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Simulation Study of CH_4 and N_2O Emission Fluxes from Rice Fields in Northeast China under Different Straw-Returning and Irrigation Methods Based on the DNDC Model

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Abstract: In order to explore the long-term variation law of methane (CH_4) and nitrous oxide (N_2O) emissions from rice fields in cold regions under different straw-returning and irrigation methods, this study set up two irrigation methods, namely, conventional flooding and controlled irrigation, and two straw-returning quantities (0 t·hm^{-2} and 6 t·hm^{-2}). Based on the field in situ test data, a sensitivity analysis of the main factors of the DNDC model affecting the emissions of CH_4 and N_2O from rice fields was conducted, and the emission fluxes of CH_4 and N_2O were calibrated and validated. Under different future climate scenarios (RCP4.5 and RCP8.5), greenhouse gas emissions from rice fields were simulated on a 60-year scale under different straw-returning and irrigation methods using the DNDC model. The results indicate that the DNDC model can effectively simulate the seasonal emission laws of CH_4 and N_2O from rice fields in cold regions under different straw-returning and irrigation methods. The simulated values have a significant correlation with the measured values ($R^2 \geq 0.794$, $p < 0.05$), and the consistency is controlled within 30%. The soil texture, soil organic carbon (SOC) content, annual average temperature, and straw-returning amount are sensitive factors for CH_4 emissions from rice fields. The total nitrogen fertilizer application amount and SOC content are sensitive factors for N_2O emissions from rice fields. Over the next 60 years, under the two different emission scenarios of RCP4.5 and RCP8.5, straw returning combined with control irrigation has a good coupling effect on the GWP of rice fields, and compared with conventional flooding without straw returning, the GWP of rice fields is reduced by 31.41% and 34.13%, respectively, and the SOC content in 0–20 cm soil layer is increased by 54.69% and 52.80%, respectively. Thus, it can be used as a long-term carbon sequestration and emission reduction tillage model for rice fields in Northeast China. The results of this study can provide a reference for a further regional estimation of greenhouse gas emissions from rice fields using models.

Keywords: straw returning; controlled irrigation; GWP; sensitivity analysis; DNDC model; CH_4; N_2O

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1. Introduction

Methane (CH_4) and nitrous oxide (N_2O) are important greenhouse gases that contribute to global warming. In the past century, the concentrations of these two gases have continued to rise, leading to an intensification of the greenhouse effect. Agriculture is an important source of CH_4 and N_2O emissions, as statistics show that 52% of CH_4 and 84% of N_2O worldwide derive from agricultural activities [1]. Therefore, reducing greenhouse gas emissions from farmland is an important measure to mitigate global climate change and develop sustainable agriculture.

The northeastern cold rice region (including the rice growing areas in Heilongjiang Province, Jilin Province, Liaoning Province, and northeastern Inner Mongolia) is an important grain-producing area in China. According to statistics, the rice planting area and total yield in this region were 526.2 × 10^4 hm^2 and 3871.7 × 10^4 t in 2018, respectively, accounting for 51.9% and 49.8% of the national japonica rice production [2], at the top in China in terms of planting area and yield, playing a crucial role in ensuring national food security. In recent years, returning straw to the field has become a protective tillage measure for cold soil, which helps to increase the carbon content of rice soil and improve the physical and chemical properties of farmland soil. However, a large number of studies have shown that returning straw to the field significantly increases CH_4 emissions from rice fields, thereby increasing the comprehensive greenhouse effect of rice fields [3,4]. Water management is another agricultural measure that affects greenhouse gas emissions from rice fields and is also an important factor affecting the effectiveness of straw returning. Controlling irrigation can accelerate the decline rate of straw residues [5]. Compared with the conventional flooded irrigation of rice, water-saving irrigation can significantly reduce CH_4 emissions from rice fields. Although water-saving irrigation promotes nitrification and denitrification, stimulating the increase in N_2O emissions, it will generally reduce the comprehensive greenhouse effect of rice fields [6,7]. Therefore, it is necessary to study the impact of straw returning combined with effective water-saving irrigation measures on carbon sequestration and emission reduction in rice fields in cold regions.

Although greenhouse gas emissions from rice fields have been researched for many years, mostly in situ field experiments have been conducted, and it is difficult to reflect the changes in greenhouse gas emissions from rice fields over a long period of time or at a regional scale. With the development of research technology, some terrestrial ecosystem models, such as the DNDC model, have been gradually applied to the integration and prediction of observation data from positioning experiments [8,9]. Since its first publication in 1992, the DNDC model (denitrification–decomposition model) has been widely used by scientific researchers in the prediction and estimation of C and N changes in soil and agricultural greenhouse gas emissions, functioning as a biogeochemistry model that has been widely verified and promoted [10,11]. Many scholars in China are also conducting simulation analysis and related practical application technology research on the utilization of local resources using DNDC, verifying that the model has good simulation and prediction effects [12,13], making up for the shortcomings of limited field experiments and small-size scales.

Given that there is currently limited research on the simulation of greenhouse gas emissions from rice fields under different straw returning and irrigation methods using the DNDC model, there are few reports on long-term simulation studies of N_2O emissions in rice fields. The existing research has frequently been based on current climate conditions, and it has been difficult to predict the long-term impact of different tillage measures on greenhouse gas emissions from rice fields under future climate conditions due to changes in temperature, CO_2 concentration in the air, and other factors. Therefore, to explore long-term carbon sequestration and emission reduction plans for rice fields based on an in situ field experiment, firstly, a DNDC model was calibrated and validated using the measured data of CH_4 and N_2O emissions from rice fields and the data of local climate and soil management measures. Secondly, the DNDC model was used to simulate the long-term variation law of greenhouse gas emissions and soil organic carbon (SOC) from rice fields under different straw-returning and irrigation modes under RCP4.5 and RCP8.5. Finally, the long-term carbon sequestration and emission reduction modes of rice fields in cold regions were proposed.

2. Materials and Methods

2.1. Overview of the Experimental Area

The test was carried out at the Qing'an National Irrigation Test Center Station in Heilongjiang Province from May to October 2018. The test station (125°44′ E, 45°58′ N) is located in Heping Town, Qing'an County, Suihua City, China (Figure 1). The annual average temperature is 2 °C to 3 °C (lower than 5 °C), the average air temperature of the coldest month (January) is lower than −3.0 °C, and only the average temperature from April to September is above 10 °C, making our test area belong to the colder regions in China [14]. The annual average precipitation is 500–600 mm, the annual average water surface evaporation is 700–800 mm, and the active accumulated temperature of ≥10 °C changes from 2300 °C to 2500 °C. The annual frost-free period lasts for around 128 days. Based on the World Reference Base for Soil Resources (WRB) 2022 system, the soil in the experimental field was classified as clay loam, with a saturated soil volume moisture content of 54.72%. The basic soil fertility is shown in Table 1. Air temperature and precipitation during the rice growth period are shown in Figure 2.

