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Discussions

Quantifying methane emissions from rice paddies in Northeast China by integrating remote sensing mapping with a biogeochemical model

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Abstract

The Sanjiang Plain located in Northeastern China is one of the major rice producing regions in the country. However, differing from the majority rice regions in Southern China, the Sanjinag Plain possesses a much cooler weather. Could the rice paddies in this domain be an important source of global methane? To answer this question, we calculated methane (CH_4) emissions from the region by integrating remote sensing mapping with a process-based biogeochemistry model, Denitrification and Decomposition or DNDC. To quantify regional CH_4 emissions from the plain, we first tested the model against a two-year dataset of CH_4 fluxes measured at a typical rice field within the domian. A sensitivity test was conducted to find out the most sensitive factors affecting CH_4 emissions in the region. Based on the understanding gained from the validation and sensitivity tests, a geographic information system (GIS) database was constructed to hold the spatially differentiated input information to drive DNDC for its regional simulations. The GIS database included a rice map derived from the Landsat TM images, which provided crucial information about the spatial distribution of the rice fields within the domain of 10.93 million hectares. The modeled results showed that the total 1.44 million ha of rice paddies in the plain emitted 0.43–0.58 Tg CH_4-C per year with spatially differentiated annual emission rates ranging between 100–800 kg CH_4-C/ha, which are comparable with that observed in Southern China. The modeled data indicated that the high SOC contents, long crop season and high rice biomass enhanced CH_4 production in the cool paddies. The modeled results proved that the northern wetland agroecosystems could make important contributions to global greenhouse gas inventory.

1 Introduction

Among all of atmospheric components, methane (CH_4) is a major greenhouse gases (GHG). According to the Intergovernmental Panel on Climate Change (IPCC), the warming forces of CH_4 are 25–30 times higher than that of CO_2 per unit of weight based on 100-yr global warming potentials (IPCC, 2007). Although there is a significant declining trend in the rate of CH_4 increase over the last two decades (Dlugokencky et al., 1998), atmospheric CH_4 concentrations have risen to 1774 ppb in 2005, which is more than doubled over the past 300 years (Blake and Rowland, 1998; Etheridge et al., 1992; IPCC, 2007). Agricultural activities are responsible for approximately 50% of global atmospheric inputs of CH_4 (Scheehle and Kruger, 2006; USEPA, 2006), wherein the rice paddies have been identified as a major sources of atmospheric CH_4. Over 10% of atmospheric CH_4 was attributed to the emissions from global rice paddies (Neue, 1993; Scheehle and Kruger, 2006; USEPA, 2006). In the perspective of GHG mitigation, it also becomes a potential opportunity through reducing CH_4 emissions from paddy fields (Oenema et al., 2001; Cole et al., 1996). Therefore, accurately estimating CH_4 emissions from rice paddies has become evidently important for GHG inventory or mitigation at country or regional levels.

China is an important rice producing country, which possesses approximately 20% of the world's rice paddies and produces 31% of the world's rice (FAO, 2004). The 30 million ha of paddy rice cropland accounting for 23% of all cultivated land in China (Frolking et al., 2002) is a large CH_4 source. To estimate the national inventory of CH_4 emission, researchers have conducted field campaigns in the major rice producing areas in Southern and Southeast of China (Cai et al., 1999, 2000). Results indicated high fluxes and spatial variations of CH_4 emitted from the tested rice areas (Van Bodegom and Scholten, 2001; Verburg and Van Der Gon, 2001; Khalil et al., 1991; Yao et al., 1996; Cai et al., 2000). Attempts have been made to explain the regional variations of CH_4 emissions although no concrete conclusions about the main controlling factors (Yao and Chen, 1994; Kern et al., 1997). Although traditional site-specific observation techniques like automatic closed chamber method have been recently improved for measuring CH_4 emission at site scale, the regional or global estimation still remains as a question due to the lack of reliable methodologies (Verburg et al., 2006). Consequently, demands are arising for new methods such as model simulations to extrapolate the understandings gained at site scale to a large spatial dimension.

