Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454

Vol. 19 | No. 2 | pp. 469-479 | 2020

Original Research Paper

https://doi.org/10.46488/NEPT.2020.v19i02.004

Open Access Journal

CH_4 Emission Flux Model in Rice Growing Season in Cold Region Under Water Saving Irrigation Mode

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Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 15-07-2019
Accepted: 06-10-2019

Key Words:
Rice paddies;
Methane emission;
Water management;
Empirical models

ABSTRACT

Rice paddies have been identified as major methane (CH_4) source induced by human activities. Water management is an important factor affecting CH_4 emission during the rice growing season, and the water depth in a rice field directly affects the production, oxidation, and transfer. Field experiments on irrigation management are generally conducted under three modes: control irrigation, intermittent irrigation, and long-term flood irrigation. Static opaque chamber gas chromatographic method was adopted in this work for *in situ* observations of CH_4 emission flux in a field in the rice growing season in a cold region of China. Test data from 2016 was adopted to establish the single factor and interaction types of the CH_4 emission flux estimation model for the rice growing season under different water management methods, and the data from 2017 was used for model inspection. The estimation models were based on NO_3-N in soil and soil temperature, 10 cm under the soil surface. All models passed the significance test for significance levels of $P<0.01$. The average forecast error of the model is 13.53-24.78%, and the coefficient of determination R_{adj}^2 is between 0.399-0.675. The calculated values of the model are consistent with the measured values. The model established in this research can be used for estimation of CH_4 emission in the rice growing season in cold regions of China for different water-saving irrigation modes.

INTRODUCTION

Methane (CH_4) is one of the most important greenhouse gases (Sass et al. 2000, Exnerová & Cienciala 2009, Liu et al. 2017) and is the second leading cause of global warming (Zhao et al. 2013). Approximately 50% of the CH_4 in the atmosphere comes from agricultural production, and 20-40% of this total comes from rice production (Scheehle & Kruger 2006). Water management is an important factor affecting CH_4 emission during the rice growing season (Xiong et al. 2007, Hadi et al. 2010, Zschornack et al. 2016), and the water depth in a rice field directly affects the production, oxidation, and transfer rate of CH_4 (Zou et al. 2003). Continuous flooding of the paddy field during the growing season will result in increased CH_4 emissions, while the amount of CH_4 produced will decline when the soil is dry (Towprayoon et al. 2005). Numerous studies have shown that CH_4 emissions from intermittent irrigation and control irrigation are significantly lower than that from long-term flood irrigation (Adhya et al. 2000, Jain et al. 2000, Minamikawa & Sakai 2005), and the rule of seasonal CH_4 emission also differs (Kreye et al. 2007).

The paddy planting area in Heilongjiang province is approximately 6000 hm^2, and it is the largest rice production area in China (Wang & Zhang 2015). It is also an important emission source of CH_4 in China. In recent years, the rice cultivation in Heilongjiang has gradually changed from traditional water storage for flood irrigation to control irrigation and intermittent irrigation modes. Zhu (2012) indicates that water-saving irrigation mode in the rice cultivation area in a cold region affects the seasonal emission flux and accumulative emission flux of CH_4 produced by the rice field, which can effectively reduce the greenhouse effect of CH_4. Therefore, it is of great importance to accurately estimate CH_4 emissions under different irrigation modes.

The most widely used model for estimating CH_4 emissions is CH_4MOD developed by Huang et al. (1998) and DNDC model developed by Li (2001). Many scholars use these two models to estimate and improve their models, and good results have been achieved thus far (Jagadeesh Babu et al. 2006, Xie et al. 2010, Minamikawa et al. 2014, Chun et al. 2016).

The previously researched estimation for rice CH_4 emission may not sufficiently reflect the actual status under multiple water management modes in the cold region of Heilongjiang in northeast China. This research is based on the statistical analysis for field determination of rice CH_4 emission flux in a cold region in China. Multiple empirical models are adopted for analysis, simulation, and verification; single-factor and two-factor interaction empirical models of environmental factors are established to estimate seasonal rice CH_4 emission flux. The least squares method is adopted for the estimation of parameters and model inspection is performed. The established model can be used for estimation of rice CH_4 emission for different water management modes in rice cultivation areas in cold regions in Heilongjiang and can provide the theoretical basis for establishing emission reduction measures for greenhouse gases.

MATERIALS AND METHODS

General Situation of the Study Area

Rice cultivation experiments were carried out in 2016 and 2017 at the Rice Irrigation Test Station of Heilongjiang (45°63'N, 125°44'E), Qing'an county, Heping town, China. The average annual precipitation here was 500-600 mm, and the annual average temperature was 2-3°C. The hydrothermal growth period of the crops is 156-171 days, and the annual frost-free period is 128 days. The soil belonged to the Lidetun series (loam, mixed, and Albic rice soil), and the pH before the study was neutral (Table 1).

Test Design

To evaluate the effect of different irrigation modes on CH_4 emissions during rice cultivation, three main treatments with different irrigation systems (control irrigation C1, intermittent irrigation C2, and long-term flood irrigation C3) were applied. There were four nitrogenous fertilizer application levels: high (N1) 130 kg/hm^2, medium (N2) 110 kg/hm^2, low (N3) 80 kg/hm^2, and no nitrogenous fertilizer application (N4). A total of 12 treatments (C1N1, C1N2, C1N3, C1N4, C2N1, C2N2, C2N3, C2N4, C3N1, C3N2, C3N3, and C3N4) and three repetitions were adopted for the test.

For long-term flood irrigation, the surface water depth is large; the air temperature in spring in Heilongjiang is low, so flooded soil is favourable to resume growth after rice transplanting. Therefore, large water depths were maintained during the seeding establishment. To reduce ineffective tillering of rice, drainage was performed during the later tillering period. Water levels were not established in the field under control irrigation mode, and the irrigation methods were mainly used to adjust the moisture content of the soil. Under intermittent irrigation mode, the irrigation water is fed to the field in several instalments, and there is no obvious water level in the field. Table 2 summarizes the moisture design for the soil under the different treatment methods.