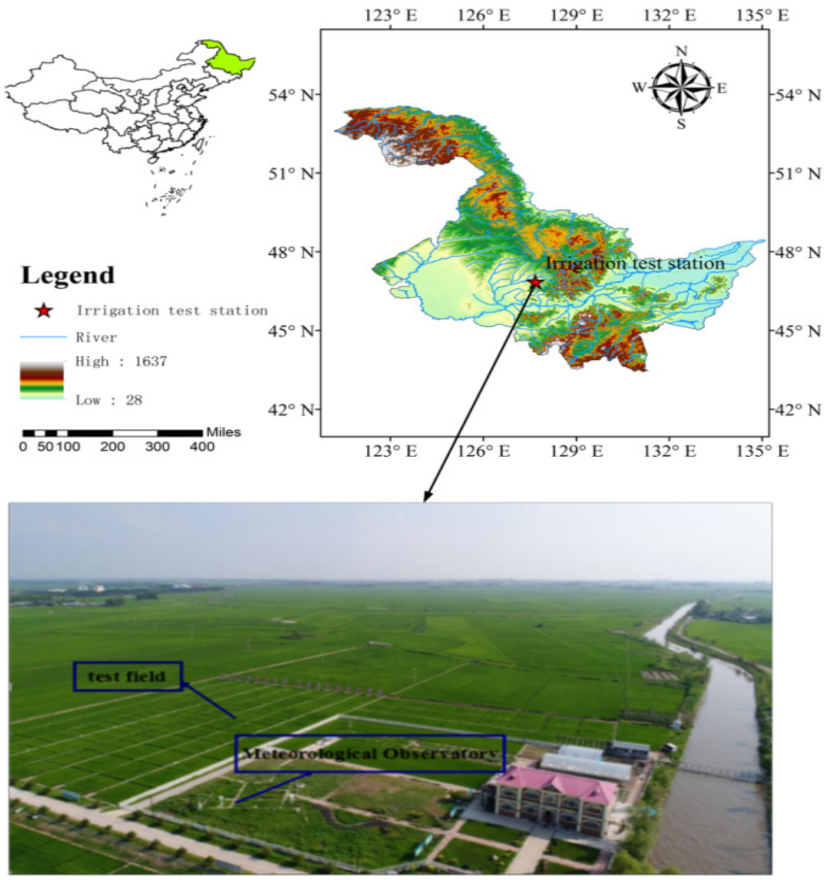

Figure 1. Study area and experimental site.

Table 1. Basic fertility of soils used in the experiments.

Organic Material	Total Nitrogen	Total Phosphorus	Total Potassium	Available Nitrogen	Available Phosphorus	Available Potassium	pH
(g·kg−1)	(g·kg−1)	(g·kg−1)	(g·kg−1)	(mg·kg−1)	(mg·kg−1)	(mg·kg−1)	
41.61	1.49	15.13	17.96	186.42	33.90	153.20	6.87

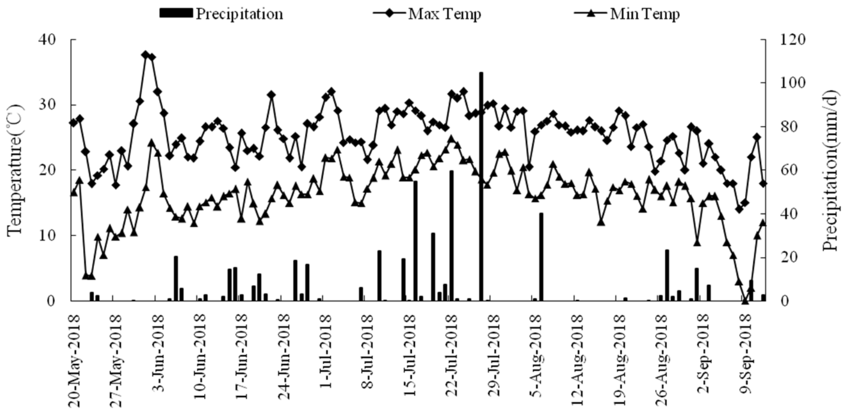

Figure 2. Air temperature and precipitation.

2.2. Design of Experiments

The experiment includes two water treatments of controlled irrigation (KF) and conventional flooding (CF), with the water management of different irrigation modes shown in Table 2, and two modes of straw returning to the field, namely, straw non-return (S0) and straw returning 6 t·hm^{-2} (S1) to the field. After harvesting rice straw in autumn, the straw was crushed and cut into fragments of about 6–7 cm and then applied to the rice field. Then, through tillage operations, the crushed straw was pressed into 15–20 cm of soil, compactly tilled without ridges. There were 4 treatments in total, CFS0 (control treatment), CFS1, KFS0, and KFS1, and each was repeated 3 times in a total of 12 cells randomly arranged in blocks with an area of 10 m × 10 m. The surrounding area of the cells was subjected to seepage isolation with impermeable materials such as plastic boards and cement ridges. The cumulative irrigation amount of rice at each growth stage in different treatments is shown in Table 3. Irrigation water was lifted by a water pump from the channel. According to the standard for irrigation water quality (GB 5084-2021) in China [15], irrigation water belonged to Class II, which satisfied the irrigation water quality.

Table 2. Water amount management of different irrigation modes.

Irrigation Modes	Growth Stages							
	Turning Green	Early Tillers	Mid Tillers	Late Tillers	Jointing	Heading	Milky	Yellow Ripe
Controlled irrigation	0–30 mm	0.7 θ_S–0 mm	0.7 θ_S–0 mm	Field drying	0.8 θ_S–0 mm	0.8 θ_S–0 mm	0.7 θ_S–0 mm	Drying
Conventional flooding	0–30 mm	0–50 mm	0–50 mm	Field drying	0–50 mm	0–50 mm	0–50 mm	Drying

Note(s): θ_S is the mass fraction of saturated moisture content in the root layer soil, which is 85.5%. The data before "–" represent the lower limit of moisture control, while the data after "–" represent the upper limit of moisture control.

The tested rice variety is Northern Oasis No. 2. Basic fertilizer was applied to the rice on 12 May, seedlings were transplanted on 20 May, and harvest was conducted on 12 September. The growth period in the field was 112 days. The planting density was 30 cm × 10 cm, with 3 plants per hole. The tested fertilizers were urea (containing 46% of N), superphosphate (containing 12% of P_2O_5), and potassium chloride (containing 60% of K_2O). The application rates were measured by N, P_2O_5, and K_2O. Nitrogen fertilizer was applied at 110 kg·hm^{-2} for each treatment with a ratio of 4.5:2:1.5:2 for straw returning, tiller fertilizer, regulating fertilizer, and panicle fertilizer; P_2O_5 45 kg·hm^{-2} and K_2O 80 kg·hm^{-2} were applied to each treatment. Potassium fertilizer was applied twice as a base fertilizer and at 8.5 leaf age (young spike differentiation stage) with a ratio of 1:1 before and after. Phosphate fertilizer was applied once as a base fertilizer.

Table 3. Accumulated irrigation amount of rice at each growth stage under different treatments.

Treatments	Growth Stages						
	Turning Green	Tillering	Jointing	Heading	Milky	Yellow Ripe	Whole Growth Period
CFS0	45.1 ± 1.21 mm	180.9 ± 2.03 mm	109.3 ± 1.95 mm	131.2 ± 2.38 mm	70.8 ± 1.38 mm	0 mm	537.3 ± 7.51 mm
CFS1	45.1 ± 1.06 mm	179.1 ± 1.99 mm	107.9 ± 2.09 mm	126.5 ± 2.19 mm	68.1 ± 1.53 mm	0 mm	526.7 ± 6.83 mm
KFS0	45.1 ± 0.53 mm	50.7 ± 2.45 mm	80.6 ± 2.32 mm	75.4 ± 1.99 mm	47.8 ± 1.23 mm	0 mm	299.6 ± 5.80 mm
KFS1	45.1 ± 0.45 mm	50.1 ± 2.57 mm	77.8 ± 2.17 mm	74.2 ± 1.69 mm	45.3 ± 1.35 mm	0 mm	292.5 ± 5.46 mm

2.3. Gas Sampling and Analysis

A static box method was adopted for gas sampling [16]. The sampling box was made of transparent organic glass with a thickness of 5 mm covered with insulation material aluminum foil for temperature insulation. The cross-sectional size of the sampling box was 50 cm × 50 cm; the box was 60 cm high in the early stage of rice growth, and this increased to 110 cm after the heading stage. Gases were collected one week after rice transplantation with a sampling time from 10:00 to 12:00 [17]. Parallel collection was performed 3 times for each treatment with an average of once a week until the end of the week before harvest. During sampling, approximately 50 mL of gas was extracted from the box using a syringe, and samples were collected at 0, 5, 10, and 15 min each. Then, the gas inside the syringe was immediately transferred to an aluminum foil sampling bag (Bitman Biotechnology Co., Ltd., Changde, China) and the sampling bag was promptly brought back to the laboratory for testing.

