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Effects of controlled irrigation on global warming potential based on CH_4, N_2O and CO_2 fluxes in plateau paddy field

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Abstract: A suitable irrigation pattern is of great significance for reducing greenhouse gas emissions. In this study, field experiments and a denitrification-decomposition (DNDC) model were used to study the global warming potential based on CH_4, N_2O and CO_2 fluxes under flooding irrigation and controlled irrigation in paddy fields in the Erhai Lake basin. The results showed that the average value of CH_4 flux under controlled irrigation was lower than that under flooding irrigation, with a reduction range of 43.21% to 48.88%, however, the average value of the N_2O and CO_2 fluxes from paddy field under controlled irrigation were higher than those under flooding irrigation. Controlled irrigation patterns can significantly reduce the global warming potential in paddy fields based on CH_4, N_2O and CO_2 fluxes. Controlled irrigation can effectively reduce the global warming potential per unit yield. For water management in the Erhai Lake basin, it is recommended the controlled irrigation treatment of soil moisture with an upper limit of 100% and a lower limit of 75–85% with irrigation, and a maximum surface water depth of 150–200 mm lasting for five days after precipitation from the jointing-booting stage to the milk stage.

Keywords: carbon; *Oryza sativa* L.; climate change; high-altitude area; rainfall

Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are three main greenhouse gases, accounting for 73.0, 18.3, and 6.0% of greenhouse gas emissions, respectively. Farmland is an important source of greenhouse gas emissions, accounting for 14% of the total greenhouse gas emissions from human activities (Liu et al. 2019). Paddy fields are not only considered the main source of anthropogenic CH_4 emissions but also the source and sink of N_2O gas (Hussain et al. 2015). Long-term and extensive agricultural production activities disrupt the balance between soil carbon storage and atmospheric carbon storage, leading to greenhouse gas emissions (Swift 2001). However, suitable agricultural irrigation patterns can reduce greenhouse gas emissions (Franco-Luesma et al. 2019, Moterle et al. 2020). By water-saving irrigation methods, soil moisture varies in paddy fields, which will inevitably lead to changes in soil physicochemical and biological characteristics, as well as changes in the conversion and output of organic carbon and carbon fixation processes in rice plants. This will affect the greenhouse gas emissions of paddy soil (Norton et al. 2008, Meng et al. 2015).

A number of research studies have been conducted on the emission of CH_4 and N_2O from paddy fields. That has shown that water management is one of the most important factors affecting CH_4 emissions in paddy fields. It affects the production, emission, and oxidation of CH_4 in paddy fields by influencing soil

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permeability and redox states (Win et al. 2015, Leon et al. 2017). The vast majority of studies have indicated that water-saving irrigation for rice can significantly reduce CH_4 emissions while increasing N_2O emissions. There is a clear "consumption-growth" relationship between the two gases, which overall reduces the global warming potential of paddy fields (Peng et al. 2012, Ahn et al. 2014, Zhou et al. 2020). However, a few studies concluded that water-saving irrigation can increase the global warming potential (Qi et al. 2018).

In addition, CO_2 is also one of the main components of agricultural greenhouse gas emissions, which cannot be ignored (Zou et al. 2005). The amount of soil moisture can directly affect the dissolution of CO_2 in soil water and the diffusion rate in soil pores, thereby affecting CO_2 emissions. Due to the long-term submerged anaerobic state of traditional flooding irrigation, the net CO_2 flux and soil respiration changes from paddy fields are relatively small. Previous research on CO_2 emissions from farmland has mainly focused on dry fields, while that on paddy fields is relatively scarce.

All the CO_2, CH_4, and N_2O should be evaluated when assessing the greenhouse reduction influence of an irrigation method in paddy fields. If only one or two greenhouse gases are considered, it may lead to incorrect proposals of emission reduction measures (Hou et al. 2019). Currently, research on the greenhouse gas emissions from paddy fields caused by irrigation mainly focuses on CH_4 or N_2O, and there is a lack of research on the comprehensive effects of all three greenhouse gas emissions, especially in high-altitude areas. Therefore, the objectives of this study were: (1) the emission flux characteristics of CH_4, N_2O and CO_2 from paddy fields under different irrigation methods during the growth period of plateau rice, especially controlled irrigation, and (2) calculate the global warming potential of the three greenhouse gases and provide an optimal irrigation pattern to reduce the greenhouse emission.