Test Management

A total of 36 areas were selected for testing, and each area was 100 m^2; the four sides of the areas were protected. To reduce lateral permeation, plastic plates were buried (40 cm underground) along the four sides of each of the areas. Water meters and water gauges were installed for each area to control the irrigation water amount and water depth. Fixed gas sampling points were set in the middle of each area with side dimensions of 4 m and were used for placement of static chambers for CH_4 artificial sampling.

The rice variety used for testing was #5 KENJIAN RICE. Seeding was performed on 15th April 2016, and the planting density was 25 cm, 12 cm and 34 caves/m^2. The rice variety, sprout cultivation, transplant, crop protection, technical measures for pesticide use, and field management conditions were the same for all the areas. Base fertilizer was applied on May 3, the transplant was performed on May 20, striking root fertilizer was applied on May 28, tillering fertilizer was applied on June 15, fertilization for head sprouting was performed on July 9, and rice was harvested on September 20. The rice growth stage is 126 days, period of the seedling establishment was from May 20-May 29, tillering stage was from May 30-July 7, jointing and booting stage was from

Table 1: Chemical properties of the initial soil.

Soil	Values
pH	6.4
Volume- weight (g/cm^3)	1.01
Porosity (%)	61.80
Organic matter (g/kg)	41.4
TN (total nitrogen) (g/kg)	1.08
TP (total phosphorus) (g/kg)	15.23
TK (total potassium) (g/kg)	20.11
Available nitrogen (mg/kg)	154.36
Available phosphorus (mg/kg)	25.33
Available potassium (mg/kg)	25.33

Table 2: Water management mode for different irrigation management methods.

Treatment	Seeding Establishment	Early tillering	Filled tillering	Later tillering	Jointing and booting	Bloom	Grouting	Yellow ripe
Control irrigation	0–30	0.7 θs	0.7 θs	Drainage	0.8 θs	0.8 θs	0.7 θs	Dry set
Intermittent irrigation	0–30	0–40	0–40	Drainage	0–30	0–40	0–40	Dry set
Long-term flood irrigation	0–30	0–40	0–40	Drainage	0–40	0–40	0–40	Dry set

Note: θs is the saturated moisture content of root layer soil. The data before "–" represents the lower limit for moisture control, and the data after "–" represents the upper limit for moisture control. The units of surface water depth: mm.

July 8-July 21, bloom stage was from July 22-August 1, grouting stage was from August 2-August 24, and the yellow ripe stage was from August 25-September 10.

Sample Collection

Field CH$_4$ samples were collected during the seven stages of main growth (steeping field, tillering, drainage, jointing and booting, bloom, grouting, and yellow ripe) of rice from May to September every year. Besides, samples were obtained for each typical stage, namely, before fertilization, after fertilization, after rain, drainage, high temperature, and high exhaust capacity. The gas samples were collected 19 times during the whole growing period, and 3 samples were collected each time.

Static chamber method was adopted for gas sampling. The static chamber (Harbin Jingwei Glass Machining Co., Ltd.) comprises of 5 mm thick transparent organic glass; the outside of the chamber was sealed by tinfoil for thermal insulation. The chamber height was 60 cm in the rice growth prophase and increased to 110 cm in the late growth stage. Mini fan and digital thermometer probe were installed at the top of the chamber to calibrate the gas mass calculation error caused by temperature rise in the chamber during the sampling process. Gas sampling tube was connected to the side of the chamber and inserted 25 cm inside the chamber. Three-way valves were connected at the end of the gas sampling tube and were connected to the gas sampling bag and injector (60 mL). The collection was performed for durations of 0, 10, 20, and 30 min under each treatment condition; two continuous samplings were performed for each gas sample, and these samples were transferred into the gas sampling bag (120 mL) (Wang & Zhang 2015).

Earth boring auger was used to obtain 0-20 cm fresh soil samples, which were packed into foam insulation boxes together with ice bags to preserve freshness until they were brought to the laboratory for refrigerated storage. The content of nitrate-nitrogen in soil and ammonium nitrogen were determined. When sampling, the water depth and soil temperature of each area at a depth of 10 cm were synchronously determined. The meteorological data were automatically recorded by the DZZ2 automatic meteorological station (Tianjin Meteorological Instrument Factory) of the test station (Fig. 1).

Sample Test

The gas concentration was determined by gas chromatog-

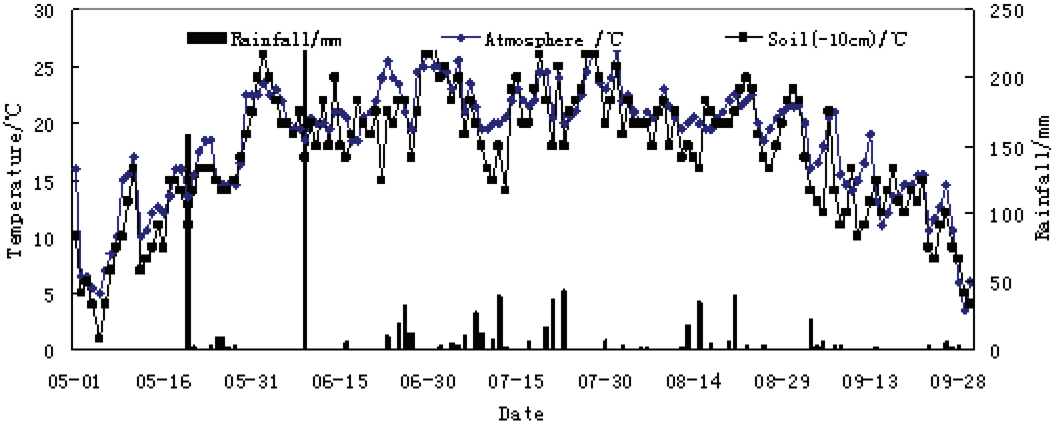

Fig. 1: Changes in atmospheric and soil temperatures and rainfall during rice cultivation in 2016.

raphy GC-17A (Shimadzu) and flame ionization detector (FID); the detection temperature was 300°C, column temperature was 65°C, carrier gas was high purity N_2, and the flow rate was 40 mL/min. The standard gas samples were provided by the National Standard Substance Center.

The colourimetric method was adopted for the determination of nitrate-nitrogen content in the soil. Synchronously, the correspondingly treated soil sample was weighed and dried at 105°C until a constant weight was obtained; the soil moisture content was then determined, to make it convenient for conversion into dry soil mass.

