	6552.942
IIS1	4000	3	375	0.36	7986.6
IIS2	4000	6	421.2	0.39	8964.612

## Analysis of the results

### *Influence between components of GWP under different irrigation amounts*

From Table 3 can be concluded that with the growth of irrigation amount, the GWP shows an increasing trend. Compared with conventional flooding irrigation treatment, the temperature increase potential of controlled irrigation treatment and intermittent irrigation treatment decreased by 36.47% and 29.44%, respectively. The temperature increase potential of controlled irrigation and intermittent irrigation decreased by 57.3% and 48.2%, respectively. The temperature increase potential of controlled irrigation treatment and intermittent irrigation treatment decreased by 56.2% and 51.9%, respectively.

From Fig. 4, it can be concluded that the GWP under conventional flooding treatment was significantly higher than the other treatments, but there were differences in CH<sub>4</sub> and N<sub>2</sub>O gas emissions between irrigation modes. The order of magnitude of CH<sub>4</sub> gas emissions was: conventional flooding > intermittent irrigation > controlled irrigation, and the order of magnitude of N<sub>2</sub>O gas emissions was: controlled irrigation > intermittent irrigation > conventional flooding, and the differences in irrigation modes significantly affected the CH<sub>4</sub> and N<sub>2</sub>O gas emissions, similar to the results of Ghosh et al. (2015). The CH<sub>4</sub> gas emission under conventional flood irrigation was mainly concentrated in the pre-tillering stage of rice, and the peak value appeared in the 1st~2nd d after soil dewatering, while the peak value of N<sub>2</sub>O gas emission under controlled irrigation appeared in the post-fertilizer stage and in the 3rd~4th d after soil dewatering, and there was no significant difference in the temperature incremental potential between the controlled and intermittent irrigation, while the highest temperature incremental potential was observed under the conventional flood irrigation, and the difference was larger than that in the other treatments. It can be seen that the water-saving irrigation mode can effectively reduce the GWP.



**Figure 4.** Changes of GWP under different irrigation modes. Note: The vertical bar represents the standard deviation of the mean,  $n=2$ . Different lowercase letters indicate significant differences in yield between different treatments ( $P<0.05$ )

Regression analysis of irrigation amount and GWP is shown in Figure 5. As can be seen from Figure 5, the fitting equation of GWP and irrigation water under different straw return treatment is as follows:

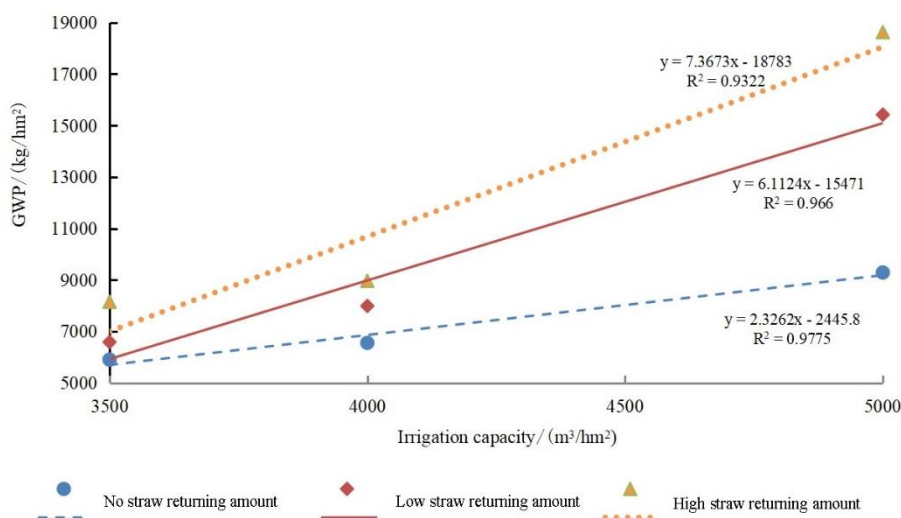
$$\text{Straw-free returning amount: } y=2.3262x-2445.8, R^2=0.9775 \quad (\text{Eq.2})$$

$$\text{Low straw returning amount: } y=6.1124x-15471, R^2=0.966 \quad (\text{Eq.3})$$