MATERIAL AND METHODS

Experimental site. The experiment was conducted at the Haixi Area Experimental Research Base in the Erhai Basin of Dali, Yunnan Province, China, from May to October 2022. The Erhai River Basin belongs to a low latitude plateau subtropical monsoon climate, with an annual average temperature of 15.7 °C, a maximum temperature of 34 °C, and a minimum temperature of –2.3 °C. The annual sunshine duration is 2 250–2 480 h, with a frost-free period of 225–345 days. The annual average rainfall is 1 000–1 200 mm. The elevation of the experimental site is 1 913.6 m a.s.l. The soil type is anthrosols, and its texture is sandy loam with pH 6.12, organic carbon of 29 g/kg, and soil bulk density of 1.39 g/cm^3. The location of the site in Erhai River Basin is shown in Figure 1.

Experimental design. The tested rice cultivar was Yunjing 37. It was transplanted by machine around

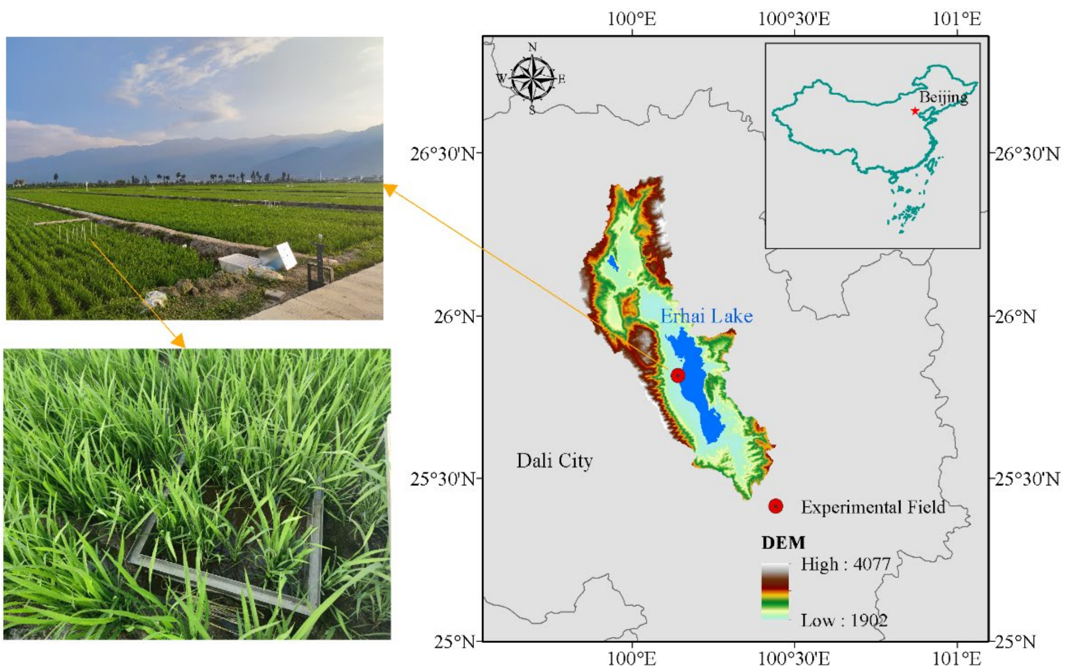

Figure 1. The location of the experimental site

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May 31st with a row spacing of 39 cm and a plant spacing of 11 cm, with 3–5 plants per point. It was harvested on October 18th, with a growth period of about 140 days. Three types of fertilisers were used, base fertiliser (19 May) was bio-organic fertiliser (N, P_2O_5, K_2O contents are 16%, 6% and 8%), tillering fertiliser (24 June) was compound fertiliser (N, P_2O_5, K_2O contents are 15%, 11% and 14%), and panicle fertiliser (28 July) was potassium fertiliser (K_2O content is 24%). The fertiliser for rice of all plots consisted of N fertiliser at 156 kg/ha (bio-organic fertiliser: 82 kg/ha; compound fertiliser: 74 kg/ha), P fertiliser at 88 kg/ha (bio-organic fertiliser: 58 kg/ha; compound fertiliser: 30 kg/ha) and K fertiliser at 169 kg/ha (bio-organic fertiliser: 72 kg/ha; compound fertiliser: 75 kg/ha; mineral fertiliser: 22 kg/ha). The experimental design consisted of traditional flooding irrigation (CK) and controlled irrigation (C1, C2, C3, and C4) treatments with three replicates per treatment. The experimental design is shown in Table 1. A water meter was placed on the irrigation pipe at the head of the field to measure the irrigation amount, and a water meter was also placed on the drainage pipe at the end of the field to measure the drainage amount after precipitation. From the regreening stage to the milk stage, the irrigation water volume of each plot under CK, C1, C2, C3, and C4 treatments was 558, 285, 280, 278, and 274 mm, respectively. While the drainage water volume of each plot under CK, C1, C2, C3, and C4 treatments was 11, 10, 4, 3, and 0 mm, respectively.