Calculation Method and Data Analysis

Rice CH_4 emission flux is calculated by the following formula (Xiang et al. 2006).

$$F = \rho h \cdot \frac{dc}{dt} \cdot \frac{273}{273+t} \cdot \frac{p}{p_0} \qquad \ldots(1)$$

In the formula, F is CH_4 emission flux, $\mu g/(m^2 h)$; ρ is CH_4 density under standard conditions, 0.714 kg/m^3 (Ma et al. 2012); h is the effective height of the chamber (when there is water in the field, it is the height from the water surface to chamber top; when there is no water, it is the chamber height) (0.6 m; 1.1 m). $\frac{dc}{dt}$ is the change rate of CH_4 concentration in the chamber, $\mu L/(m^3 \cdot h)$, t is the average temperature, °C in the sampling chamber, p is pressure in the chamber, Pa; and p_0 is the standard atmospheric pressure, Pa. The area was a plain area, so the atmospheric pressure had a small impact; p was thus deemed to be equal to the standard atmospheric pressure. The gas emission flux was calculated based on the gas sample concentration-time relation curve.

Excel 2003 software was used for conventional graph processing; SPSS 17.0 software was used for statistical analysis to fit the single factor and two-factor interaction models. The significance level was $p=0.05$, and the extreme significant level was $p=0.01$. Standards used for model selection were as follows: (1) model–model fitting parameter probability is extremely significant or significantly correlative ($p<0.01$ or $p<0.05$); (2) residual sum of squares (RSS) of the model is small, and F value is large; (3) the coefficient of determination (R_{adj}^2) of the model is relatively high. Two types of models were established in this work to simulate the rice soil CH_4 emission flux in cold regions. The first type was a single factor model based on NO_3-N content in soil and single-factor model based on soil temperature at -10 cm; the other type was an interaction model based on the synergistic effect of the two factors: NO_3-N content in the soil and soil temperature at -10 cm (Table 3). The data for establishing the model was sourced from the test data of 2016, and the data for testing the model was sourced from the test data of 2017.

RESULTS

Data Analysis of CH_4 Emission

In different irrigation modes, the season change of the rice field CH_4 emission ranges from 0.14 $\mu g/(m^2 \cdot h)$ to 53.77 $\mu g/(m^2 h)$. For the whole growing period of rice, the peaks of the CH_4 emission in different irrigation modes all occur at two stages of tillering and field drying: jointing and booting, and the emission is relatively low in the early growth resuming stage to early tillering stage and yellow ripe (Fig. 2).

Establishment of the Model

Single-factor model for CH_4 emission flux based on soil temperature: Temperature is the important environmental factor affecting CH_4 emission of paddy fields; the change of soil temperature causes changes in the activity of methane-producing microorganisms and microorganism causing CH_4 oxidation, the biochemical reaction rate also changes, which affects CH_4 emission. Previous research indicates that temperature has an obvious impact on CH_4 emission (Qin et al. 2006), and points out during a study on double cropping rice in the south area that there is exponential function relation between CH_4 emission flux and the average temperature of 10 cm soil layer. In this research, fitting is performed for the relation between CH_4 emission flux and temperature of the 10 cm deep soil layer by using linear model, logarithmic model, exponential model, and cubic model (Table 4). For the three irrigation modes, the degree of fitting R_{adj}^2 of the three models has a big difference; the adjusted correlation coefficient R_{adj}^2 is between 0.135-0.613. All models passed

Table 3: CH_4 emission flux model based on single and double predictors.

Single predictor	Double predictor
$f=aN^3+bN^2+cN+d$	$f= a N^3+b T^3+c N^2+ dT^2+eN+f T+g$
$f=a\, EXP(b N)$	$f=EXP(a+b*N/T)$
$f=aT^3+bT^2+cT+d$	

Note: f, CH_4 emission flux in $\mu g/m^2/h$; N, content of nitrate nitrogen in soil in mg/kg; T, soil temperature at -10 cm in °C; a, b, c, d, e, f, g: parameters of the model.

the significance test, and the extremely significant level was reached (P<0.01). Comprehensively considering the parameters of the model, RSS, F value, R_{adj}^2, and significance, the optimal model of all the three irrigation modes was the cubic model; the adjusted correlation coefficient of control irrigation is the largest (R_{adj}^2=0.613), intermittent irrigation is next (R_{adj}^2=0.488), and long-term flood irrigation is the least (R_{adj}^2=0.387).

Single-factor model for CH_4 emission flux based on the content of nitrate-nitrogen in soil: Under the circumstance that soil temperature is not considered, linear model, logarithmic model, exponential model, exponential function model and cubic model are used to simulate the relation between the content of NO_3-N in soil and CH_4 emission flux of paddy field (Tables 5 and 6). The adjusted correlation coefficient R_{adj}^2 of a fitting model of the three irrigation modes is 0.219-0.534, and the correlation reaches the extremely significant level (P<0.01). The parameter sensitivity of power function model of the cultivation mode of long-term flood irrigation reaches the extremely significant level; RSS is the smallest, and F value is the largest, so the optimal model of long-term flood irrigation is the power function model (R_{adj}^2=0.534). Comprehensively considering the parameter sensitivity, RSS, F value, and R_{adj}^2, the optimal model of control irrigation and intermittent irrigation are confirmed as the cubic model (R_{adj}^2=0.467). Through comparison for the optimal model of the three irrigation modes, the probability value of correlation index of long-term flood irrigation is the highest, and it is a little better than that of control irrigation and intermittent irrigation (Tables 5, 6).