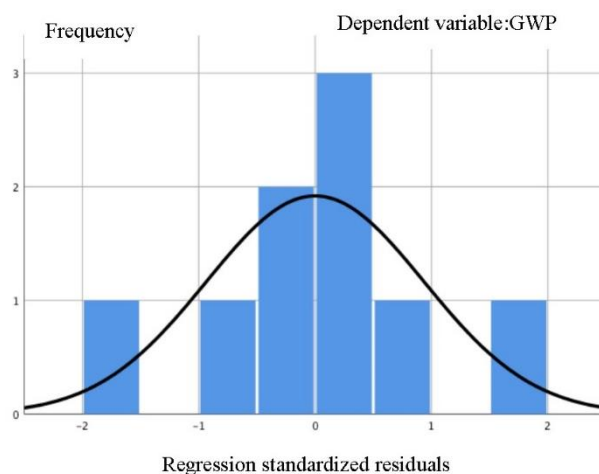
$$\text{High straw returning amount: } y=7.3673x-18783, R^2=0.9322 \quad (\text{Eq.4})$$

In Equation (2) ~ Equation (4),  $x$  is the amount of irrigation water ( $\text{m}^3/\text{hm}^2$ ). It can be obtained from the equation that for every  $1 \text{ m}^3/\text{hm}^2$  growth in irrigation water, the GWP of straw-free returning, low straw returning and high straw returning increased by 2.3262,

6.1124 and 7.3673 kg/hm<sup>2</sup>, respectively. The GWP and irrigation water amount were linearly related, and the GWP increased the most with the growth of irrigation water under the treatment of high straw returning amount, indicating that when the amount of irrigation was constant, the promotion effect of each straw returning amount on the GWP was arranged in the following order: high straw returning amount > low straw returning amount > no straw returning amount. The residual distribution of this regression analysis is shown in *Figure 6*, and it can be concluded that the residuals follow a normal distribution, indicating that this regression analysis has good reliability.



**Figure 5.** Relationship between GWP and irrigation amount

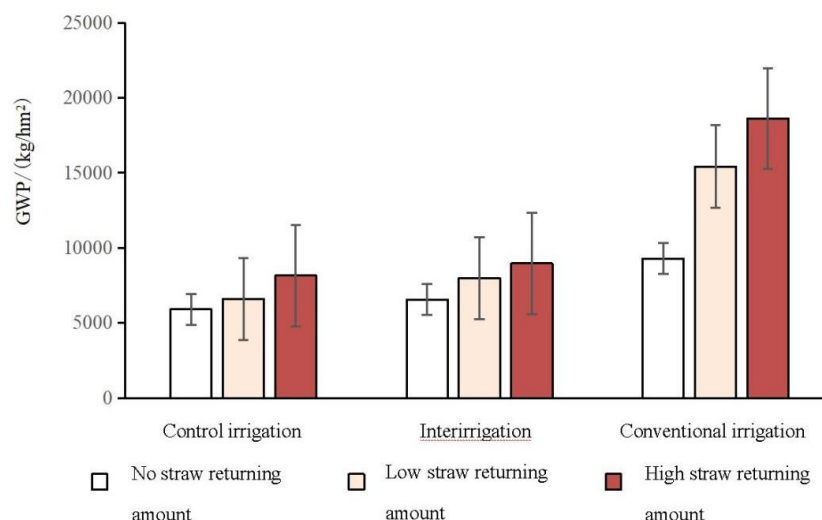


**Figure 6.** Histogram of regression-standardized residuals

### ***Influence between the components of GWP under different amounts of straw returning***

From *Figure 7*, it can be concluded that with the growth of straw returning to the field, the GWP shows an increasing trend. Compared with the treatment of high straw returning to the field, the GWP of no straw returning and low straw returning was reduced by 27.6% and 19.2%, respectively, and the GWP of no straw returning and low straw returning was

reduced by 26.9% and 10.9%, respectively. The GWP of no straw returning and low straw returning was reduced by 50.1% and 17.2%, respectively.