Gas samples were measured using a meteorological chromatograph (GC-2010Plus, Shimadzu Corporation, Kyoto, Japan). FID was used as the CH_4 detector with a detection temperature of 200 °C, a column temperature of 60 °C, and a carrier gas of nitrogen; ECD was used as the N_2O detector with a detection temperature of 250 °C, a column temperature of 60 °C, and a carrier gas of a mixture of argon and methane. The calculation formula for the gas emission flux is as follows:

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

where F is the gas emission flux (mg·m^{-2}·h^{-1} or µg·m^{-2}·h^{-1}), ρ is the gas density in a standard state (kg·m^{-3}), h is the net height of the box (distance from the box top to the water surface, m), $\mathrm{d}c/\mathrm{d}t$ is the concentration change rate of the gas in the sampling box (mL·m^{-3}·h^{-1}), 273 is the gas equation constant, and T is the average temperature (°C) in the sampling box during the sampling process. The gas emission flux was calculated based on the relationship curve between the gas sample concentration and time. Cumulative emissions during the growing season were obtained by multiplying the average daily emission flux between two sampling intervals and the number of days between the two sampling intervals by the accumulated sum [18], as follows:

$$R = \sum_{i=1}^{n} \frac{F_i + F_{i+1}}{2} (D_{i+1} - D_i) \times 24 \quad (2)$$

where R represents the cumulative emissions of CH_4 or N_2O during the rice growing season (kg·hm^{-2}), n represents the number of observations, F_i and F_{i+1} represent the CH_4 emission flux (mg·m^{-2}·h^{-1}) or N_2O emission flux (µg·m^{-2}·h^{-1}) during the i-th and i + 1-th gas collection, respectively, and D_i and D_{i+1} represent the i-th and i + 1-th sampling times (d), respectively.

This study used global warming potential (*GWP*) to represent the relative radiation effect of different greenhouse gases of the same mass on the enhancement of the greenhouse effect. Based on the comprehensive greenhouse effect of the unit mass of CH_4 and N_2O, which was 25 times and 298 times that of CO_2 on a 100-year scale [19], the CO_2 equivalent

(E-CO_2) of CH_4 and N_2O emissions for each treatment were calculated, and the *GWP* (kgCO_2-eq/hm^2) of CH_4 and N_2O emissions for each treatment was obtained using the following calculation formula:

$$GWP = 25 \times R_1 + 298 \times R_2 \quad (3)$$

where R_1 and R_2 represent the cumulative emissions (kg·hm^{-2}) of CH_4 and N_2O from rice fields during the growing season.

2.4. DNDC Model

2.4.1. Introduction

The DNDC (denitrification–decomposition) model is a biogeochemistry model developed in the early 1990s. It was first designed to predict the biogeochemistry behavior of carbon and nitrogen in the terrestrial ecosystem. At present, it has been used by some countries to predict the long-term fertility of agricultural soil and greenhouse gas emissions, mainly to simulate the release process of agricultural CH_4 and N_2O [20].

This model consists of two parts [9]: The first part is to simulate the environmental conditions of the soil with ecological driving factors (including climate, soil, and human activities), such as soil temperature and humidity, pH value, reduction potential, and the substrate concentration of related nutrients. It includes three sub-models, namely, the soil climate sub-model, crop growth sub-model, and organic matter decomposition sub-model. The second part is to simulate the impact of the soil environment on microbial activity, including the nitrification sub-model, denitrification sub-model, and fermentation sub-model, which can simulate the emission flux of CH_4 and N_2O in a crop soil ecosystem.

2.4.2. Parameter Input and Correction

The input parameters of the DNDC model include geography, meteorology, soil, and crop management methods. The default operating parameters in the model are all set based on the climate and soil environment of United States regions, which cannot effectively simulate the growth status of rice under the four management modes in this study. Therefore, it is necessary to calibrate the localization parameters of the model and verify the simulation results. Meteorological data of this study include daily maximum temperature, daily minimum temperature, and daily average rainfall from the Qing'an Meteorological Station of China Meteorological Administration. Soil and yield data include soil texture, bulk density, organic carbon content, pH value, and other data from actual sampling results at the experimental station. Field management data include fertilizer application, tillage, straw-returning rate, etc., from field management records in 2018. The specific parameters are shown in Table 4.

Four global climate models (GCMs) [21,22] were selected to generate daily scale meteorological data for the next 60 years (2021–2080) via the weather generator LARS-WG using the emission scenarios of RCP4.5 (the concentration of CO_2 in the atmosphere will reach 1.3 mg·L^{-1} by 2100, and the solar radiation forcing will rise to 4.5 W·m^{-2}) and RCP8.5 (the concentration of CO_2 in the atmosphere will reach 2.7 mg·L^{-1} by 2100, and the solar radiation forcing will rise to 8.5 W·m^{-2}) given in the 5th IPCC report, including daily maximum air temperature, daily minimum air temperature, and daily rainfall. The main information for the four GCMs used is shown in Table 5. Assuming that the soil attribute information and cultivation management methods remain unchanged for the next 60 years, the changes in annual CH_4 and N_2O emissions from rice fields under different straw-returning and irrigation measures were simulated using the corrected DNDC model.

Table 4. Correct parameters in DNDC model.

Parameter Type	Parameter Name	Unit	Value
Climate parameters	Latitude	°	45.63
	Average nitrogen concentration in rainfall	$mgN \cdot L^{-1}$	1.3
	Ammonia concentration in the air	$ugN \cdot m^{-3}$	0.06
	CO_2 concentration in the air	ppm	350
	Annual growth rate of CO_2 concentration	$ppm \cdot yr^{-1}$	2.6
Crop parameters	Maximum biomass	$kgC \cdot ha^{-1}$	4600
	Biomass allocation of grain/leaf/stem/root	/	0.41:0.27:0.27:0.05
	Biomass C/N of grain/leaf/stem/root	/	46:58:58:72
Soil parameters	Soil texture	/	Clay loam
	Bulk density	$g \cdot cm^{-3}$	1.22
	pH value	/	6.87
	Clay content	%	41
	Field water capacity	%	54.6
	Saturated hydraulic conductivity	m/h	0.015
	Organic carbon content of topsoil	$kgC \cdot kg^{-1}$ soil	0.055
	Initial nitrate nitrogen content	$mgN \cdot kg^{-1}$	5.0
	Initial ammonium nitrogen content	$mgN \cdot kg^{-1}$	9.1

Note(s): see the design of the experiment for details of water management (controlled irrigation and conventional flooding), number, time, depth, type, and quantity of fertilizer application.

Table 5. Four GMCs selected for LARS-WG simulation in this study.