Measurement items and methods. CH_4, N_2O and CO_2 samples were collected using the static chamber technique (Yuan et al. 2019). The static box was customised from 2 mm thick stainless steel, with a size of 50 × 50 × 50 (100) cm; the box was wrapped with a layer of insulation sponge about 2 cm thick and then wrapped with a layer of aluminium foil to reduce the impact of solar radiation on the temperature changes of the gas inside the box. Insert the stainless-steel base about 5 cm below the surface of the field, including 6–8 holes of rice inside the base. The static box was covered on the base (the slot needed to be sealed with water during sampling to ensure that no external gas would enter). The gas samples were collected at 0, 10, 20, and 30 min after the static box was covered on the base with 50 mL. The top of the static box was equipped with a gas collection tube, and the tube was connected to a syringe and a sealed gas bag through a three-way valve. Before collecting the gas sample, the tube was cleaned 3 times using the syringe by pumping the gas inside the box; for that, the collected gas sample was from the box, and then the gas sample was transferred to the gas bag through the syringe. Meanwhile, the temperature of the gas inside the box and the depth of the field water layer were recorded. The gas sample was collected at 10:00–11:00 a.m. at 5–7 days intervals. Gas samples were analysed using a gas chromatography analyser (ShimadzuGC – 14B, Kyoto, Japan). The CH_4, N_2O and CO_2 fluxes were calculated according to the Eq. (1) (Zheng et al. 1998):

Table 1. The irrigation and drainage scheme of rice under flooding irrigation and controlled irrigation

Treatment	Regreening stage	Tillering stage			Jointing-booting stage	Heading and flowering period	Milk stage	Ripening stage
		initial	middle	late				
CK	25~5	50~100% 60 (2d)	50~100% 100 (2d)	50~100% 50 (2d)	50~100% 150 (3d)	50~100% 200 (3d)	50~100% 200 (3d)	
C1	25~5	100~80% 60 (2d)	100~70% 100 (2d)	100~65% 50 (2d)	100~80% 150 (3d)	100~85% 200 (3d)	100~75% 200 (3d)	
C2	25~5	100~80% 60 (2d)	100~70% 100 (2d)	100~65% 50 (2d)	100~80% 150 (5d)	100~85% 200 (5d)	100~75% 200 (5d)	naturally drying
C3	25~5	100~80% 60 (2d)	100~70% 100 (2d)	100~65% 50 (2d)	100~80% 200 (3d)	100~85% 300 (3d)	100~75% 300 (3d)	
C4	25~5	100~80% 60 (2d)	100~70% 100 (2d)	100~65% 50 (2d)	100~80% 200 (5d)	100~85% 300 (5d)	100~75% 300 (5d)	