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During the past two decades, many empirical and physical models have been developed to predict GHG emissions from rice fields. In a number of empirical models, the regression relationships between CH_4 emission rate and rice biomass or yield were used to estimate CH_4 production (Sinha, 1995; Kern et al., 1997; Anastasi et al., 1992). Although these empirical approaches were easy to use, the accuracy and precision of estimated results could not be ensured, and the variation in emissions at regional scale also couldn't be explained reasonably. Since many biogeochemical processes are involved in CH_4 production, oxidation and emission, it would be difficult to predict the gas fluxes with over-simplified equations across a wide range of soil conditions and management practices. To meet the gaps, process-based biogeochemical models were developed to incorporate the comprehensive biogeochemical reactions and their environmental drivers. The major models that are able to simulate CH_4 production include MEM (Cao et al., 1995b), MERES (Matthews et al., 2000), InfoCrop (Aggarwal et al., 2004), DNDC (Li et al., 1992a) and so on. In recent years, these models played an important role in describing CH_4 production and oxidation process in paddies and estimating the CH_4 emissions at regional or global scales (Cao et al., 1995a, 1996; Bachelet and Neue, 1993; Li et al., 2004; Pathak et al., 2005; Zhang et al., 2009a). Among the candidate models, DNDC has been tested for the rice paddies in China and other Asian countries. We adopted DNDC in the study to implement the upscaling.

The denitrification and decomposition (DNDC) model is a generic model that simulates the biogeochemical processes leading to greenhouse gas emissions from soil. It is originally developed to model N_2O emissions and SOC levels in the US cropping systems (Li et al., 1992a,b, 1994), it has subsequently been adapted to model simulations of GHG emissions from a wide range of systems such like crop, pasture, rice paddy, and forest systems in a number of countries across the world (see a summary by Giltrap et al., 2010). As a process-based biogeochemical model, DNDC is able to track carbon (C) and nitrogen (N) cycles in agroecosystems driven by both the environmental factors and management practices. The DNDC has been tested against observed CO_2, N_2O or CH_4 fluxes from rice fields, and continuously improved based on comments or suggestions from a wide range of researchers worldwide during the past about 20 years (Zhang et al., 2002; Li et al., 2002, 2004; Cai et al., 2003). Calibration and validation of the model were performed for the US, China, Thailand, India, Japan and Italy with satisfactory results (Zheng et al., 1997; Li et al., 2002; Cai et al., 2003; Babu et al., 2005, 2006). Recently, Pathak et al. (2005) applied the DNDC model to estimate total GHG emissions from Indian rice paddies based on agricultural census data. And also, Zhang et al. (2009a) quantified CH_4 emissions from rice fields in the Taihu Lake region in China using DNDC. These studies proved that DNDC is applicable for estimating CH_4 emissions from rice paddies at regional scale.

In the study reported in the paper, we decided to take a new step to advance the DNDC regional applications. Remote sensing technology is capable of providing spatially explicit information of land surface in time. Remote sensing analysis could provide more accurate rice field area data to supplement the census data which are often inadequate or problematic. In fact, many researchers have utilized remotely sensed data (optical or microwave) for mapping the extent of paddy rice at local or regional scale (Frolking et al., 2002; Xiao et al., 2005; Le Toan et al., 1997; Ribbes and Le Toan, 1999; Zhang et al., 2009b). DNDC has been discussed for upsacling in add of the remote sensing technique to compile greenhouse gas inventories, identify spatial patterns in emission, or explore scenarios for mitigation (Takeuchi et al., 2001; Salas et al., 2007).

Except the introduction of remote sensing analysis into the DNDC upscaling, we selected a northern paddy rice domain in China, which possesses climate, soil and management conditions differing from that in the tropical or subtropical rice regions, which have been studied by other researchers.