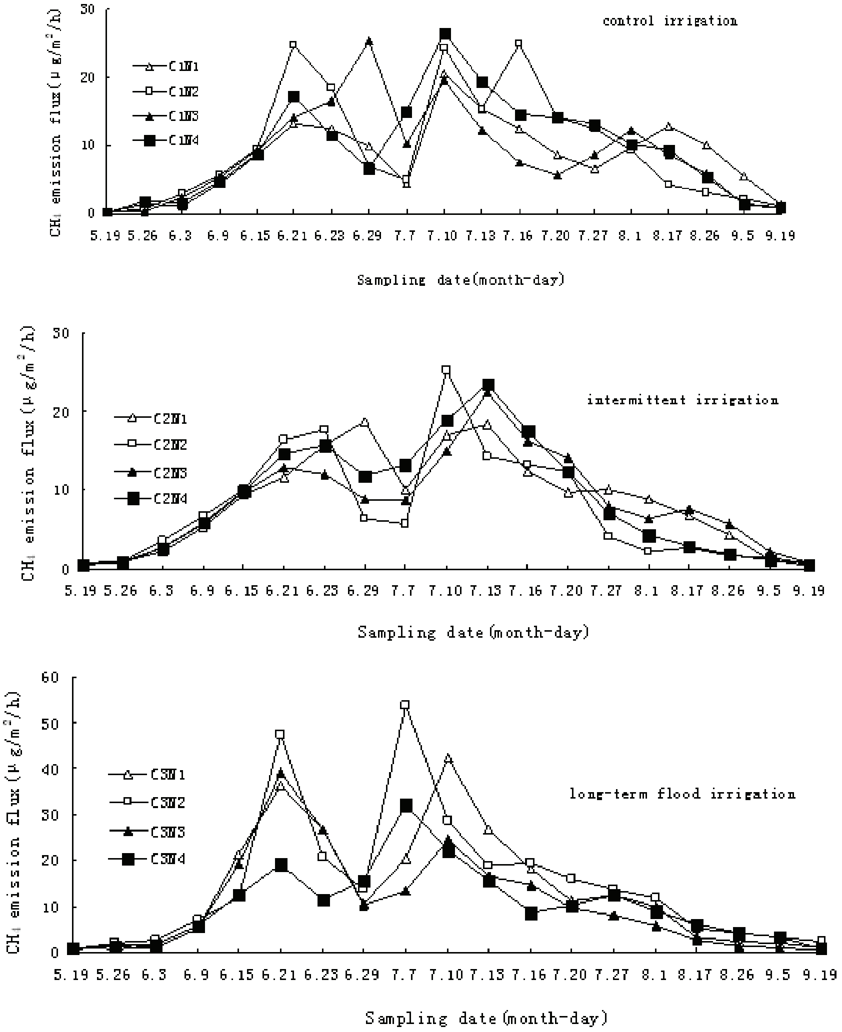

Fig. 2: Seasonal variations of CH_4 emission from rice field for three irrigation models.

The interaction model for CH_4 emission flux based on soil temperature and content of nitrate nitrogen: The proposed model was adopted to fit the relation between soil temperature, the content of nitrate nitrogen, and CH_4 emission flux. The result shows that the degree of fitting of interaction (R_{adj}^2) is higher than that of the single-factor model (Tables 7 and 8). Compared with single-factor models, two-factor models can predict CH_4 emission better; the coefficient of determination R_{adj}^2 is between 0.340-0.715. Soil fertilizer and temperature have a significant impact on CH_4 emission, and all models reach the extremely significant level ($P<0.01$). Through comprehensive consideration, the optimal model for control irrigation is $f=EXP(a+b\cdot N/T)$, and the explanatory power is 71.5%; the optimal model of intermittent irrigation is $f = aN^3+bT^3+c N^2+ dT^2+eN+f T+g$, and the explanatory power is 53.6%, and the optimal model of long-term flood irrigation is $f =EXP(a+b\cdot N/T)$, and the explanatory power is 57.6%. The degree of fitting of control irrigation is the highest.

Inspection of Model

The experimental data in 2017 was adopted for inspection of the single factor and interaction optimal model of the three irrigation modes (Table 9). Mean prediction error (MPE) and adjusted correlation coefficient R_{adj}^2 are adopted for inspection of prediction accuracy of the model. All models passed the significance inspection and reached an extremely significant level ($P<0.01$). The mean prediction error of the model is 13.53-24.78%, and the adjusted correlation coefficient R_{adj}^2 is 0.399-0.675. The result shows that the calculated value of the model and measured values are consistent, and the model has good applicability.

$$MPE = \frac{100}{n}\sum_{i=1}^{n}\frac{\left|Y_{iMeasured} - Y_{iCalculated}\right|}{Y_{iMeasured}}$$

DISCUSSION

CH_4 Emission Model Based on Content of Nitrate Nitrogen in Soil and Temperature

In rice cultivation area in the cold region of Heilongjiang, the single factor optimal model for the three irrigation models for CH_4 emission flux based on soil temperature is the cubic model; the optimal model of control irrigation is $f=0.152T^3-7.886T^2+132.251T-682.337$ ($R_{adj}^2=0.613$), intermittent irrigation is $f=0.035T^3-1.559T^2+22.363T-86.908$ ($R_{adj}^2=0.488$), and long-term flood irrigation is $f =0.169T^3-9.345T^2+167.281T-921.248$ ($R_{adj}^2=0.387$). For the single-factor model of CH_4 emission flux based on the content of nitrate nitrogen in the soil, the optimal model of control irrigation and intermittent irrigation is the cubic model: $f=1.904N^3-14.267N^2+14.598N+63.470$ ($R_{adj}^2=0.467$) and $f=-1.301N^3+15.907N^2-62.968N+101.461$ ($R_{adj}^2=0.467$). The optimal model of long-term flood irrigation is the exponential model: $f=363.903\ EXP(-0.981\ N)$ ($R_{adj}^2=0.534$). For interaction model of CH_4 emission flux based on soil temperature and content of nitrate nitrogen in the soil, the optimal model

Table 4: Parameters of soil temperature (-10 cm) based CH_4 emission flux models.