% – percentage of saturated volumetric moisture content of the soil when there is no water layer; h_{max}~h_{min} – upper limit and lower limit of suitable surface water depth (mm) or soil moisture content (%) with irrigation in field respectively; $h_p(nd)$ – maximum surface water depth controlled that lasts for n days after precipitation; CK – control (558 mm); controlled irrigation: C1 – 285, C2 – 280, C3 – 278 and C4 – 274 mm

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$$F = \frac{10^{-5} \mu P}{R(T + 273.2)} H \frac{d_c}{d_t} \quad (1)$$

Where: F – gas emission flux (mg/m^2/h for CH_4 and CO_2; μg/m^2/h for N_2O); P – average air pressure inside the box, 78.11 kPa provided by the Dali Meteorological Bureau was used due to the high altitude area of Dali; μ – molar mass of the gas, g/mol; R – universal gas constant, J/mol/K; T – average temperature inside the box, °C; H – height of chamber above the water surface, m; d_C/d_t – gas mixing ratio concentration (mg/m^3/h for CH_4 and CO_2; μg/m^3/h for N_2O).

Global warming potential and global warming potential per unit yield were calculated according to the Eqs. (2–3) (Yang et al. 2018):

$$GWP = F_{CO_2} + 34F_{CH_4} + 298F_{N_2O} \quad (2)$$

$$GWP_y = \frac{GWP}{Y} \quad (3)$$

Where: GWP – global warming potential value of CH_4, N_2O and CO_2 emissions, kg/ha; F_{CO_2}, F_{CH_4} and F_{N_2O} – cumulative emission of CO_2, CH_4 and N_2O throughout the entire growth period of rice, kg/ha. GWP_y – global warming potential per unit yield, kg/kg; Y – yield, kg/ha.

Meteorological data (precipitation, temperature and humidity) were obtained from a nearby small meteorological station. The depth of field water and soil moisture were measured daily at 10:00 a.m. using vertical rulers and a time domain reflectometer (TDR, Japan SK-100, Tokyo, Japan), respectively. Three representative 1 m^2 areas were selected to estimate one plot yield during the rice harvest period. After natural drying and artificial threshing, the yield was measured separately. In the study, analysis of variance was analysed using least significant difference (*LSD*) tests.

Denitrification-decomposition model. The denitrification-decomposition (DNDC) model is a process-oriented computer simulation model of carbon and nitrogen biogeochemistry in agroecosystems. It was used widely in the study of greenhouse gas emissions. The study used the normalised root mean square error (NRMSE) for model calibration (Gjettermann et al. 2008). It indicates that the fitting effect of the model is relatively good when NRMSE is less than 25% and is acceptable when NRMSE is 25~30%. NRMSE was calculated according to the Eq. (4):

$$NRMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \frac{(p_i - o_i)^2}{o_m^2}} \quad (4)$$

Where: p_i – i-th simulated value; o_i – i-th observed value; o_m – average of the observed values; n – the number of observed values.

RESULTS AND DISCUSSION

The variation characteristics of CH_4 fluxes. The changes in CH_4, N_2O, and CO_2 fluxes from paddy fields are shown in Figure 2. It showed that the trend of CH_4 emission flux was an initial increase followed by a decrease under both CK and four controlled irrigation treatments. The maximum emission flux occurred on July 15th (the 45th day after transplantation), when rice was in the tillering stage. Subsequently, they continued to decrease until the rice harvest period, when its value almost reached zero. Throughout the entire growth period of rice, the CH_4 emission fluxes under the four controlled irrigation treatments were lower than that under the CK treatment, with their mean values being 48.02, 48.88, 43.21, and 43.38% lower than those under the CK treatment, respectively.