2 Method

2.1 Study area

As target domain of this study, the Sanjiang Plain is located in Northeast China. “Sanjiang” in Chinese means “Three Rivers”, which represent Songhuajiang River, Wusulijiang River and Heilongjiang River, three major rivers whose watersheds cover almost the entire territory (10.93 million hectares) of the eastern part of Heilongjiang Province (48.5°–43.8° N and 129.2°–135.1° E) (Fig. 1). This region lies at 45 m to 60 m geographic elevation above sea level with a gentle and flat topographic relief. Annual precipitation ranged from 310 to 750 mm during the period of 1980–2009. The local soils are fertile rich in soil organic matter. The flat topography, abundant precipitation and fertile soils have made the alluvial plain favorable for agricultural cultivation. In the 1970s reclamation campaigns were launched by the Chinese authorities to convert the natural swamplands into farmlands. Since then, the region has experienced drastic changes in the land use. For example, the rice fields have increased from zero to 1.44 million ha during the past about 40 years. The rice fields are the rice-producing region with the highest latitude in not only China but also the world.

The rice is planted as a single-season crop in the region. Continuously flooding is extensively practiced in the rice fields. Urea and synthetic fertilizer are dominatingly applied without any organic matter amended. The rice straw is normally left as stubble in the fields after harvest in October, and the stubble is incorporated into the soils with tillage before the beginning of the next rice season.

2.2 Model validation tests

To validate the DNDC model for its applicability for the rice fields in the Sanjiang Plain, field experiments were conducted at a paddy rice site in the Honghe Farm (at 47°35′ N and 133°31′ E) within the plain (Fig. 1). Two-year (2004 and 2006) experiments were conducted in a same paddy field with three treatments. In 2004, the field was treated with two fertilizer application rates, i.e., 60 and 150 kg N/ha (C04-N60 and C04-N150); in 2006, only one application rate, 150 kg N/ha (C06-N150), was applied. For C04-N60, the 60 kg N of synthetic fertilizer was split into two applications at the rice transplanting (24 kg N/ha) and in the tillering stage (36 kg N/ha). The same split method was also applied for the rate of 150 kg N/ha (Table 2). CH_4 fluxes were measured with chamber method (0.5 m × 0.5 m) with automated opening and closure. The CH_4 measurements were conducted twice per week through the whole rice-growing period (from late May to early October) (see details in Wang et al., 2008). The measured data of CH_4 fluxes were used to calibrate/validate the DNDC model. Daily meteorological data (air temperature and precipitation) were acquired from the local climate station, a part of the Ecological Experimental Station of Mire-Wetland in the Sanjiang Plain run by the Chinese Academy of Science. Soil properties were obtained from the ground-based measurements, and agricultural management information was collected based on the local farming practices (see details in Tables 2 and 3).

DNDC simulates CH_4 production mainly based on four factors, i.e., the soil redox potential (Eh), soil C sources (DOC and CO_2) available for the methanogens, soil temperature, and CH_4 diffusion rate which is controlled by the plant conductivity (aerenchyma) and soil texture (Li, 2000). Among the factors, plant (i.e., rice) growth plays a key role in determining the soil C availability. So, the parameters defining the rice growth in DNDC were first calibrated against observed crop biomass/yield data. Using the turn-and-adjust method, we obtained a set of physiological and phenology parameters for the rice cultivar (Kongyu-131) which was widely planted in the Sanjiang Plain. The calibrated crop parameters are listed in Table 4. With the crop parameters, DNDC correctly simulated the crop biomass growth and yield and hence set a sound basis to quantify the root exudation and respiration, which provided DOC and CO_2 to the soil methanogens.

For the model validation, the local climate, soil and farming management data were utilized to compose input scenarios, which were used to run DNDC for the experimental site. The measured CH_4 flux data were used to compare with the modeled CH_4 fluxes at daily time step as well as for the seasonal total emissions. Statistical tools such as the root mean square error (RMSE), the coefficient of model efficiency (EF) and the coefficient of model determination (CD) were adopted to assess the “goodness of fit” of model predictions (see details in Smith et al., 1997).