Treatment	Model	Parameter				RSS Parameter	F	R_{adj}^2	Sig
		a	*b*	*c*	*d*				
Control irrigation	f= aT+b	3.047^{***}	-28.504^{ns}			14846.101	10.322	0.257	***
	f=aLn(T)+b	47.819^{***}	-108.947^{**}			15417.700	8.975	0.228	***
	$f=aT^b$	0.001^{ns}	3.527^{***}			24.807	15.236	0.521	***
	$f=aT^3+bT^2+cT+d$	0.152^{***}	-7.886^{***}	132.251^{***}	-682.337^{***}	140.532	30.339	0.613	***
Intermittent irrigation	f= aT +b	2.790^{***}	-24.759^{ns}			12714.429	14.237	0.329	***
	f=aLn(T+b)	36.923^{***}	-77.521^{**}			14137.505	10.187	0.254	***
	$f=aT^b$	0.019^{ns}	2.274^{***}			36.807	9.575	0.3393	***
	$f=aT^3+bT^2+cT+d$	0.035^{***}	-1.559^{**}	22.363^{**}	-86.908^{ns}	156.606	14.841	0.488	***
Long-term flood irrigation	f= aT +b	3.403^{**}	-27.336^{ns}			29828.600	5.789	0.151	***
	f=aLn(T)+b	57.294^{**}	-128.828^{ns}			30368.942	5.223	0.135	***
	$f=aT^b$	0.001^{***}	3.257^{ns}			36.975	6.688	0.323	***
	$f=aT^3+bT^2+cT+d$	0.169^{***}	-9.345^{***}	167.281^{***}	-921.248^{***}	163.841	13.863	0.387	***

Note: Significance: ns, not significant; **, the model or the parameters was significant; ***, the model or the parameters was extreme significant; the same as below.

of control irrigation and long-term flood irrigation is the exponential model: $f=EXP(4.762-9.302N/T)(R_{adj}^2=0.715)$ and $f=EXP(4.739-10.564N/T)$ ($R_{adj}^2=0.576$), and the optimal model of intermittent irrigation is cubic model $f=0.189N^3+0.017T^3-0.693N^2-0.661N-7.572T-0.216$ ($R_{adj}^2=0.536$).

Impact of Water-saving Irrigation Mode on CH_4 Emission

Water management mode in the rice-growing season has an obvious impact on CH_4 emission. During the growth period of rice, the water depth in different growing stages is different, so water management for paddy field affects the seasonal change of CH_4 emission to a large degree. Using the interaction model to predict the seasonal emission of CH_4, the numbers are as follows: control irrigation 257.25 $kg{\cdot}hm^{-2}$; intermittent irrigation 235.25 $kg{\cdot}hm^{-2}$; and long-term flood irrigation 343.75 $kg{\cdot}hm^{-2}$. The total amount of seasonal methane emissions from controlled irrigation and intermittent irrigation respectively decrease by 25.16% and 31.56% compared with that from long-term flooding irrigation. CH_4 emission of paddy field subject to water-saving irrigation mode is lower than that of paddy field subject to long-term flood irrigation.

When Adhya et al. (2000) and Jain et al. (2009) studied CH_4 emissions from paddy fields in India, they found that CH_4 emissions from intermittently irrigated paddy fields decrease by 15% and 22%, respectively, compared with that from continuously flooded paddy fields. Minamikawa & Sakai (2005) found from field experiments that the CH_4 emissions from mid-season drained field and midseason drained-intermittently irrigated paddy fields are 64% and 26% of the CH_4 emissions from flooded paddy fields. From the field experiments, Jiao et al. (2006) found that CH_4 emissions from intermittently irrigated paddy fields decrease by 24.22% compared with that from flooded paddy fields. Towprayoon et al. (2005) found that moisture deficit during rice growth can significantly reduce CH_4 emissions from paddy fields, with the mid-season drainage and the multiple drainages in the course, and the CH_4 emissions from continuously flooded paddy fields respectively reduce by 27% and 35%. Thus, the method of water management has a significant impact on seasonal CH_4 emissions.

The research of Yuan (Yuan et al. 2008) for CH_4 emission effect of paddy field in southern China showed that CH_4 emission of paddy field subject to intermittent irrigation is 46.23% lower than that of paddy field subject to long-term flood irrigation. Peng et al. (2013) obtained the following conclusion according to 5 years' of *in situ* field observation data for paddy areas in southeast China: CH_4 emission of paddy field subject to control irrigation is 83.5% lower than that of paddy field subject to long-term flood irrigation, and the difference reaches the extremely significant level.

Some researchers show that CH_4 emission peak value of paddy field subject to intermittent irrigation mainly occurs in the early stage and middle stage of rice tillering (Yuan et al. 2008), and CH_4 emission peak value of paddy field subject to control irrigation mainly occurs in seeding establishment period-middle stage of tillering (Peng et al. 2013). CH_4 emission peak value of paddy field subject to long-term flood irrigation is relatively lagging. It was found during the research that three emission peak values occur in the tillering stage, jointing and booting stage and bloom stage, and there

Table 5: Parameters of nitrate nitrogen-based CH_4 emission flux models.

Treatment	Model	Parameter			
		a	*b*	*c*	*d*
Control irrigation	f= aN +b	-8.328^{***}	63.605^{***}		
	f=aLn(N)+b	-17.599^{***}	51.754^{**}		
	f=a EXP(b · N)	75.519^{ns}	-3.94^{***}		
	$f=aN^3+bN^2+cN+d$	1.904^{***}	-14.267^{**}	14.598^{**}	63.470^{***}
Intermittent irrigation	f= aN +b	-8.631^{***}	60.931^{**}		
	f=aLn(N)+b	-21.560^{***}	52.308^{**}		
	f=a EXP(b · N)	77.829^{ns}	-0.468^{***}		
	$f=aN^3+bN^2+cN+d$	-1.301^{**}	15.907^{**}	-62.968^{***}	101.461^{***}
Long-term flood irrigation	f= aN +b	-21.233^{***}	104.040^{***}		
	f=aLn(N)+b	-58.376^{***}	100.279^{***}		
	f=a EXP(b N)	363.903^{***}	-0.981^{***}		
	$f=aN^3+bN^2+cN+d$	-2.006^{ns}	21.435^{ns}	-91.560^{ns}	172.668^{ns}

are differences in the change amplitudes of the peak values.

CH_4 formation by paddy field soil includes three processes: generation, oxidation, and emission. CH_4 is produced in an anaerobic environment by methanogens in the soil; most CH_4 is oxidized by methane-oxidizing bacteria, and the remaining CH_4 is emitted into the atmosphere (Lv et al. 2005). Water management influences the generation, oxidation, and emission of CH_4. Methane bacteria are anaerobes; water flooding will cause the reduction of the redox potential of soil; this creates a good soil environment for the generation process of CH_4, finally causing the increase in CH_4 emission. Long-term flood irrigation mode is favourable for the generation and emission of CH_4. Methane-oxidizing bacteria are aerobes; alternation of wetting and drying or soil drying is favourable to gas exchange for increasing the activity, which largely improves the oxidation rate of CH_4 and inhibits the activity of methanogens, reducing the production and emission of CH_4. Therefore, water-saving irrigation mode is significant for relieving the greenhouse effect.