GCMs	Research Center	Countries and Regions	Grid Resolution
EC-EARTH	EC: Earth Consortium	Europe	1.125° × 1.125°
HadGEM2-ES	UK Meteorological Office	UK	1.25° × 1.88°
MIROC5	University of Tokyo, National Institute for Environmental	Japan	1.39° × 1.41°
MPI-ESM-MR	Max Planck Institute for Meteorology	Germany	1.85° × 1.88°

2.4.3. Sensitivity Analysis

The sensitivity index (S) reveals the sensitivity of different meteorological parameters, soil parameters, and farmland management parameters on the greenhouse gas emissions of CH_4 and N_2O from rice fields [23]. The formula is as follows:

$$S = \left(\frac{O_2 - O_1}{O_{avg}}\right) / \left(\frac{I_2 - I_1}{I_{avg}}\right) \quad (4)$$

In the formula, S is the relative sensitivity index; I_1 and I_2 are the minimum and maximum values of the input parameters, respectively; I_{avg} is the average of I_1 and I_2; O_1 and O_2 are the output values relative to the I_1 and I_2 models, respectively; and O_{avg} is the average value of O_1 and O_2. The higher the absolute value of S is, the larger the impact of the input factor on the simulation results is, while a negative value indicates an "inverse relationship" between the input parameters and the simulation results.

In this study, seven variables were selected from three aspects, i.e., soil properties, climate factors, and farmland management methods as the test parameters for sensitivity analysis of CH_4 and N_2O in rice fields, namely, soil texture, soil SOC content, soil pH value, annual average temperature, annual rainfall, total nitrogen fertilizer application amount, and straw-returning amount. The basic scenario (background value) was established based on the actual climate, soil environment, and agricultural management measures of the test site, while the alternative scenario (test value) was established by changing one of the tested parameter values while other parameters remain unchanged in the basic scenario, as shown in Table 6. The impact degree of these factors on the output results of the model was determined using the introduced sensitivity index.

Table 6. Parameter settings for sensitivity analysis and sensitivity index (S) affecting CH_4 and N_2O flux.

Parameters	Background Value	Test Value	S_{CH4}	S_{N2O}
Soil quality	Clay loam	Sandy loam, loam, sandy clay loam, clay	−0.74	0.267
Soil SOC content (%)	5.50	Reduce by 10%, 20%, increased by 10%, 20%	0.55	0.47
Soil pH value	6.05	Reduced by 10%, 20%, increased by 15%, 40%	0.0049	−0.149
Annual average temperature (°C)	2.97 °C	Reduced by 2 °C and 4 °C, increased by 2 °C and 4 °C	0.495	0.182
Annual rainfall (cm)	55.0	Reduced by 10% and 20%, increased by 10% and 20%	0.0198	−0.083
Total nitrogen fertilizer application amount (kg N ha^{-1} y^{-1})	110	Reduced by 10% and 20%, increased by 10% and 20%	−0.051	2.14
Straw return amount (kg C/hm^{-2})	0	1350, 2700, 5400	0.68	0.006

2.4.4. Model Validation

In this study, the relative root-mean-square deviation (*RRMSE*) of the model and the effectiveness coefficient of the model (R^2) [24] were selected to verify the fitting degree and correlation effect of the simulated value and the measured value. R^2 approaching 1 indicates good consistency between measured data and simulated data. When *RRMSE* < 20%, this indicates good simulation performance. When 20% < *RRMSE* < 30%, this indicates that the simulation performance is within an acceptable range. When *RRMSE* > 30%, this indicates a significant deviation in simulation performance.

$$RRMSE = \sqrt{\sum_{i=1}^{n} \frac{(x_i - y_i)^2}{n\overline{y}}} \quad (5)$$

In the formula, x_i, y_i, and $\overline{y}$ are the i-th simulated value, the i-th measured value, and the average of the measured values, respectively, and n is the times of the actual measurement.

$$R^2 = \left(\frac{\sum_{i=1}^{n} (O_i - \overline{O})(P_i - \overline{P})}{\sum_{i=1}^{n} (O_i - \overline{O})^2 (P_i - \overline{P})^2} \right) \quad (6)$$

In the formula, O_i and P_i represent the observed and simulated values, respectively, $\overline{O}$ and $\overline{P}$ represent the average of the observed and simulated values, respectively, and n represents the number of data.

2.5. Data Processing

Data were sorted and mapped using Microsoft Excel 2013, and correlation analysis between the simulated values and observed values, the significance t-test of the validity coefficient, and the statistical analysis of relative root-mean-square deviation were completed using SPSS 22.0 software (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Analysis of Sensitivity Factors

The analysis results in Table 6 indicate that among the three soil parameters selected in this study, the soil texture factor is the most sensitive one, with a sensitivity index of −0.74, indicating a negative correlation with CH_4 emission flux. CH_4 emissions are also sensitive to SOC, with a sensitivity index of 0.55. The release of CH_4 is positively correlated with the SOC content. The soil pH value is relatively low in sensitivity, with a sensitivity index of only 0.0049. CH_4 emissions from rice fields are more sensitive to temperature than rainfall in meteorological factors. A higher temperature drives the soil temperature to increase the activity of soil microorganisms, promote the growth of rice, and, thus, promote the production and emissions of CH_4 in rice fields. The sensitivity index of rainfall is 0.0198, indicating that CH_4 from rice fields is not sensitive enough to rainfall. The management methods of farmland vary with regional differences. The total nitrogen fertilizer application amount selected in this study has a weak impact on CH_4 emissions from rice fields, with a sensitivity index of only −0.051, indicating that an increase in the total nitrogen fertilizer application amount has a certain inhibitory effect on CH_4 emissions from rice fields. The amount of straw returning to the field is the main sensitive factor for CH_4 emissions from rice fields, with a sensitivity index of 0.68. The CH_4 emissions from rice fields significantly increase with the increase in straw returning, which is also confirmed by the field experiments in this study.

The sensitivity analysis of N_2O emissions showed that the sensitivity index of the soil SOC content was 0.47, which was the most sensitive factor among the three soil parameters, followed by soil texture, and had a positive relationship with N_2O emissions. The soil pH value has a small sensitivity index to N_2O emissions from rice fields, such as −0.149. In meteorological factors, temperature has a sensitivity index of 0.182 to N_2O emissions from rice fields, which is greater than the sensitivity index, −0.083, of rainfall to N_2O emissions from rice fields; both are not sensitive factors for N_2O emissions. The total amount of nitrogen fertilizer application is the most sensitive factor affecting N_2O emissions from rice fields, with a sensitivity index of 2.14, having a significant promoting effect on N_2O emissions from rice fields, indicating that the amount of nitrogen fertilizer application should be particularly considered in greenhouse gas emission reduction measures. The sensitivity index of straw returning to N_2O emissions from rice fields is 0.006, indicating that N_2O emissions from rice fields are not sensitive to straw returning.

3.2. Site Simulation of CH_4 Emissions from Rice Fields

Figure 3 shows that the DNDC model has a good simulation effect on the seasonal variation in CH_4 emissions under different straw-returning treatments under conventional flooding, and the emission peak is consistent with the measured values. The simulation results show that straw returning significantly increases the CH_4 emissions from rice fields. Through the simulation of different straw-returning treatments under controlled irrigation by the model, the peak emissions of CH_4 and the seasonal emission pattern of CH_4 were basically captured. The simulation results also showed that straw returning increased CH_4 emissions. In addition, the simulation results also reflect that under the same straw-returning method, controlled irrigation significantly reduces the seasonal CH_4 emissions compared with conventional flooding.

