Seasonal changes of methane emission on black soil rice field in cold region and its DNDC simulation

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Abstract: Methane (CH4) emission from black soil rice field has obvious contribution on the greenhouse effect, however, scare investigations was done on the valuable issue. Static chamber method with DNDC simulation is a novel method to study greenhouse gases in rice field. The seasonal changes of methane emission were studied and simulated in a controlled and flooding irrigation by means of field-fixed position test. The results showed that irrigation patterns of methane emission peak has obvious difference, and total methane emission amount in growing season in controlled irrigation mode was about 47%, which was lower than that in flooding irrigation mode. The verification result showed the DNDC model may well describe the methane emission of black soil rice field in cold region. Therefore, controlled irrigation is an effective irrigation mode in reducing CH4 emission from rice field and the DNDC model may be a powerful tool for assessing CH4 emission quantities of black soil rice fields in cold region.

Keywords: black soil; rice field; methane; flooding irrigation; controlled irrigation; simulation.

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1 Introduction

Methane (CH$_4$) has obvious contribution to greenhouse effect, which is regarded as important greenhouse gas second only to carbon dioxide (Bouwman, 1990). According to the report of Intergovernmental Panel on Climate Change (IPCC) in 2001, global CH$_4$ concentration in the atmosphere had reached 1.75 ppmv and progressively increased at the rate of 0.8% per year. Among various CH$_4$ emission sources, rice fields account for about 20% as to the total amount of CH$_4$ emission, so rice field ecosystem is viewed as major source of CH$_4$ emission (Cai et al., 2008; Jiang, 2001; Wang, 2001).

Observational study of CH$_4$ emission on rice field began in late 1980s in China. Most of related studies were focused on the main rice production area in the south of the Yellow River, and less related studies involved in Northeast of China, which was limited to the area of Liaohe River Basin. Greenhouse gas emission on black soil rice field in cold region of Heilongjiang Province in China as major commodity grain production base is seldom reported. Existing reports are limited to traditional flooding irrigation.

In the past ten years, the controlled irrigation technique for rice field has been widely applied in Heilongjiang Province with controlled irrigation rice field area at growth rate of two million Mu (approximate to 1,333 million m$^2$) per year. Especially in Qing’an location, controlled irrigation technique had significant effect on the increase of rice yield and decreased of consumption of agricultural water (Wang and He, 2008; Zhong and Si, 2014), which had the feasibility to rice field in alpine-cold region. The changes of greenhouse gas emission of black soil rice field in cold region is less paid attention under the popularisation of controlled irrigation.

Changes of greenhouse gas emission depend upon the multiple factors in terms of climate, soil and agricultural activity. However, traditional experimental research methods of greenhouse gases in the rice field fixed position inevitably have time and space limitations, and can hardly forecast the future rule of CH$_4$ emission on rice fields in different natural conditions and cultivation modes. In recent years, ecological model has been successfully applied to the integration and forecast of the observed data of fixed position test, thereof denitrification and decomposition (DNDC) model has successfully simulated farmland greenhouse gas emission in many areas of China including Guizhou Province, Zhejiang Province and the Yangtze River Delta (Xu and Li, 2002; Wang and Ouyang, 2001; Zhang and Qi, 2007).

CH$_4$ fluxes from rice field have been measured at Qing’an location of Heilongjiang Province in China, which provides basic data for the CH$_4$ reduction measures and its estimation. This study aims to obtain the changes of methane emission under classic irrigation modes and verified DNDC model to simulate the rice field CH$_4$ emission in different irrigation conditions. The results may provide guidance for the quantitative estimate and analysis of CH$_4$ emission on black soil rice field in cold region.

2 Materials and method

2.1 Brief introduction to DNDC model

Based on the geochemical circulation rule of carbon and nitrogen in agricultural soil, Li et al. (1994, 1992a, 1992b) developed DNDC model, which not only simulate rice
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Field CH₄ emission flux at a test point but also estimate rice field CH₄ emission amount in a region.