Since the last century, water management practices for rice production in Heilongjiang have begun to change. Before the 1950s, paddy fields were dominated by long-term flooding. Since the 1980s, mid-term soil drying has been widely used as the agricultural management measure to reduce ineffective tillers and improve seed setting rate. With the continuous increase of global greenhouse effects, the reduction of CH_4 emission in paddy fields needs to be solved urgently. In recent years, paddy fields in Heilongjiang have gradually changed from traditional water-filled irrigation to water-saving irrigation modes such as control irrigation and intermittent irrigation (Wang & Zhang 2015). Compared with long-term flooding irrigation, water-saving irrigation technology not only solves the problem of water shortage but also contributes to methane emission control in the paddy field for a win-win strategy.

Uncertainty of Model Simulation

Besides water management, CH_4 emission in paddy planting area in the cold region is also affected by other environmental factors, such as physical and chemical properties of soil, fertilization measures, climatic conditions, variety difference, and cropping system. The rice area in the cold region in Heilongjiang is large; the soil types are diversified, and there are differences in soil pH, redox potential, the content of organic matter, texture, etc. All these will affect CH_4 emission of paddy fields. Some researches show that the heavier the soil, the lower is the CH_4 emission flux (Jiao et al. 2002), there is a negative correlation between the number of methane bacteria and content of clay particles in soils (Neue & Roger 1993). Soil pH mainly affects CH_4 emission from three aspects: decomposition of organic matters in soil, CH_4 production, and CH_4 oxidation (Qin et al. 2006). The research of Wei et al. (2012) indicates that the CH_4 emission increases with the reduction of soil pH; CH_4 emission of acid soil is higher than that of alkaline soil. The impact of soil type on CH_4 emission flux is not considered in this research, so uncertainty exists for the model fitting result.

Fertilization measure is the important factor affecting CH_4 emission of paddy field. In recent years, to protect the environment and realize the sustainable development of agriculture, the fertilization method for paddy field in the cold region in Heilongjiang is changing from traditional

Table 6: Testing results of CH_4 emission flux models based on nitrate content

Treatment	Model	RSS	F	R_{adj}^2	Sig
Control irrigation	f= aN +b	14796.018	10.445	0.259	***
	f=aLn(N)+b	14284.451	8.871	0.285	***
	f=a EXP(b N)	40.448	8.554	0.219	***
	$f=aN^3+bN^2+cN+d$	134.908	11.750	0.467	***
Intermittent irrigation	f= aN +b	12513.424	14.884	0.340	***
	f=aLn(N)+b	10454.825	8.884	0.448	***
	f=a EXP(b N)	36.733	14.923	0.340	***
	$f=aN^3+bN^2+cN+d$	123.399	22.934	0.467	***
Long-term flood irrigation	f= aN +b	21821.874	17.452	0.379	***
	f=aLn(N)+b	21573.832	17.952	0.386	***
	f=a EXP(b N)	25.419	31.985	0.534	***
	$f=aN^3+bN^2+cN+d$	357.328	5.661	0.341	***

application of chemical fertilizer to combined application of inorganic fertilizer, green manure, and animal manure; traditional fertilizer and controlled-release fertilizer are thus used together, and straw mulching is performed. The type, use amount, and application method of fertilizer will affect the emission rules and emission amount of CH_4 of paddy fields. Some researchers show that application of organic fertilizer and straw mulching increase CH_4 emission flux of paddy field (Zhao et al. 2014), and the higher the C/N, the larger is the CH_4 emission (Wu & Ye 1993). CH_4 is mainly generated under the action of methanogens; the applied organic fertilizer makes the nutrient substance of methane-producing microorganisms in soil increase, which causes an increase in CH_4 emission. In this research, only the impact of application amount of nitrogen fertilizer on CH_4 emission flux of paddy field is considered, and the impact of fertilization measure is not considered, which enhances the uncertainty of model fitting.

Heilongjiang province is an important commodity grain production base in China; the paddy planting area involves four accumulated temperature zones, and there are more than 100 varieties. The geographic position is varied, and the climate and the corresponding rice varieties are also different; all these cause the difference in CH_4 emission rules and emission amounts. The following conclusions are obtained by Wei et al. (2012) by the analysis on CH_4 emission data of paddy field (495 groups, 67 observation points): CH_4 emission of single cropping rice area decreases as the increase of latitude and longitude. There is a big difference in CH_4 emission for different rice varieties. More than 50% of unoxidized CH_4 is transferred into the atmosphere after root absorbing via leaves, and the size and activity of roots will affect its absorbing rate (Shao et al. 2011). The metabolic secretions of roots can enhance the activity of CH_4 oxidizing bacteria, which will promote CH_4 oxidation and inhibit its emission (Cao et al. 2000). CH_4 absorbing and inhibition of root system may have different expressions for different varieties, but it enhances the uncertainty for model estimation.

In addition, different test frequencies will also result in uncertainty in model estimation. Data are the basis for model establishment; theoretically, the data determination shall be performed multiple times, so that it is possible to detect the change characteristics of CH_4 emission with time. In this research, static chamber method is adopted to collect CH_4 samples in key growing stages of rice, and 20 repetitions of sample collection were performed in total during the whole growing stage; sampling shall be delayed if sampling cannot be performed due to special weather conditions. Compared with automatic sampling observation systems, some CH_4 emission peak values may be omitted by the static chamber method. Thus, there is still a large uncertainty for model fitting results in this research.

CONCLUSIONS

The interaction model has been designed in this study. Compared with a single factor model, the interaction model further improves the prediction ability. The water-saving irrigation mode changes the characteristics of CH_4 emission flux during the rice-growing season in the cold region; the seasonal CH_4 emission flux models are different under the three irrigation modes. Even if the model structure is the same, the parameters are different. The verification result for the data in 2017 shows that the average forecast error of the interaction model is 13.53%-24.78%; the adjusting correlation coefficient R_{adj}^2 is 0.399-0.675. The calculated value of the model and the measured value show good agreement, thus verifying the applicability of the model.