As shown in Figure 4, under different straw-returning and irrigation methods, the R^2 between the simulated and measured values of the four treatments ranged from 0.796 to 0.945, and there was a significant correlation between the simulated and measured values of the two treatments of KFS1 ($p < 0.05$). The simulated values of CFS0, CFS1, and KFS0 showed a highly significant correlation with the measured values ($p < 0.01$). Table 7 shows that the relative root-mean-square deviation between the simulated value and the measured value of CH_4 emission flux under different straw-returning and irrigation treatments by the DNDC model varies from 17.53% to 26.85%, indicating that the simulation effect of the model is acceptable.

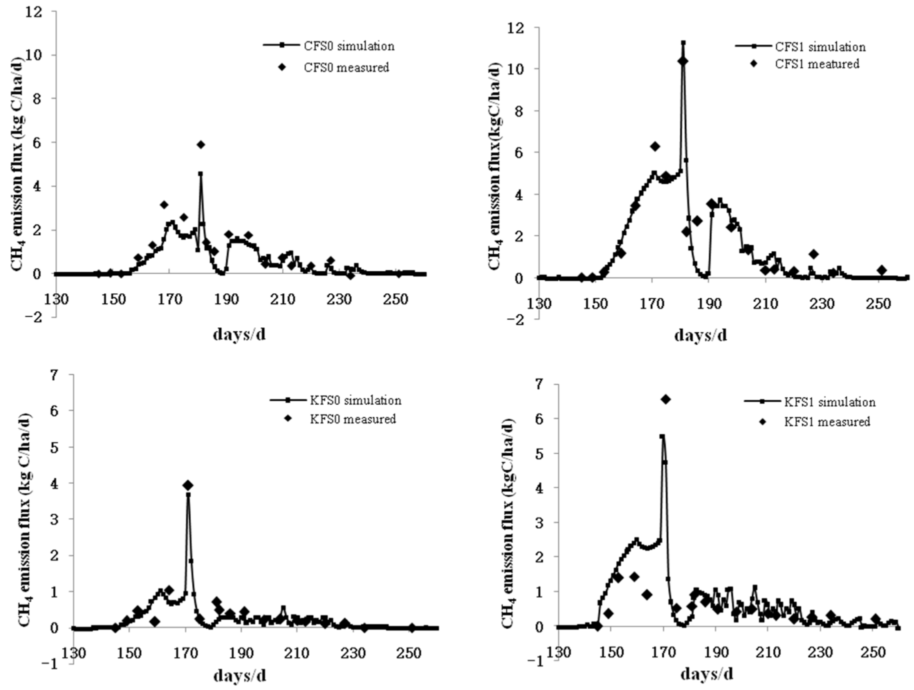

Figure 3. Emission flux simulation in CH_4 under different straw-returning and irrigation methods.

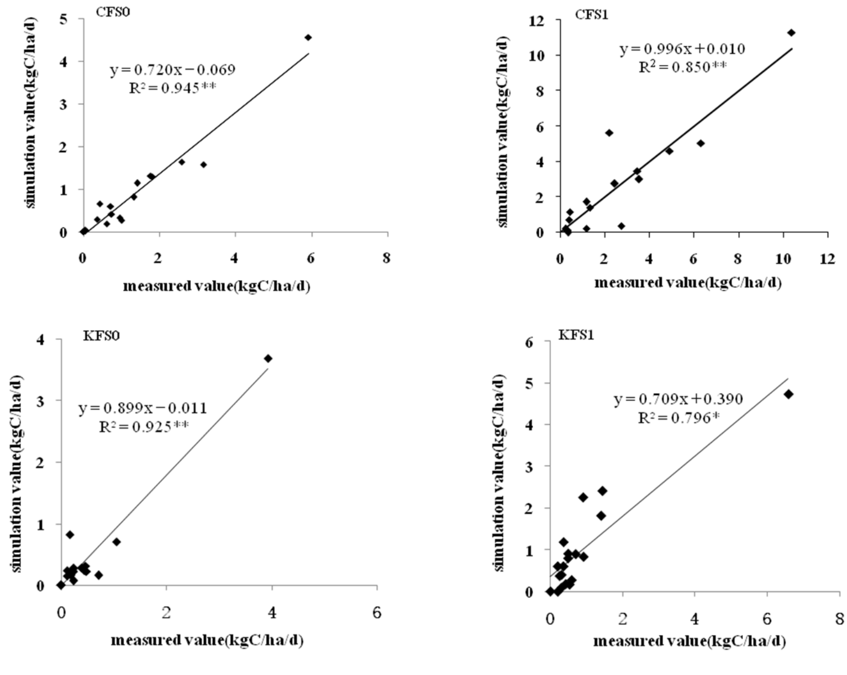

Figure 4. Analysis of the correlation effect of DNDC model on the simulated value and the measured value of CH_4 emission flux. Note: ** indicates a significant difference at the 0.01 level, * indicates a significant difference at the 0.05 level. Sample size n = 19.

Table 7. Analysis of the consistency between the measured value of CH_4 and N_2O emission flux and the simulated value of the DNDC model.

Treatments	CH_4 *RRMSE* (%)	N_2O *RRMSE* (%)
CFS0	17.53	22.56
CFS1	21.09	18.81
KFS0	18.44	22.98
KFS1	26.85	24.26

3.3. Site Simulation of N_2O Emissions from Rice Fields

Figure 5 shows that the DNDC model has a good simulation effect on the seasonal variation in N_2O emissions from rice fields under different straw-returning and irrigation modes, reflecting the characteristic of multi-peak N_2O emissions and a relationship between this and the CH_4 emissions from rice fields. The model simulated that the effect of straw returning to the field under different irrigation methods on N_2O emissions from rice fields was not significant, while controlled irrigation significantly increased seasonal N_2O emissions compared with conventional flooding.

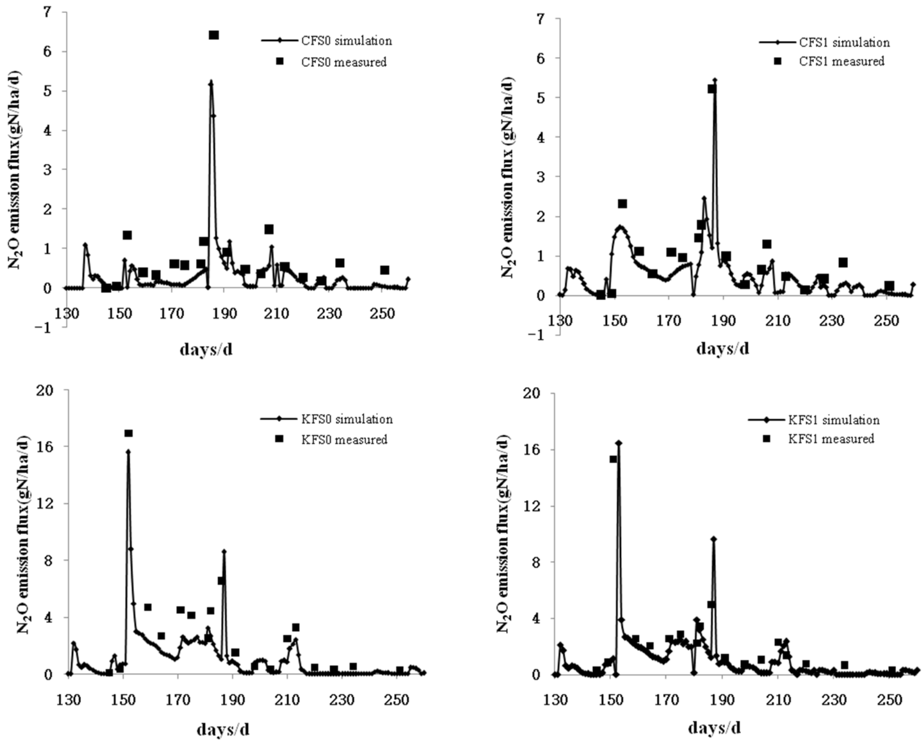

Figure 5. Emission flux variation in N_2O under different strain returning and irrigation methods.