DNDC model consists of two major parts. At part 1, three submodels include soil-climate, crop growth and soil organic matter decomposition, which simulate soil environment conditions including soil temperature, moisture, pH value, oxidation reduction potential, and related chemical substrate concentration gradient under ecological driving factors (i.e., climate, soil, vegetation and human activities). At part 2, three submodels including nitrification, denitrification and fermentation, simulate the influence of soil environment conditions on microbial activities, and calculates the emission of CO₂, CH₄, N₂O and N₂ in plant-soil system. Fermentation submodel in DNDC simulates the effects of soil environment conditions on CH₄ production, transmission and emission to calculate amount of CH₄ emission in soil. DNDC model involves factors in day-to-day meteorological data (air temperature and rainfall), soil properties (texture, volume weight, initial organic carbon content, pH value, etc.), land cultivation (crop type and rotation) and farmland management (proportion of straw returning to field, fertiliser application, irrigation, etc.). Simulation results are presented if mentioned parameters input DNDC model (Institute for the Study of Earth, Oceans and Space University of New Hampshire, 2010).

2.2 Test design

The test point, located in Heilongjiang Rice Field Irrigation Test Central Station, Ping’an Town, Qing’an County, is a typical black soil distribution area at east longitude of 125°44’ and north latitude of 45°63’. The test location is in cold temperate continental monsoon climate, with annual mean air temperature of 2 to 3°C, annual mean precipitation of 500 to 600 mm and annual average evaporation from water surface of 700 to 800 mm. The effective accumulative temperature change (≥ 10°C) is 2,500 to 2,800°C, and annual frost-free season is about 128d.

Surface soil in the test area is black soil (0~20 cm) with the basic properties as follows: field capacity of 39.60%, bulk density of 1.10 g/cm³, organic matter content of 4.96%, total nitrogen of 0.188%, total phosphorus of 0.083%, total potassium of 1.89%, pH value of 6.05. The test rice variety is North Oasis No. 2 that was transplanted on June 7, 2010 and harvested on Sep 22. Thereof, the basic fertiliser applied on May 20 included 72 kg·hm⁻² nitrogen, 72 kg·hm⁻² phosphorus and 104 kg·hm⁻² potassium; the tillering fertiliser applied on June 12 included 54 kg·hm⁻² nitrogen; the ear fertiliser applied on Aug 1 included 36 kg·hm⁻² nitrogen, 18 kg·hm⁻² phosphorus and 26 kg·hm⁻² potassium; the grain fertiliser applied on Aug 15 included 18 kg·hm⁻² nitrogen.

Two irrigation modes in terms of flooding irrigation and controlled irrigation were adopted in the research. The test area was divided into six subareas with each area of 100 m² and each irrigation mode was repeated for three times through random arrangement. Flooding irrigation began from rice seedling transplanting to maintain a 3 to 8 cm water depth till yellow ripe stage, drying and harvest. After transplanting, controlled irrigation maintained water depth of 10 to 30 mm at the field surface in the returning green stage, and there were no irrigated water layers on field surface after irrigation in every subsequent growth stage except productive water. Root layer soil moisture was regarded as control indicator to determine irrigation time and quota, and moisture management was shown in Table 1.
Table 1  Controlled thresholds in different stages for irrigation managements (%)

<table>
<thead>
<tr>
<th>Moisture treatment</th>
<th>Tillering stage</th>
<th>Jointing and booting stage</th>
<th>Earing and flowering stage</th>
<th>Milk stage</th>
<th>Yellow ripe stage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Early stage</td>
<td>Middle stage</td>
<td>Late stage</td>
<td>Early stage</td>
<td>Late flowering stage</td>
</tr>
<tr>
<td>Upper limit of irrigation (proportion in percentage of saturated water content)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Lower limit of irrigation (proportion in percentage of saturated water content)</td>
<td>100</td>
<td>85</td>
<td>75</td>
<td>85</td>
<td>100</td>
</tr>
</tbody>
</table>

Note: Water layer height of field irrigation in returning green stage: 10 to 30 mm.

Static chamber method was adopted to collect the field gas. Chamber specification was 50 cm × 50 cm × 50 cm or 80 cm × 80 cm × 110 cm (layer increase in late stage), the detection began three days after rice seedling transplanting, the detection time was at morning 10:00–12:00 (Li et al., 1998; Epstein and Burke, 1998). Each collection operation were repeated three times and 1–2 times collected operations every week until the last one week before harvesting. For sampling, an injector was used to extract about 100 mL gas from the chamber once at the initial time, five min, ten min and 15 min, respectively, then collected gas in the injector was immediately diverted into an aluminium foil sampling bag, and the sampling bag was taken back to the lab for measurement in time. CH₄ gas concentration was detected by using gas chromatograph (Shimadzu GC-14B) and hydrogen flame ionisation detector (FID), the change rate of methane concentration was calculated by using linear regression for the methane concentration of every group of four samples and corresponding sampling interval, then CH₄ emission flux was calculated by equation (1). The integral interpolation method was used to obtain the monthly rice field CH₄ emission flux, and the sum of all monthly emission fluxes is the total CH₄ emission amount through the whole growth stage of rice.