Soil moisture is one of the important factors affecting CH_4 emissions in paddy fields, and irrigation patterns directly affect soil moisture. There is a significant positive correlation between soil moisture content and CH_4 flux (Mori et al. 2008). The CH_4 flux peak appeared during the tillering stage of each treatment in this experiment, which was consistent with the previous research results (Kreye et al. 2007). Furthermore, different controlled irrigation methods would have significant differences in the reduction of CH_4 emissions (Yang et al. 2012). In this study, the CH_4 fluxes under the four controlled irrigation treatments decreased by 43.38~48.88% compared to the CK treatment, indicating that controlled irrigation significantly reduced the CH_4 emission compared to flooding irrigation, proven by previous studies (Wang et al. 2019, 2021).

The variation characteristics of N_2O fluxes. The N_2O emission flux of the four controlled irrigation treatments is totally higher than that of the CK treatment in the whole rice growth period. The average N_2O emission fluxes of the four controlled irrigation treatments were significantly higher than the CK treatment, with an increase of 176.03–244.60%. The maximum N_2O emission flux occurred in the early and middle stages of tillering (22nd and 29th days after transplanting), as well as on the 5th day after applying basal fertiliser and the 5th day after applying tillering fertiliser, respectively.

N_2O is an intermediate product of soil microbial nitrification and denitrification processes, and nitrogen fertiliser and water are the two main factors affecting N_2O emissions (Peng et al. 2012). In this

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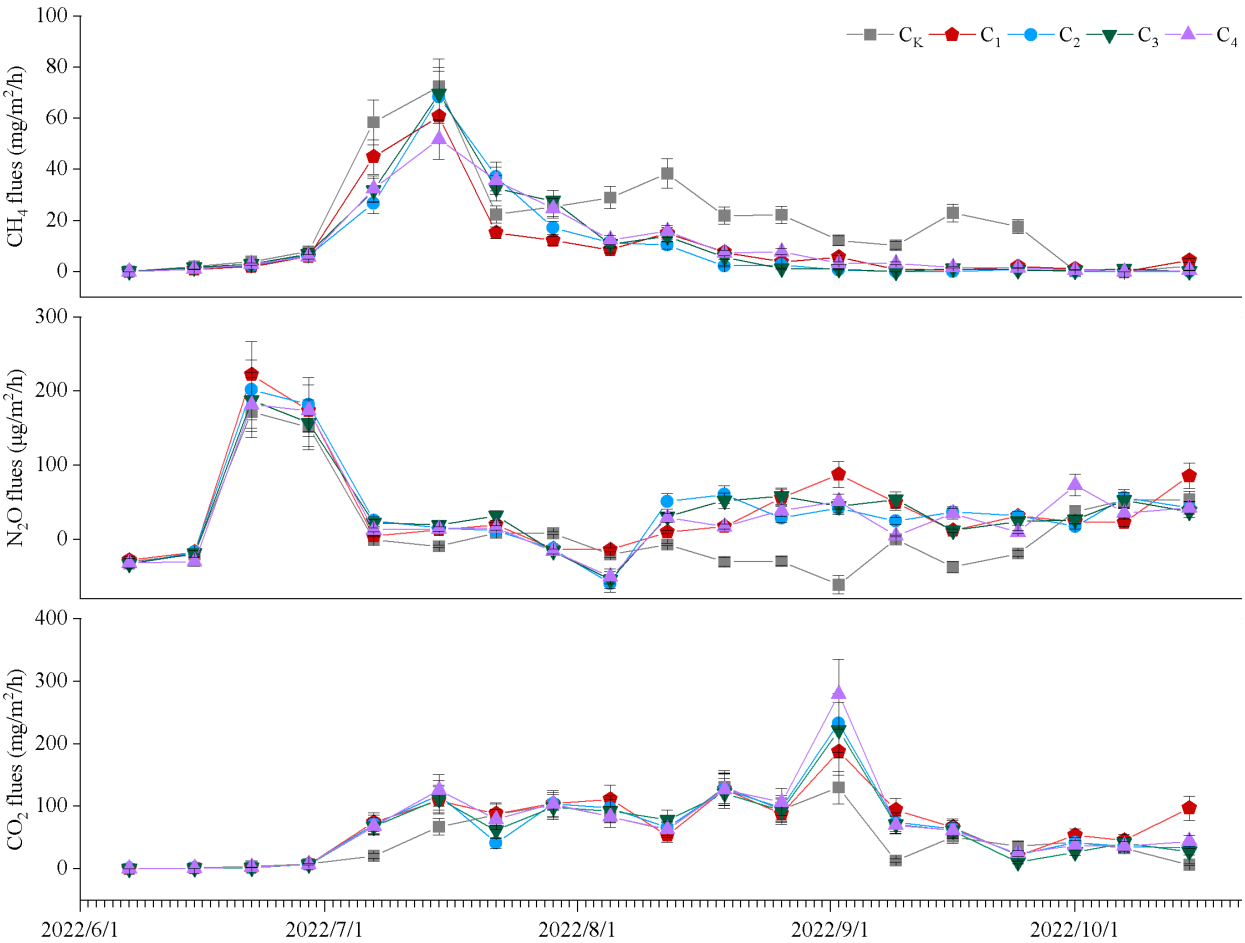