As shown in Figure 6, the R^2 values between the simulated and measured N_2O emission fluxes of the four treatments under different straw-returning and irrigation methods ranged from 0.852 to 0.912, and there was a very significant correlation between the simulated and measured values ($p < 0.01$). Combined with the results in Table 7, the variation in the range of the relative root-mean-square deviation between the simulated and measured values of N_2O emission flux under different treatments was 18.81–24.26%, indicating that the simulation effect of the model is within an acceptable range.

3.4. Simulation of Greenhouse Gas Changes in Rice Fields under Long-Term Straw Returning and Controlled Irrigation

3.4.1. Simulation of Changes in CH_4 in Rice Fields under Long-Term Straw Returning and Controlled Irrigation

As shown in Figure 7, under two climate change scenarios, the annual CH_4 emissions from rice fields under the four treatments show an upward trend in the future. Under the RCP4.5 scenario, the annual growth rate of CH_4 emissions from rice fields under each treatment is stable. Compared with the current climate, the annual CH_4 emissions from rice fields under CFS0, CFS1, KFS0, and KFS1 will increase by 73.89%, 52.13%, 45.15%, and 44.45% in the next 60 years, respectively. Under the RCP8.5 scenario, the annual CH_4 emissions from rice fields under controlled irrigation have maintained a stable growth trend, while the annual CH_4 emissions from rice fields under conventional flooding remain relatively stable in the first 20 years and accelerate in the latter 40 years. In the next 60 years, the annual CH_4 emissions from rice fields under CFS0, CFS1, KFS0, and KFS1 increase by 173.67%, 138.31%, 117.94%, and 109.63% compared with those in the current climate, respectively. Long-term simulations show that under two climate change scenarios, the annual CH_4 emissions from rice fields with straw returning combined with controlled irrigation KFS1 were consistently lower than those in control treatment CFS0 on a 60-year time scale.

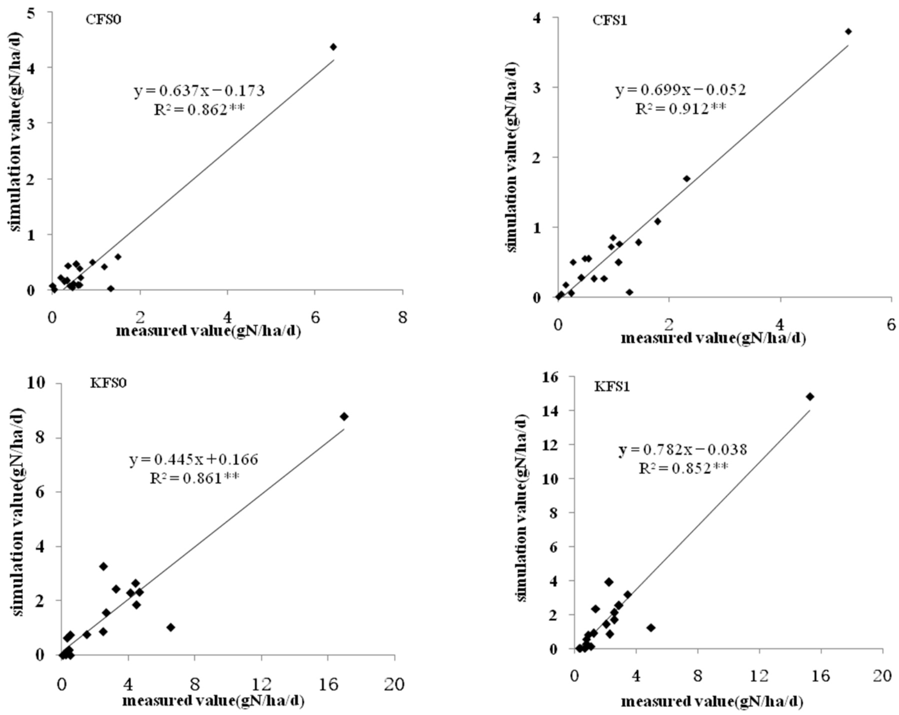

Figure 6. Analysis of the correlation effect of DNDC model on the simulated value and the measured value of N_2O emission flux. Note: ** indicates a significant difference at the 0.01 level. Sample size n = 19.

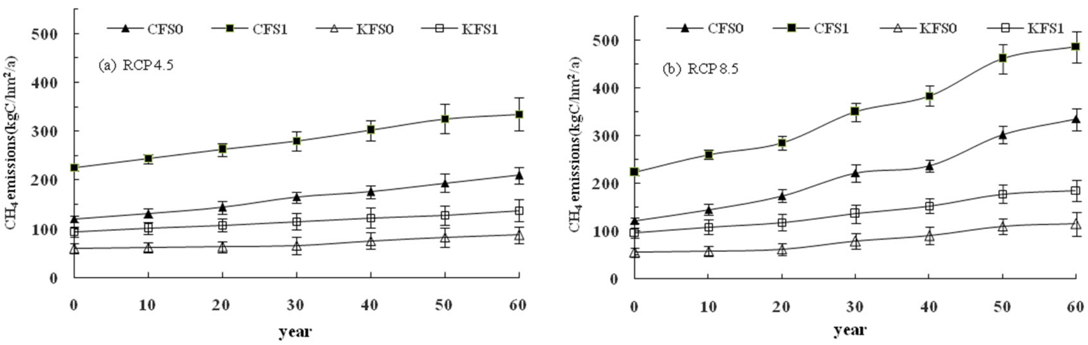

Figure 7. Changes in annual CH_4 emissions from rice fields with different treatments under (**a**) RCP4.5 and (**b**) RCP8.5 scenarios in the next 60 years.

3.4.2. Simulation of Changes in N_2O in Rice Fields under Long-Term Straw Returning and Controlled Irrigation

Figure 8 shows that under the RCP4.5 scenario, the annual N_2O emissions of four rice fields with four treatments show a similar trend, with an upward trend in the first 30 years and a downward trend in the latter 30 years. Compared with the current climate, the annual N_2O emissions from the rice fields of CFS0, CFS1, KFS0, and KFS1 will increase by 44.67–95.54%, 32.93–66.17%, 22.29–62.33%, and 21.27–57.05% in the next 60 years, respectively. In the RCP8.5 scenario, the annual N_2O emissions under controlled irrigation in the next 60 years are similar to those in the RCP4.5 scenario, with increases of 11.61–51.38% and

13.63–50.87% for KFS0 and KFS1 treatments, respectively. However, under conventional flooding, the annual N_2O emissions from rice fields under CFS0 and CFS1 treatments show a fluctuating trend of increase and decrease, with increases of 15.88–28.34% and 19.31–50.87% in the next 60 years, respectively. The long-term simulation results show that under both climate change scenarios, there is no significant difference in the annual N_2O emissions under different straw-returning treatments under the same irrigation mode, while the annual N_2O emissions under controlled irrigation are significantly higher than those under conventional flooding, which means that returning straw to the field has a much smaller impact on N_2O emissions than irrigation methods.