**Figure 7.** Changes in GWP under different straw fields. Note: The vertical bar represents the standard deviation of the mean,  $n=2$ . Different lowercase letters indicate significant differences in yield between different treatments ( $P<0.05$ )

From Table 3, it can be concluded that with the growth of straw returning to the field, the  $\text{CH}_4$  gas emission flux and  $\text{N}_2\text{O}$  gas emission flux also increase, but the  $\text{N}_2\text{O}$  gas emission flux increases less and the  $\text{CH}_4$  gas emission flux increases greatly. Correlation analysis showed that straw returning was significantly positively correlated with  $\text{CH}_4$  gas emissions ( $r = 0.459, P = 0.026 < 0.05$ ), and straw returning was positively correlated with  $\text{N}_2\text{O}$  Gas emissions were significantly positively correlated ( $r = 0.227, P = 0.027 < 0.05$ ). Thus, the correlation between straw returning and greenhouse gas emissions is obtained:  $\text{CH}_4$  gas  $>$   $\text{N}_2\text{O}$  gas.

The regression analysis of the GWP and straw returning amount is shown in Figure 8. From Figure 8, it can be seen that the fitting equation of GWP and straw returning under different irrigation mode treatment is as follows:

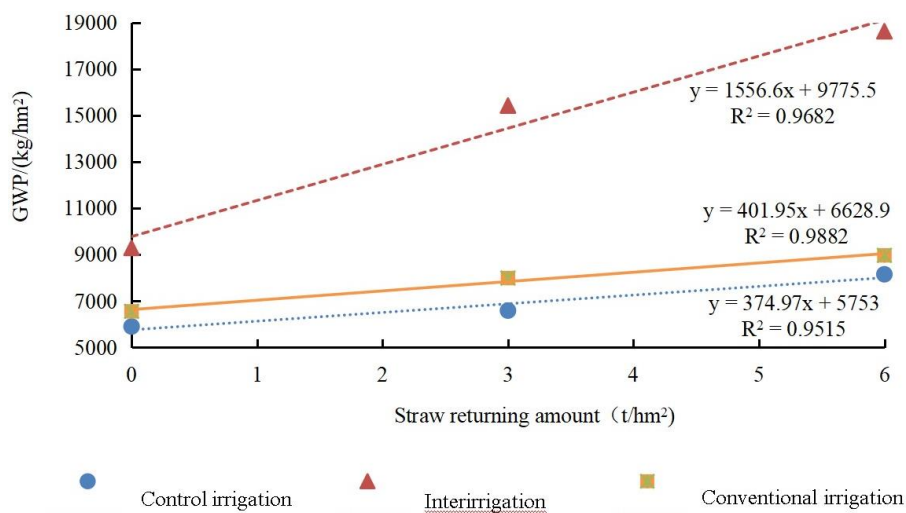
$$\text{Controlled irrigation: } y=374.97x+5753, R^2=0.9515 \quad (\text{Eq.5})$$

$$\text{Intermittent irrigation: } y=401.95x+6628.9, R^2=0.9882 \quad (\text{Eq.6})$$

$$\text{Conventional flooding: } y=1556.6x+9775.5, R^2=0.9682 \quad (\text{Eq.7})$$

In Equations (5) to (7),  $x$  is the amount of straw returned to the field ( $\text{t}/\text{hm}^2$ ). From the equation, for every  $1\text{t}/\text{hm}^2$  increase in the amount of straw returned to the field, the GWP increased by 374.97, 401.95 and  $1556.6 \text{ kg}/\text{hm}^2$  under controlled irrigation, intermittent irrigation and conventional flooding treatment, respectively. It was 4.15 and 3.87 times higher than that of controlled irrigation and intermittent irrigation, respectively. It can be seen that water management mode is an important factor affecting the warming potential,

and both controlled and intermittent irrigation modes can effectively suppress the greenhouse effect.