Figure 2. The changes in CH_4, N_2O, and CO_2 fluxes from paddy fields during the entire growth period of rice. CK – control (558 mm); controlled irrigation: C1 – 285, C2 – 280, C3 – 278 and C4 – 274 mm

study, the two highest N_2O fluxes were observed on the 5th day after applying basal fertiliser and the 5th day after applying tillering fertiliser, which was basically consistent with the results of the previous study where the N_2O flux reached its peak on the 7th day after fertilisation (Yu et al. 2008). In the early stage of traditional flooding treatment, the soil has always been in an anaerobic environment, and the N_2O flux has always been at a low level, even with negative values. This is mainly due to the inhibition of soil organic nitrogen mineralisation, which is not conducive to the formation of N_2O (Liu et al. 2010).

The variation characteristics of CO_2 fluxes. The change trend of CO_2 emission flux under the four controlled irrigation treatments was basically consistent with that under long-term flooding irrigation treatment in a rice growth period. During the turning green stage of rice, the CO_2 emission flux was small, and it began to increase in the tillering stage, then maintained a certain level, reached maximum at milk maturity, and later decreased until harvesting. The observed mean CO_2 emission flux of the four controlled irrigation treatments was higher than that of the long-term flooding irrigation treatment, with C1 reaching a maximum of 70.34 mg/m^2/h and C3 reaching a minimum of 62.96 mg/m^2/h, which was 36.56% and 22.24% higher than CK, respectively.

Due to the use of the static chamber technique to observe changes in CO_2 flux, the photosynthesis of rice was temporarily completely interrupted during this process. The CO_2 flux observed was mainly composed of the respiration of aboveground plants and the respiration of soil emissions (Zhou et al. 2004). The plant was small after transplantation, while CO_2 flux was low, and one reason was the low respiration rate during the turning green period. However, during the tillering stage, the CO_2 flux gradually increased and remained at a high level. By the heading and flowering stage, CO_2 flux was the highest, during which the water demand of rice was

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Table 2. The normalised root mean square error (NRMSE) of CH_4 and N_2O emissions fluxes fitting test between the simulation value obtained from the denitrification-decomposition (DNDC) model and observed value (%)

Greenhouse gas types	CK	C1	C2	C3	C4
CH_4	19.8	24.5	25.2	23.7	26.8
N_2O	21.2	28.1	27.0	29.6	27.3

CK – control (558 mm); controlled irrigation: C1 – 285, C2 – 280, C3 – 278 and C4 – 274 mm

the highest, and the photosynthesis and respiration of rice were very vigorous, resulting in a peak in the CO_2 flux measured. In addition, rice photosynthesis absorbs a large amount of CO_2, and further research is needed on the net exchange of CO_2 flux between paddy fields and the atmosphere.