Table 7: Parameters of CH_4 emission flux models based on soil temperature (-10 cm) and nitrate nitrogen.

Treatment	Model	Parameter						
		a	b	C	d	e	f	g
Control irrigation	$f= a N^{3}+b T^{3}+c N^{2}+ eN+f T+g$	3.070^{***}	0.010^{***}	-29.725^{***}	-	72.922^{***}	-7.314^{**}	61.769^{**}
	$f=EXP(a+b*N/T)$	4.762^{***}	-9.302^{***}	-	-	-	-	-
	$f=aN +bT+c$	-7.269^{***}	2.656^{***}	6.074^{ns}	-	-	-	-
Intermittent irrigation	$f= a N^{3}+b T^{3}+c N^{2}+ dT^{2}+eN+f T+g$	0.189^{***}	0.017^{***}	-0.693^{**}	-0.661^{***}	-7.572^{***}	8.906^{**}	-0.216^{**}
	$f=EXP(a+b*N/T)$	3.603^{***}	-3.913^{***}	-	-	-	-	-
	$f=aN +bT+c$	-6.261^{***}	1.987^{***}	13.130^{ns}	-	-	-	-
Long-term flood irrigation	$f=EXP(a+b*N/T)$	4.739^{***}	-10.564^{***}	-	-	-	-	-
	$f= a N^{3}+b T^{3}+c N^{2} + eN+f T+g$	0.214^{ns}	0.006^{ns}	-1.886^{ns}	-	-13.522^{ns}	-4.938^{ns}	138.397^{ns}
	$f=aN +bT+c$	-18.748^{***}	1.196^{ns}	72.169^{ns}	-	-	-	-

Note: - means “none”

Table 8: Testing results of CH_4 emission flux models based on soil temperature (-10 cm) and nitrate nitrogen.

Treatment	Model	RSS	F	R_{adj}^2	Sig
Control irrigation	$f= a N^3+b T^3+c N^2+ eN+f T+g$	173.353	13.240	0.694	0.000
	$f=EXP(a+b*N/T)$	14.778	68.575	0.715	0.000
	$f(M)=aN +bT+c$	10414.216	12.394	0.458	0.000
Intermittent irrigation	$f= a N^3+b T^3+c N^2+ eN+f T+g$	100.166	15.491	0.536	0.001
	$f=EXP(a+b*N/T)$	36.230	6.200	0.349	0.001
	$f=aN +bT+c$	9521.207	13.333	0.477	0.000
Long-term flood irrigation	$f=EXP(a+b*N/T)$	23.147	37.679	0.576	0.000
	$f= a N^3+b T^3+c N^2+ dN+e T+f$	112.992	3.782	0.340	0.013
	$f=aN +bT+c$	21201.933	9.001	0.372	0.001

The climate, soil type, and cropping system of different regions are different; therefore, CH_4 emission has a considerable variation based on time and space. Similar to other empirical models, the proposed CH_4 emission model has no universality. However, for specific climatic features in the rice area in the cold region in Heilongjiang, the model can predict the seasonal emission flux of CH_4 for rice.

In future research, a comprehensive evaluation model for coupling of wetting and drying-physical and chemical properties of soil-agricultural management measures will be established to continually improve the calculation accuracy of CH_4 emission flux.

ACKNOWLEDGEMENTS

This work was supported by the Heilongjiang Bayi Agricultural University cultivate project funding scheme (Project title: "Greenhouse gas Emission Flux Model in Rice Growing Season in Cold Region under Water-Saving Irrigation Mode", XZR2017-2).

REFERENCES

Adhya, T., Kollah, B., Mohanty, S. R., Ramakrishnan, B., Rao, V. R., Sethunathan, N. and Wassmann, R. 2000. Methane emission from rice fields at Cuttack, India. Nutr. Cycl. Agroecosys., 58(1): 95-105.

Cao, Y. Y., Zhu, Q. S., Lang, Y. Z., Yang, J. C., Wang, Z. Q. and Xue, D. Z. 2000. Effect of rice varieties and cultivation approach on methane emission from paddy rice. Jiang Su Agricultural Research, 21(3): 22-27.

Chun, J.A., Shim, K.M., Min, S.H. and Wang, Q. 2016. Methane mitigation for flooded rice paddy systems in South Korea using a process-based model. Paddy and Water Environ., 14: 123-129.

Exnerová, Z. and Cienciala, E. 2009. Greenhouse gas inventory of agriculture in the Czech Republic. Plant Soil Environ., 55: 311-319.

Hadi, A., Inubushi, K. and Yagi, K. 2010. Effect of water management on greenhouse gas emissions and microbial properties of paddy soils in Japan and Indonesia. Paddy Water Environ, 8: 319-324.

Huang, Y., Sass, R. L. and Fisher, F.M. 1998. A semi-empirical model of methane emission from flooded rice paddy soil. Glob. Change Biol., 4: 247-268.

Jagadeesh B. Y., Li, C., Frolking, S., Nayak, D. R. and Adhya, T. K. 2006. Field validation of DNDC model for methane and nitrous oxide emissions from rice-based production systems of India. Nutrient Cycling in Agroecosytems, 74: 157-174.

Jain, M.C., Kumar,S., Wassmann, R., Mitra, S., Singh, S. D., Singh, J. P., Singh. R., Yadav, A. K. and Gupta, S. 2000. Methane emissions from

Table 9: Test results for the optimal model for the three irrigation modes.

Treatment	Optimal model	MPE/%	R_{adj}^2	Sig
Control irrigation	$f=aN^3+bN^2+cN+d$	24.78	0.429	***
	$f=aT^3+bT^2+cT+d$	15.34	0.399	***
	$f=EXP\ (a+b*N/T)$	18.52	0.652	***
Intermittent irrigation	$f=aN^3+bN^2+cN+d$	23.11	0.456	***
	$f=aT^3+bT^2+cT+d$	18.43	0.397	***
	$f= a N^3+b T^3+c N^2+ dT^2+eN+f T+g$	15.24	0.675	***
Long-term flood irrigation	$f=a\ EXP(b\ N)$	16.58	0.476	***
	$f=aT^3+bT^2+cT+d$	20.46	0.416	***
	$f=EXP(a+b*N/T)$	13.53	0.625	***

irrigated rice fields in northern India New Delhi. Nutrient Cycling in Agroecosystems, 58: 75-83.