**Figure 8.** Relationship between GWP and straw returning

**Correlation and regression analysis of irrigation water and straw returning to the field and GWP**

Table 4 shows that there are different degrees of correlation between different greenhouse effect components, with straw returning and irrigation amount positively correlated ( $r = 0.324$ ), irrigation water amount and GWP ( $r = 0.962$ ), straw returning amount and GWP showing a significant positive correlation ( $r = 0.305$ ).

**Table 4.** Correlation analysis between GWP and constituent factors of greenhouse effect

Index	Amount of irrigation water	The amount of straw returning to the field	Warming potential
Amount of irrigation water	1		
The amount of straw returning to the field	0.324	1	
Warming potential	0.962**	0.305*	1

Note: \* and \*\* indicates a significant correlation at the  $P < 0.05$  level and a very significant correlation at the  $P < 0.01$  level, respectively

Since this test is a small sample material, the Shapiro-Wilk test is suitable. As shown in Table 5, the normality test of the GWP is performed, and the statistical value obtained from the results is 0.889, and the significant level  $\text{Sig.} = 0.379 > 0.05$  indicates that the GWP of the dependent variable is a normal variable. Regression analysis can be performed, and the regression equation is as follows:

$$y = -14566.8 + 5.269X_1 + 777.848X_2 \tag{Eq.8}$$

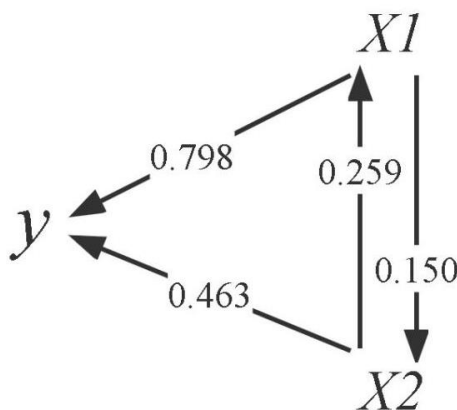
It can be seen from Equation (8) that when  $X_1$  (irrigation water) increases by  $1 \text{ m}^3/\text{hm}^2$ ,  $X_2$  (straw return amount) is fixed,  $y$  (warming potential) increases  $5.269 \text{ kg}/\text{hm}^2$ . When  $X_2$  (straw return amount) increases by  $1 \text{ t}/\text{hm}^2$ ,  $X_1$  (irrigation amount) is constant,  $y$  (warming potential) increased by  $777.848 \text{ kg}/\text{hm}^2$ .

**Table 5.** Normal test results

Dependent variable	Shapiro-Wilk test		
	Statistics	DF	Itself.
Warming potential (y).	0.889	9	0.379

**Pathway analysis of GWP under the combined effect of irrigation water and straw returning amount**

Pathway analysis can be used to analyze the linear relationship between multiple independent variables and the dependent variable, which is an extension of regression analysis. The correlation analysis has limitations due to the interaction between the amount of irrigation water and the amount of straw returning to the field. Therefore, the diameter analysis of the independent variables  $X_1$  (irrigation amount),  $X_2$  (straw returning amount) and the dependent variable  $y$  (warming potential) can obtain in Figure 9 and Table 6.



**Figure 9.** Diameter coefficient diagram. Note: The independent variable  $X_1$  is the amount of irrigation,  $X_2$  is the amount of straw returned to the field, and the dependent variable  $y$  is the warming potential

The amount of irrigation amount ( $X_1$ ) is one standard deviation unit  $sx1=661.44 \text{ m}^3/\text{hm}^2$ . The amount of straw returning to the field ( $X_2$ ) is one standard deviation unit  $sx2=2.60 \text{ t}/\text{hm}^2$ . GWP ( $y$ ) one standard deviation unit  $sy=4366.52 \text{ kg}/\text{hm}^2$ .