Correlation between soil moisture and emission fluxes. The soil moisture level under the CK treatment and four controlled irrigation treatments all met the experimental design. There was a correlation between the CH_4 and N_2O emission fluxes and whether the rice field had a water layer. When the water layer value in the field was positive, the CH_4 emission flux was generally high, while the N_2O emission flux was small, even negative; when the water layer value was negative, the CH_4 emission flux was small, even almost zero, but at this time, the NO_2 emission flux was high. However, there was no correlation between the CO_2 emission flux and whether the rice field had a water layer. In addition, linear correlation analysis showed that there was no significant correlation between the three greenhouse gas emission fluxes and the depth of the paddy water layer.

Denitrification-decomposition simulation. The NRMSE of CH_4 and N_2O emissions fluxes fitting test between the simulation value obtained from the DNDC model and observed value under all treatments in the Erhai Basin are shown in Table 2. The NRMSE of the DNDC model for simulating CH_4 and N_2O emission fluxes under CK treatments were 19.8% and 21.2%, respectively, while the ranges of NRMSE values under controlled irrigation treatments were 23.7–26.8% and 27.0–29.6%, respectively. That indicated the DNDC model was feasible for simulating the greenhouse gas emissions of CH_4 and N_2O from paddy fields in the Erhai Basin.

The global warming potential. According to the simulation results of DNDC, the global warming potential and global warming potential per unit yield of CH_4, N_2O and CO_2 under all treatments throughout the entire growth period of rice were shown in Table 3. The cumulative CH_4 emissions under controlled irrigation treatments were significantly lower than those under traditional flooding irrigation, with C2 treatment having the smallest cumulative CH_4 emissions; on the contrary, the cumulative N_2O and CO_2 emissions under controlled irrigation treatments were significantly higher than those under traditional flooding irrigation. The global warming potential under controlled irrigation treatments was significantly reduced compared to traditional flooding irrigation, with a reduction range of 37.28–42.86%, with C2 treatment having the smallest value of global warming potential. Due to the yield of rice increased under controlled irrigation treatment compared to CK

Table 3. Cumulative emissions of CH_4, N_2O and CO_2, crop yield, comprehensive greenhouse effect and greenhouse effect per unit yield in paddy fields under different water treatment

Treatment	Cumulative emissions (kg/ha)			GWP (10^3 kg/ha)	Crop yield (kg/ha)	GWP_y (kg/kg)
	CH_4	N_2O	CO_2			
CK	496.05^a	0.11^b	1 814.71^c	18.71^a	9 800^b	1.91^a
C1	244.54^c	0.39^a	2 320.36^a	10.75^c	9 900^b	1.09^c
C2	244.42^c	0.37^a	2 271.20^b	10.69^c	11 000^a	0.97^c
C3	270.29^b	0.36^a	2 189.51^b	11.49^b	9 900^b	1.16^b
C4	271.60^b	0.32^{ab}	2 406.49^a	11.74^b	10 300^{ab}	1.14^b

GWP – global warming potential value of CH_4, N_2O and CO_2 emissions; GWP_y – global warming potential per unit yield. Values with the same letter within a column are not significantly different at P = 0.05. CK – control (558 mm); controlled irrigation: C1 – 285, C2 – 280, C3 – 278 and C4 – 274 mm

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treatment. In view of the greenhouse effect caused by producing 1 kg of rice, the global warming potentials per unit yield were significantly lower under all the controlled irrigation treatments than under the CK treatment, with the C2 treatment having the smallest warming potential per unit yield.

This study indicated that controlled irrigation can significantly reduce the irrigation water consumption and global warming potentials of paddy fields without reducing rice yield, which was consistent with previous research results (Yang et al. 2012, Wang et al. 2021). The contribution of CH_4 emissions to global warming potentials was the highest under both traditional flooding irrigation and controlled irrigation treatments, ranging from 77.34% to 90.12%, while N_2O contributed the least, accounting for less than 1.10%. Therefore, although the N_2O and CO_2 emission fluxes under controlled irrigation treatments were higher than those under traditional flooding irrigation treatment, the smaller CH_4 flux ultimately led to a lower GWP under controlled irrigation compared to traditional flooding irrigation.

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