\[
F = \rho \cdot h \cdot \frac{dc}{dt} \cdot \frac{273}{(273 + T)}
\]

where \(F\) means gas emission flux (mg·m⁻²·h⁻¹), \(\rho\) means gas density (kg·m⁻³) in standard state, \(h\) means chamber height (m), \(\frac{dc}{dt}\) means rate of concentration change (mL·m⁻³·h⁻¹) of gas in sampling chamber, 273 means gaseous equation constant, and \(T\) means mean temperature (°C) in sampling chamber during sampling.

2.3 Acquisition of basic input parameters

Meteorological data including daily highest air temperature, lowest air temperature and rainfall needed by the model were acquired from China Meteorological Data Sharing Services Network. Soil and yield data, mainly including soil texture, volume weight, organic carbon content, pH value and other data, were sourced from the actual measured data of test station. Field management data, including fertiliser application, ploughing,
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rate of straw returning to field and others, were sourced from the field management records of 2010.

3 Results and discussion

3.1 CH₄ emission rule in growing season on black soil rice field under different irrigation modes

Results showed that influence of different irrigation modes on rice field CH₄ emission was significant (Wang, 2001; Peng and Li, 2006) in Figure 1, rice field CH₄ emission flux is at low level in the returning green stage, but it surges up in the middle tillering stage and the highest peak occurs through the whole growth period under the water flooding irrigation conditions. This peak continued until the end of the middle tillering stage after which the rice growth entered the booting stage and heading and flowering stage when the CH₄ emission flux reduced gradually. But it remained at a high level in the jointing stage and CH₄ emission flux reduced to a very low level in milk stage and yellow ripe stage. In the controlled irrigation conditions in the rice field, the CH₄ emission flux in the returning green stage was small. The first emission peak occurred at the early tillering stage and the peak of the entire growth stage occurred in the middle tillering stage. Two peaks come up 14 days and seven days, respectively, earlier than those in water flooding irrigation conditions. This result can be explained by difference in field water management. High duration of water layer in the water flooding rice field resulted a slow decomposition of soil organic matter and CH₄ emission is a slow release process. While no-water layer management is executed in controlled irrigation rice field at early tillering stage. Therefore, the decomposition of soil organic matter increased which impels the arrival of CH₄ emission peak ahead of time (Peng and Li, 2006; Yagi et al., 1996). CH₄ emission flux reduced from the late tillering stage and maintained at a very low level until the end of yellow ripe stage.

Figure 1 Rice growth stage and transplantation days
By calculation, in this experiment emission amount in growth season for water flooding irrigation was 6.64 g m⁻² and that for controlled irrigation was 3.52 g m⁻² which indicated that total amount of CH₄ emission of controlled irrigation in the rice field is 47% less than that of water flooding irrigation in the entire growth stage. Water management of farmland is an effective measure to reduce methane emission from paddy fields (Hussain et al., 2015). Yang et al. (2012) reported that CH₄ emission was decreased by 79% in rice field under controlled irrigation as compared with traditional flooded rice and global warming potential (GWP) of controlled irrigation was far less (67%) than traditional flooded rice. This result can be explained that the rice field in controlled irrigation came into a no-water layer management from the tillering stage to cause the release of stored methane. In addition, rice grows fast to cause the surge of CH₄ emission flux compared with the early stage. And in the following booting stage, heading and flowering stage, milk stage and yellow ripe stage, no-water layer management increase the soil oxidation-reduction potential, which destroys the anaerobic environment for methane production. Thus, the production of CH₄ was inhibited, which resulted in the low level of methane emissions in the middle and late growth of rice, so that the total CH₄ emissions decreased in the whole growth period. In this experiment, the seasonal changes characteristics of CH₄ emission under two different irrigation modes are similar to the observations at Kunshan region of Jiangsu Province in China (Peng and Li, 2006), but the difference is that emission amount in growth season under flooding irrigation is significantly lower than their observations. It may be because the annual temperature in Heilongjiang is lower than other regions. The low soil temperature affected soil microbial activity and reduced the conversion rate of soil organic matter and nutrients, so that the production and emission of CH₄ was reduced.