**Table 6.** Diameter coefficient table

	$X_1$	$X_2$
$X_1 \rightarrow$	0.798	0.150
$X_2 \rightarrow$	0.259	0.463

From *Figure 8 and Table 6*, it can be seen that the direct diameter of irrigation amount ( $X_1$ ) to GWP ( $y$ )  $q1=0.798$  indicates that when the irrigation amount increases by one standard deviation unit, the GWP will increase by 0.798 standard deviation units, that is, the growth:  $4366.52 \times 0.798 = 3484.48 \text{ kg/hm}^2$ . The irrigation water increase is at  $1 \text{ m}^3/\text{hm}^2$  and the GWP will increase by  $3484.48 \div 661.44 = 5.27 \text{ kg/hm}^2$ . In the same way, the direct diameter of straw return amount ( $X_2$ ) to GWP ( $y$ )  $q2=0.463$  indicates the amount of straw returning ( $X_2$ ). Adding one standard deviation unit will increase the GWP by 0.463 standard deviation units, i.e. the growth of  $2021.7 \text{ kg/hm}^2$ , that is, the GWP when the amount of straw returning to the field ( $X_2$ ) increases by  $1 \text{ t/hm}^2$  ( $y$ ) will increase by  $777.58 \text{ kg/hm}^2$ .

The indirect diameter  $q1 \rightarrow 2 \rightarrow y = 0.150$  indicates that the growth of one standard deviation unit in the amount of irrigation water ( $X_1$ ) will promote the effect of straw return ( $X_2$ ), thereby affecting the GWP ( $y$ ) by 0.150 standard unit difference, that is, the amount of irrigation ( $X_1$ ) When increasing  $1 \text{ m}^3/\text{hm}^2$ , the GWP ( $y$ ) increased by  $251.91 \text{ kg/hm}^2$  by affecting the amount of straw returning to the field ( $X_2$ ). Similarly, the indirect diameter  $q2 \rightarrow 1 \rightarrow y = 0.259$  indicates that increasing the amount of straw return ( $X_2$ ) by one standard unit difference will promote the effect of irrigation water, thereby affecting the GWP ( $y$ ) and increasing the standard unit difference by 0.259 standard units, that is, the amount of straw return ( $X_2$ ). The growth of  $1 \text{ t/hm}^2$  increased the GWP by  $1.71 \text{ kg/hm}^2$  by promoting the effect of irrigation amount ( $X_1$ ).

## Discussion

The study of the GWP of greenhouse gases, such as  $\text{CH}_4$  and  $\text{N}_2\text{O}$ , in different agricultural management modes in rice fields can help to scientifically evaluate the role of management measures in reducing greenhouse gas emissions and mitigating global warming (Song et al., 2013). Understanding the changing patterns of different greenhouse effect components can recognize the correlation between the factors and thus minimize greenhouse gas emissions.

There was an extinction relationship between  $\text{CH}_4$  gas emissions and  $\text{N}_2\text{O}$  gas emissions under different water management modes, with conventional flood irrigation having the highest  $\text{CH}_4$  gas emissions but the lowest  $\text{N}_2\text{O}$  gas emissions, and controlled irrigation having the lowest  $\text{CH}_4$  gas emissions but the highest  $\text{N}_2\text{O}$  gas emissions. The results of this study showed that controlled irrigation and intermittent irrigation significantly reduced GWP compared with conventional flooding irrigation, which is consistent with the findings of Zhang et al. (2021) and Wang et al. (2021). As the continuous flooding environment of conventional flooding irrigation promoted the activity of methanogenic bacteria, resulting in significantly higher  $\text{CH}_4$  emissions than other treatments (Wang et al., 2017). Meanwhile, controlled irrigation effectively reduced  $\text{CH}_4$  production by suppressing anaerobic environment through soil wet-dry alternation (Fa et al., 2024). However, under controlled irrigation, the peak of  $\text{N}_2\text{O}$  emission occurred at the dehydration period after fertilization, which was considered to be possibly related to the enhanced soil nitrification-denitrification (Pei et al., 2017), but the warming effect of  $\text{N}_2\text{O}$  was much lower than that of  $\text{CH}_4$ , and thus the overall GWP was still dominated by  $\text{CH}_4$  (Liu et al., 2022). Although the controlled irrigation process achieved a balance between  $\text{CH}_4$  emission reduction and yield by optimizing the soil redox state, the potential risk of  $\text{N}_2\text{O}$  emission needs to be noted (Xia et al., 2020). Therefore, when seeking water

management models, suppressing CH<sub>4</sub> production and reducing N<sub>2</sub>O emissions will play an important role in reducing the greenhouse effect.