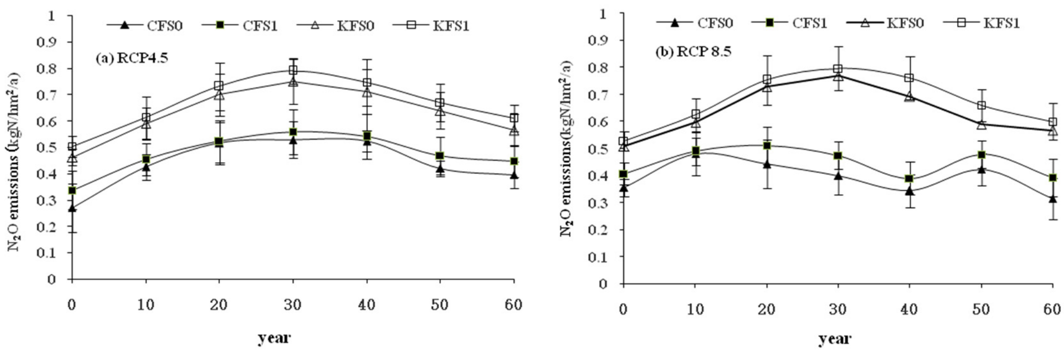

Figure 8. Changes in annual N_2O emissions from rice fields with different treatments under (**a**) RCP4.5 and (**b**) RCP8.5 scenarios over the next 60 years.

3.4.3. Simulation of Changes in GWP and SOC in Rice Fields under Long-Term Straw Returning and Controlled Irrigation

Long-term simulation shows (Figure 9) that under two climate change scenarios, the GWP of rice fields in the future shows an upward trend under different straw-returning and irrigation modes, with GWP values of CFS1 > CFS0 > KFS1 > KFS0 being significantly different. Under the RCP4.5 scenario, the growth rate of GWP in the rice fields of the four treatments was relatively stable compared with the RCP8.5 scenario. Compared with the current climate, the GWP in the rice fields of CFS0, CFS1, KFS0, and KFS1 increased by 67.47%, 49.52%, 48.54%, and 44.15% on a scale of the next 60 years, respectively. Under the RCP8.5 scenario, GWP changes in rice fields under controlled irrigation were in a relatively stable trend for the two treatments, with GWP increases of 96.83% and 85.42% for KFS0 and KFS1, respectively. However, GWP changes in the two conventional flooding treatments were in a relatively stable trend in the first 20 years and accelerated in the next 40 years. Compared with the current climate, GWP increased by 146.43% and 97.33% for the CFS0 and CFS1 treatments, respectively. Long-term simulations show that under two climate change scenarios, the GWP of the rice fields with straw returning combined with controlled irrigation KFS1 was consistently lower than that of the control treatment CFS0 on a 60-year time scale, indicating that long-term straw returning combined with controlled irrigation showed a good interaction effect on the GWP of the rice field.

The long-term simulation of SOC in 0–20 cm soil layer (Table 8) shows that the SOC content of the four treatments varies under different RCPs. The SOC content of CFS0 and KFS0 slowly decreased over time, compared with the initial content, which decreased by 9.84% and 9.70% after 60 years under the RCP4.5 scenario, respectively, and decreased by 8.71% and 8.61% after 60 years under the RCP8.5 scenario, respectively. The SOC content of CFS1 and KFS1 steadily increased over time, compared with the initial content, which increased by 35.85% and 37.29% after 60 years under the RCP4.5 scenario, respectively, and increased by 37.81% and 38.18% after 60 years under the RCP8.5 scenario, respectively.

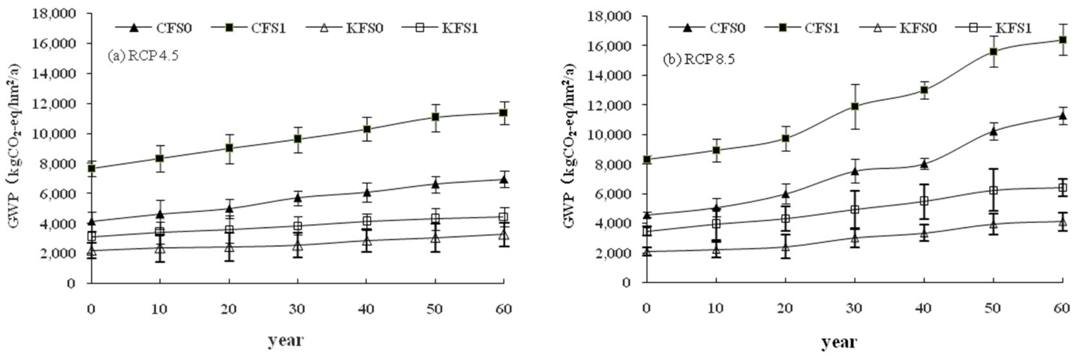

Figure 9. Changes in GWP in rice fields with different treatments under (**a**) RCP4.5 and (**b**) RCP8.5 scenarios in the next 60 years.

Table 8. Changes in SOC content in 0–20 cm soil layer with different treatments under RCP4.5 and RCP8.5 scenarios in the next 60 years.

Periods (a)	SOC Content in 0–20 cm Soil Layer (10^4 kg C·hm^{-2})							
	RCP 4.5				RCP 8.5			
	CFS0	CFS1	KFS0	KFS1	CFS0	CFS1	KFS0	KFS1
0	5.063 ± 0.002	5.172 ± 0.003	5.064 ± 0.002	5.176 ± 0.004	5.062 ± 0.003	5.171 ± 0.002	5.064 ± 0.003	5.175 ± 0.002
10	4.984 ± 0.002	5.656 ± 0.021	4.988 ± 0.016	5.670 ± 0.018	4.996 ± 0.012	5.689 ± 0.017	5.000 ± 0.012	5.698 ± 0.017
20	4.902 ± 0.028	5.993 ± 0.037	4.907 ± 0.027	6.014 ± 0.034	4.937 ± 0.022	6.033 ± 0.029	4.942 ± 0.022	6.094 ± 0.027
30	4.809 ± 0.044	6.270 ± 0.060	4.815 ± 0.043	6.295 ± 0.056	4.854 ± 0.041	6.356 ± 0.061	4.860 ± 0.041	6.371 ± 0.058
40	4.727 ± 0.060	6.542 ± 0.088	4.734 ± 0.059	6.571 ± 0.082	4.793 ± 0.061	6.637 ± 0.091	4.800 ± 0.061	6.624 ± 0.086
50	4.637 ± 0.077	6.778 ± 0.113	4.645 ± 0.076	6.811 ± 0.106	4.695 ± 0.093	6.830 ± 0.141	4.701 ± 0.093	6.871 ± 0.135
60	4.565 ± 0.095	7.026 ± 0.145	4.573 ± 0.094	7.106 ± 0.138	4.621 ± 0.117	7.126 ± 0.181	4.628 ± 0.116	7.151 ± 0.172

4. Discussion

4.1. Sensitivity Analysis of Parameters

The sensitivity analysis results show a negative correlation between soil texture and CH_4 emission flux, that is, the CH_4 emissions from clay soil are lower than that from soil and sandy soil, and the clay content in cold soil is higher. This is also one of the reasons why the CH_4 emission flux observed in this study is lower than that observed in southern rice fields [16]. The sensitivity index of SOC and straw returning to the field is relatively high, and there is a positive correlation with CH_4 emissions. The main reason is that straw returning to the field affects soil carbon content, which helps to increase the carbon content of rice soil [25]. However, the increase in SOC fixed to the soil increases the content of CH_4 substrates produced in the rice field, thereby increasing the production of CH_4 [26,27]. The total nitrogen fertilizer application rate is the most sensitive factor affecting N_2O emissions from rice fields. The increase in the total nitrogen fertilizer application rate has a significant promoting effect on N_2O emissions from rice fields. However, for rice soil, frequent nitrogen application may also reduce N_2O emissions from rice fields, and this may result from that when soil carbon and nitrogen are not limiting factors for soil emissions, a low available iron content in the soil will also limit N_2O emissions from the soil [28]. Therefore, straw returning to the field and the application amount of nitrogen fertilizer should be particularly considered in greenhouse gas emission reduction measures in cold regions combined with reasonable irrigation methods.