3.2 DNDC model verification

The model verification aims to test the feasibility of DNDC model in simulating CH₄ emission from this rice field. By comparison of 26 simulation and observed values, verification results shown in Figures 3(a) and 3(b) indicated simulation results and observation ones were consistent well, except that the CH₄ emission peak simulation in controlled irrigation is slightly lagging behind. T-test (Chatfield, 1983) is adopted to verify the conformity of DNDC simulation. Before t-test, the difference between the observed value and the simulation value must obtained first, and the normal test of the difference should be carried out by using the PP diagram (Figure 2). Figures 2(a) and 2(b) described the frequency tracing points are all nearby the positive diagonal line of the square areas and are evenly distributed with slight fluctuation up and down. It shows that the difference between simulated value and measured value are all complied with normal distribution in the two different irrigation conditions. The average error of simulated value and observed value for water flooding irrigation was 0.121 kgCha⁻¹d⁻¹, \( t = 1.918, P = 0.067 > 0.05 \) and that for controlled irrigation was 0.041 kgCha⁻¹d⁻¹, \( t = 2.049, P = 0.052 > 0.05 \); the two treatments were not significant at \( \alpha = 0.05 \) level. Statistics analysis results further showed that DNDC model is reliable in simulation of CH₄ emission of black soil rice field in growing season of cold region and can be applied to rice field CH₄ assessment in regional scale.
Figure 2  PP diagram of normal distribution test for the difference between simulated value and measured value

Figure 3  Comparison of CH$_4$ simulated value and observed value of rice field in different irrigation modes, (a) flooding irrigation (b) controlled irrigation
3.3 Rice field CH₄ emission factor sensitivity analysis

Sensitivity analysis for the model is to find sensitive factors that have important influence on rice filed CH₄ emission among numerous uncertain factors and meanwhile, analyse and measure influence degree or sensitivity degree of this factor on target results. In light of research results of Cai (1999) and Peng et al. (1998), eight variables describing soil property, climatic factors and farmland management are selected as the testing parameters for sensitivity analysis in this study, which are soil texture, soil SOC content, soil PH value, annual average temperature, annual rainfall, straw returning rate, application quantities of nitrogen fertilisers and water layer depth. The basic scene (background value) is established by climate, soil environment and agricultural management measures in the test point and the substitute scene (testing value) is established by replacing one testing parameter value while keep all the other parameters in the basic scene. In Table 2, to compare these simulation results, sensitivity indexes can be used to judge influence degree of these factors on the model output results. The sensitivity indexes are defined as equation (2) (Walker et al., 2000).

\[
S = \left( \frac{O_2 - O_1}{O_{avg}} \right) \left( \frac{I_2 - I_1}{I_{avg}} \right)
\]

where S is relative sensitivity indexes; I₁ and I₂ are the minimum value and maximum value of input parameters respectively; I_{avg} is the average of I₁ and I₂; O₁ and O₂ are the output value corresponding to I₁ and I₂ model. O_{avg} is the average of O₁ and O₂. The higher the absolute value of S is, the more significant the influence of the input factor on simulation results. Negative value means that the input parameter and the simulation result are in ‘inverse relations’.

**Table 2** Parameter setting for sensitivity analysis and sensibility index (S) affecting CH₄ flux

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Background value</th>
<th>Testing value</th>
<th>Sensibility index (S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil texture</td>
<td>Clay loam</td>
<td>Sandy soil, loam, sandy clay soil, clay</td>
<td>–1.3097</td>
</tr>
<tr>
<td>SOC content in soil (%)</td>
<td>2.53</td>
<td>1.518, 2.024, 3.036, 3.542</td>
<td>0.6308</td>
</tr>
<tr>
<td>PH value in soil</td>
<td>6.05</td>
<td>5, 7, 8</td>
<td>0.2325</td>
</tr>
<tr>
<td>Annual average temperature (°C)</td>
<td>1.69°C</td>
<td>Reduced by 2°C and 4°C, increased by 2°C and 4°C</td>
<td>0.1243</td>
</tr>
<tr>
<td>Annual rainfall (cm)</td>
<td>57.7</td>
<td>Reduced by 10% and 20%, increased by 10% and 20%</td>
<td>–0.0407</td>
</tr>
<tr>
<td>Water layer depth (cm)</td>
<td>10</td>
<td>0, 2, 5, 10</td>
<td>0.3256</td>
</tr>
<tr>
<td>Application quantities of nitrogen fertilisers (kg N ha⁻¹ y⁻¹)</td>
<td>150</td>
<td>100, 180, 200</td>
<td>–0.1429</td>
</tr>
<tr>
<td>Straw returning rate (%)</td>
<td>0.2</td>
<td>0, 0.5, 0.9</td>
<td>0.0044</td>
</tr>
</tbody>
</table>