Jiao, Y., Huang, Y., Zong, L.G., Zhou, Q. S., Sass, R. L. and Fisher, F. M.2002. Methane emission from rice paddy soils as influenced by soil physicochemical properties. Environmental Science, 23(5): 1-7.

Jiao, Z.H., Hou, A., Shi, Y., Huang, G. H., Wang, Y. H. and Chen, X. 2006. Water management influencing methane and nitrous oxide emissions from rice field in relation to redox and microbial community. Commun. Soil Sci. Plant Anal., 37: 1889-1903.

Kreye, C., Dittert, K., Zheng, X. H., Zhang, X., Lin, S., Tao, H. B. and Sattelmacher, B. 2007. Fluxes of methane and nitrous oxide in water-saving rice production in North China. Nutr. Cycl. Agtoecosys., 77: 293-304.

Li, C.S. 2001. Biogeochemical concepts and methodologies. Development of the DNDC mod. Quaternary Sciences, 21: 89-99.

Liu, X., Qi, Z.M., Wang, Q., Ma, Z. W. and Li, L. H. 2017. Effects of biochar addition on CO_2 and CH_4 emissions from a cultivated sandy loam soil during freeze-thaw cycles. Plant Soil Environ., 63: 243-249.

Lv, Z.M., Hang,M., Chen, Z.Y. and Lv, Q. 2005. Contribution of anaerobic oxidation of methane to whole methane oxidation. Environmental Science, 26(4): 13-17.

Minamikawa, K. and Sakai N. 2005. The effect of water management based on soil redox potential on methane emission from two kinds of paddy soils in Japan. Agriculture Ecosystems and Environment, 107: 397-407.

Minamikawa, K., Tamon, F., Itoh, M., Hayano, M., Sudo, S. and Yagi, K. 2014. Potential of prolonged midseason drainage for reducing methane emission from rice paddies in Japan. A long-term simulation using the DNDC-Rice model. Biology and Fertility of Soils, 50: 879-889.

Neue, H.U. and Roger, P.A. 1993. Rice agriculture: factors controlling emissions. In: (Khalil, M.A.K. ed.) Atmospheric Methane Sources, Sinks, and Role in Global Change. New York. Springer-Verlag, pp. 254-298.

Peng, S. Z., He, Y. P., Yang, S. H., Xu, J. Z. and Hou, H. J. 2013. Mitigation of methane emissions from paddy fields under controlled irrigation, Transactions of the Chinese Society of Agricultural Engineering, 29(8): 100-107.

Qin, X. B., Li, Y., Liu, K.Y. and Wan, Y. F. 2006. Methane and nitrous oxide emission from paddy field under different fertilization treatments. Trans. CSAE, 22: 143-148.

Sass, R.L., Fisher, F.M., Jr., Huang, Y. 2000. A process-based model for methane emissions from irrigated rice fields. experimental basis and assumptions. Nutrient Cycling in Agroecosystems, 58: 249-258.

Scheehle, E.A. and Kruger D. 2006. Global anthropogenic methane and nitrous oxide emissions. The Energy Journal, Multi-Greenhouse Gas Mitigation and Climate Policy, 3: 33-34.

Shao, M., Sun, J. and Ruan, G. 2011. Review on greenhouse gases emission and reduction technology in rice fields. Acta Agriculturae Zhejiangensis, 23(1): 181-187.

Towprayoon, S., Smakgahn, K. and Poonkaew, S. 2005. Mitigation of methane and nitrous oxide emissions from drained irrigated rice fields. Chemosphere, 59: 1547-1556.

Wang, M.X. and Zhang, Z.X. 2015. Optimal water-saving irrigation model reducing N_2O emission from rice paddy field in cold region and increasing rice yield. Transactions of the Chinese Society of Agricultural Engineering, 31: 72-79. (In Chinese)

Wei, H., Sun, W. and Hang, Y. 2012. Statistical analysis of methane emission from rice fields in China and the driving factors. Scientia Agricultura Sinica, 45(17): 3531-3540.

Wu, H. and Ye, Z. 1993. Preliminary estimated amount of methane emission in China rice paddy field. China Environmental Science, 13(1): 76-80.

Xie, B.H., Zhou, Z.X., Zheng, X.H., Zhang, W. and Zhu, J. G. 2010. Modeling methane emissions from paddy rice fields under elevated atmospheric carbon dioxide conditions. Advances in Atmospheric Sciences, 27: 100-114.

Xiong, Z.Q., Xing, G.X. and Zhu, Z.L. 2007. Nitrous oxide and methane emissions as affected by water, soil and nitrogen. Pedosphere, 17: 146-155.

Yuan, W. L., Cao, C. G., Cheng, J. P. and Xie, N. N. 2008. CH_4 and N_2O emissions and their GWPs assessment in intermittent irrigation rice paddy field. Scientia Agricultura Sinica, 41(12): 4294-4300.

Zhao, B., Zhang, J., Lv, X., Peng, L. and Padilla, H. 2013. Methane oxidation enhancement of rice roots with stimulus to its shoots. Plant Soil Environ., 59: 143-149.

Zhao, Z., Yue, Y.B., Zhang, Y., Lu, X. X. and Cao, L. K. 2014. Impact of different fertilization practices on greenhouse gas emission from paddy field. Journal of Agro-Environment Science, 33(11): 2273-2278.

Zhu, S.J. 2012. Experiment for water-saving and greenhouse effect of irrigation mode in cold rice area. Haerbin. Northeast Agricultural University, 2012. (In Chinese)

Zou, J. W., Huang, Y., Zong, L. L., Zheng, X. H. and Wang, Y. S. 2003. A field study on CO_2, CH_4 and N_2O emissions from rice paddy and impact factors. Acta Scientiae Circumstantiae, 23: 758-765.

Zschornack, T., Rosa, C. M., Pedroso, G. M.,Marcolin, E., Ferreira da Silva, P. R. and Bayer, C. 2016. mitigation of yield-scaled greenhouse gas emissions in subtropical paddy rice under alternative irrigation systems. Nutrient Cycling in Agroecosystems, 105: 61-73.