4.2. Site Simulation Effect of DNDC Model

In this study, the DNDC model was used to simulate greenhouse gas emissions in cold regions, achieving a good site simulation effect for CH_4 and N_2O emissions from rice fields with straw returning under different irrigation methods, and generally simulating the peak values of CH_4 and N_2O emissions from rice fields in the study area. Zou et al. [29] used the

DNDC model to verify the simulation of annual CH_4 and N_2O emissions under 3 cropping modes of rice-wheat, rice-rape and rice-fallow of Jianghan Plain. Their results showed that the coefficient of determination, R^2, of CH_4 emissions from field observations and simulation values was 0.92–0.93, and the N_2O emissions R^2 was 0.85–0.98, which are both similar to the results of this study. However, there are also some unsatisfactory aspects, such as lag in some peaks simulated by this experimental model for N_2O (Figure 5). Xue et al. [30] validated the DNDC model and its parameters based on the field experimental data of a crop rotation system of winter wheat/summer corn with reclaimed water irrigation, observing similar phenomena. Although the model can capture the peak N_2O emissions caused by irrigation, rainfall, and fertilization, the actual measured values often lag behind the simulated values. Li et al. [31] believe that the chemical reaction of the DNDC model to the simulation of N_2O depends on the nitrite content in the soil, soil pH value, and temperature. When pH < 5.0, the relevant chemical reaction starts. Therefore, the deviation in the experiment may be due to the insufficient sensitivity of the model to soil pH value and temperature, and the relevant parameters need to be further adjusted.

4.3. Comparison of Long-Term Simulation of Greenhouse Gas Emissions in Rice Fields with Straw Returning under Different Irrigation Methods

Long-term simulation of CH_4 emissions from rice fields found that straw returning significantly increased CH_4 emissions, but the annual CH_4 emissions from rice fields with straw returning combined with controlled irrigation were consistently lower than those of conventional flooding over the next 60 years, indicating that water management has a decisive impact on the process of CH_4 emissions from rice fields. The results of this study show that in the next 60 years, under two different emission scenarios of RCP4.5 and RCP8.5, the annual CH_4 emissions from rice fields under KFS1 treatment decreased by an average of 30.24% and 36.52%, respectively, compared with CFS0 treatment, reflecting the significant inhibitory effect of controlled irrigation on methane emissions from rice fields. This is because with controlled irrigation, in the tillering stage, the water layer is no longer established on the field surface, and the relative soil moisture content is used as the upper and lower limits of irrigation. The soil is in an alternative state of dry and wet conditions, and the soil surface is in contact with the atmosphere even in the upper limit of irrigation. Therefore, controlled irrigation seriously damages the anaerobic environment formed by conventional flooding, and CH_4 is greatly reduced. In addition, under controlled irrigation, the methane-oxidizing bacteria in the soil need more oxygen to further oxidize and consume CH_4 in the environment, leading to the reduction in CH_4 emissions from rice fields with controlled irrigation [32,33]. Controlled irrigation can also promote the aerobic decomposition of organic matter in straw, reducing the conversion of decomposition products to CH_4 and significantly reducing CH_4 emissions [34]. The long-term simulation of DNDC showed that straw returning increased the annual N_2O emissions from rice fields compared with non-returning, different from the field experiment results of this study, but with the common feature of an insignificant increase and decrease in both results. This may be caused by the fact that the DNDC model underestimated the nitrogen lost through runoff and underground leakage during the simulation process, resulting in a higher simulation value. On the other hand, it is also possible that some parameters that are not easy to obtain during model validation have adopted default values, which, to some extent, affects the simulation accuracy of the model in the local area. Therefore, long-term positioning experiments to update the required field parameters of the model in a timely fashion and explore the mechanism of the input and output parameters of the model are fundamental work to ensure model accuracy and improve the model.

There is a tradeoff between CH_4 and N_2O emissions from rice fields [28]. Long-term simulations show that compared with the control treatment CFS0, the KFS1 treatment, although in two different emission scenarios of RCP4.5 and RCP8.5, reduced the annual CH_4 emissions from rice fields by an average of 30.24% and 36.52% while also increasing the annual N_2O emissions from rice fields by an average of nearly twice (Figure 8); ultimately, the GWP of rice fields was reduced by an average of 31.41% and 34.13%, respectively. The rice field management mode of straw returning and controlled irrigation can not only reduce the greenhouse effect caused by straw returning exacerbating CH_4 emissions but can also alleviate the greenhouse effect caused by controlled irrigation exacerbating N_2O emissions, indicating that straw returning and controlled irrigation have a significant interaction effect on GWP in rice fields. This is similar to the experimental results of Xu et al. [35] on the effects of moist irrigation under straw-tillage-free conditions on CH_4 and N_2O in rice fields.

Long-term simulation of SOC showed that the SOC content of the 0–20 cm soil layer under the treatments with no straw returning decreased year by year, indicating that the SOC pool was slowly declining. This was because there was no external carbon input into the soil, and only the carbon secreted by crop roots could not meet the needs of crop growth, and once the income was insufficient, this would ultimately lead to a decline in SOC [36]. The SOC content of the two treatments with straw returning showed a significant increase compared to the first year, especially in the KFS1 treatment, which increased by 54.69% and 52.80% compared with the CFS0 after 60 years under RCP4.5 and RCP8.5. Long-term straw returning to the field was an important carbon source for improving soil organic carbon storage in farmland, which is consistent with previous research results [36,37]. Therefore, long-term straw returning combined with controlled irrigation can serve as a carbon sequestration and emission reduction measure for rice fields in cold regions.

5. Conclusions

The DNDC model can be used to simulate greenhouse gas emissions in cold regions under different straw-returning and irrigation modes. The model basically simulates the peak and seasonal emission patterns of CH_4 and N_2O from rice fields in the study area. The simulated values have a significant correlation with the measured values ($p < 0.05$), and the consistency is controlled within 30%. The sensitivity analysis shows that the soil texture, soil SOC content, annual average temperature, and straw-returning amount are the sensitive factors for CH_4 emissions from rice fields. The total nitrogen fertilizer application amount and soil SOC content are sensitive factors for N_2O emissions from rice fields. The long-term prediction simulation of the DNDC model shows that controlled irrigation combined with straw returning has a good coupling effect on the GWP of rice fields over the next 60 years under the two emission scenarios of RCP4.5 and RCP8.5, compared with conventional flooding without straw returning, the GWP of KFS1 from rice fields is reduced by 31.41% and 34.13%, respectively, and the SOC content in a 0–20 cm soil layer is increased by 54.69% and 52.80%, respectively. Therefore, long-term straw returning combined with controlled irrigation can be used as a carbon sequestration and emission reduction measure for rice fields in cold regions.

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