Results of sensitivity analysis show that soil property was the key factor influencing CH₄ emission flux of black soil rice field in cold region; soil texture was most sensitive with a sensitivity index of –1.3097, which means CH₄ emission from clay soil was remarkably lower than loam and sandy soil; CH₄ emission rose with increase of SOC content and PH
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value in soil but PH value sensitivity in soil was low. The reason was that soil texture determines soil permeability and decomposition rate of soil organic matter to affect soil oxidation-reduction potential and substrate supply for producing CH\textsubscript{4} microorganism, which will further affect CH\textsubscript{4} emission. Higher SOC content may improve decomposition rate of soil organic matter to increase DOC concentration to induce the methyl in the wet soil to produce more CH\textsubscript{4} (Li, 2007). Among metrological factors, temperature had the most sensitive on rice field CH\textsubscript{4} emission. Higher temperature may increase soil temperature and improve soil microbial activity to promote rice growth and therefore impel production and emission of rice field CH\textsubscript{4}. Rainfall on black soil rice field in cold region is negligible compared with irrigations for the influence on CH\textsubscript{4} emission. According to sensitivity analysis of farmland management mode, water layer depth was the most sensitive factor and CH\textsubscript{4} emission rose with the increase of water depth in the rice field. This conclusion is consistent with Ren and Wang’s (2002) research result. This result means water management of rice field is economical and feasible method to reduce the CH\textsubscript{4} emission. This result means water management of rice field may become the economical and feasible CH\textsubscript{4} emission reduction measure. The increase of total nitrogen fertilisers may suppress CH\textsubscript{4} to some extent and increase rice output (Zhu and Sun, 2013), but excessive fertilisers affect the severely the soil and ecological environment. The straw returning rate sensitivity index of 0.0044 means its influence on CH\textsubscript{4} emission on black soil rice field in cold region is insignificant.

4 Conclusions

CH\textsubscript{4} emission of black soil rice field in growing season of cold region shows significant difference in different irrigation modes. Two CH\textsubscript{4} emission peaks of flooding irrigation rice field all appear in the middle tillering stage and emission drops gradually from the late tillering stage but remains at a high level in jointing stage. Then CH\textsubscript{4} emission falls to a very low level in milk stage and yellow ripe stage. Two CH\textsubscript{4} emission peaks of controlled irrigation rice field appear in the early and middle tillering stages respectively, and 14 days and seven days earlier than those of flooding irrigation. Then CH\textsubscript{4} emission flux quickly decreases to a very low level from the jointing stage. The total CH\textsubscript{4} emission amount in growing season of controlled irrigation rice field is 3.52 g m\textsuperscript{-2}, 47% lower than 6.64 g m\textsuperscript{-2} of flooding irrigation. Controlled irrigation may guarantee rice output and reduce CH\textsubscript{4} emission to form an economical and effective irrigation mode. Therefore, the quantitative research between irrigation quota, fertiliser and methane emissions amount will become a study emphasis in further research. The accurate estimation of methane emission from the global rice field depends on the quantitative relationship between these factors and methane emissions from rice field.

DNDC model verification results show peak in controlled irrigation model appears slightly later than the observed value, so the model parameters need to be further adjusted. DNDC model may simulate CH\textsubscript{4} emission of rice field under different natural conditions and cultivation methods, which is a powerful tool for assessing CH\textsubscript{4} emission quantities of black soil rice fields in cold region. Sensitivity analysis results show that soil texture, SOC content in soil, temperature, water layer depth and total quantities of nitrogen fertilisers have significant effect on the CH\textsubscript{4} emission of black soil rice fields in cold region. However, considering the complexity and operability of the method of
greenhouse gas reduction, the current methods of reducing emissions are mainly concentrated in the management of water and fertiliser and other fields. When the water layer depth is in range of 0~10 cm, CH$_4$ emission in the rice field rise with increase of water layer depth. This means water-saving irrigation is an effective method to control CH$_4$ emission in rice fields. Increase of nitrogen fertiliser application may also suppress CH$_4$ emission and increase output, but its sensitivity is less than that of water layer depth. And influence of long-term fertilisation on soil and ecological environment and that on N$_2$O in rice field need to be further studied.

References

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