With the increase of straw volume, CH<sub>4</sub> gas emission and N<sub>2</sub>O gas emission were both increasing under different straw return management modes, and it was found that the sensitivity of GWP to the increase of irrigation volume was the highest under high straw volume, which revealed that the synergistic effect of straw return and irrigation volume amplified the greenhouse effect. This is because straw fielding enhances carbon sequestration potential by increasing soil organic matter (Ma et al., 2023), but high straw volume accelerates anaerobic decomposition under flooded conditions, leading to a surge in CH<sub>4</sub> emissions (Deng et al., 2024). At the same time, straw also provides an additional carbon source and promotes microbial activities, which may increase N<sub>2</sub>O emissions through nitrification (Wang et al., 2022). However, the indirect effect of straw return on N<sub>2</sub>O in this study was small, and its effect was found to be constrained by the irrigation pattern. Although increasing the amount of straw returned to the field can increase the water and fertilizer retention capacity of the soil, it will also increase the emission of greenhouse gases. Therefore, the above two aspects should be combined when choosing the amount of straw returned to the field.

Through the flux analysis, it can be seen that the direct flux coefficient of irrigation volume ( $q_1=0.798$ ) was larger than that of straw return volume ( $q_2=0.463$ ), and the contribution of irrigation volume to the GWP was larger between the two. The difference between the direct flux coefficient ( $q_1=0.798$ ) and the indirect flux coefficient ( $q_1 \rightarrow 2 \rightarrow y=0.150$ ) for the amount of irrigation water was larger, which indicated that the amount of irrigation water affected the change of the GWP mainly through the direct effect, while the difference between the direct flux coefficient ( $q_2=0.463$ ) and the indirect flux coefficient ( $q_2 \rightarrow 1 \rightarrow y=0.259$ ) for the amount of straw returned to the field was smaller. Both direct and indirect effects have considerable influence on the warming potential, which is consistent with the mechanism of "moisture and straw synergistically affect the carbon and nitrogen cycle" mentioned by Zhou et al. (2020). Therefore, GHG emission reduction in cold rice fields should be based on the optimization of water management mode, and the appropriate adjustment of the amount of straw returned to the field, to improve the physical and chemical properties of the soil, and at the same time, to reduce GHG emissions.

## Conclusion and future perspective

### Conclusion

Irrigation volume and the amount of straw returned to the field were positively correlated with the warming potential. The amount of irrigation water had a significant effect and played a dominant role in the greenhouse effect components, mainly affecting the GWP through direct effects. The indirect effect of the amount of straw returned to the field through promoting the effect of the amount of irrigation water and thus affecting the GWP accounted for 36% of the effect of the amount of straw returned to the field.

Irrigation volume and the amount of straw also promote each other. An increase of one standard deviation unit in irrigation volume will promote the increase of 0.150 standard deviation unit in GWP of the influence of the amount of straw returned to the field, and an increase of one standard deviation unit in the amount of straw returned to the field will promote an increase of 0.259 standard deviation unit in the GWP of the influence of the irrigation volume.

### *Future perspective*

As the amount of straw returned to the field increased, the water and fertilizer holding capacity of the soil improved, but the GWP of the paddy field also increased and the higher the amount of straw returned to the field, the higher the irrigation volume contributed to the warming potential, so a low amount of straw returned to the field could be used, which would improve the physical properties of the soil and at the same time reduce the greenhouse gases emission. Since, the adoption of water-saving irrigation mode can effectively reduce the GWP by reducing the irrigation water volume. Therefore, under the low straw reduction treatment, both controlled irrigation and intermittent irrigation required less water than conventional flood irrigation, which resulted in a significant reduction of CH<sub>4</sub> emissions but an increase of N<sub>2</sub>O emissions, and a reduction of 57.3% and 48.2% of the warming potential, respectively. It can be concluded that the use of controlled irrigation and low straw return rate in paddy fields can facilitate the transformation of soil nutrients and effectively inhibit greenhouse gas emissions, and significantly reduce the warming potential.

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