The measured CH_4 fluxes at the three treatments, C04-N60, C04-N150 and C06-N150, were compared with modeled results. Figure 2 shows the comparisons between the modeled CH_4 fluxes with observations. As a whole, the modeled results showed a fair agreement with observations although minor discrepancies exist across the three treatments (Fig. 2a1, b1, c1). Regression analysis demonstrated that the simulated emissions explained over 85% of the variation in observed emissions for all the three cases. The intercept of three regression lines is very closer to 0 at the 0.05 confidence level. The RMSE values for the three cases are 0.190, 0.304 and 0.344 for C04-N60, C04-N150 and C06-N150, respectively (Fig. 2a2, b2, c2). All three EF are positive (>0.8), and three CD are greater than 1 (Table 5). The results indicated that DNDC is capable of capturing the seasonal patterns as well as the magnitudes of CH_4 emissions from the experimental site in the Sanjinag Plain.

2.3 Model sensitivity test

Methane emissions from rice fields are controlled by many factors (Yan et al., 2005). However, some factors could be more sensitive than others. A sensitivity test was conducted with DNDC to find out the most sensitive factors for CH_4 emissions from the Sanjiang Plain. The baseline scenario was set based on the actual climate, soil and management conditions at the experimental site in the Sanjiang Plain. In the test, we varied climate variables (temperature or percipitation), soil properties (SOC content, clay fraction, pH and bulk density), or agricultural management practices (flooding regime, residue management and N-fertilizer application rate). The sensitivity test was conducted by varying a single input parameter in a predefined range while keeping all other input parameters constant. All the parameters for sensitivity analysis were listed in Table 3. The model responses to changes of these factors on CH_4 emissions were presented respectively in Fig. 3.

The likely response of CH_4 emission to changes in climate was investigated by running DNDC using alternative climate scenarios. Precipitation was either increased or decreased by 20% of the baseline value (~560 mm/year); and temperature was varied by 1 or 2 °C. The modeled results indicated that (1) the precipitation changes had was insignificant or negligible impact on CH_4 emissions (Fig. 3a), and (2) the higher temperature elevated CH_4 emissions due to the accelerated soil organic matter (SOM) decomposition and fermentation process (Fig. 3b). The results are in agreement with previous studies reported by other researchers (e.g., Cao et al., 1998).

Four soil properties (SOC content, clay fraction, pH and bulk density) were investigated in the sensitivity test. The results showed that (1) soil texture was the most sensitive factor due to its effects on the soil anaerobic status: the clay loam soil was more likely to produce more CH_4 than the sandy soil (Fig. 3c), and (2) SOC content was the second most sensitive factor due its effects on the soil DOC availability as well as the methanogen population (Fig. 3f). The modeled results in line with observations reported by other researchers (Yagi and Minami, 1990; Wassmann et al., 1998; Holzapfel-Pschorn and Seiler, 1986; Li et al., 2004).

In rice paddy, flooding regime, residue management and application rate of N-fertilizer are three major anthropogenic activities affecting not only rice productivity but also GHG emissions. Figure 3 shows that when the draining time duration for the mid-season drainage increased to 10 days, the CH_4 emission was reduced by 25% (Fig. 3g). This trend has been reported in many studies (Sass et al., 1992; Yagi et al., 1996; Li et al., 2006). In the test, crop straw incorporation didn't show strong effect on CH_4 emission. The modeled results indicated that in the one-year simulation, the straw was incorporated at the end of the rice season when the soil was drained already (Fig. 3h). The variation in fertilizer application rate didn't show strong impact on CH_4 emission either (Fig. 3i).

The sensitivity test provided crucial information for regional simulations as we learnt which input parameters could most sensitively affect the modeled results and hence should be paid with the greatest considerations.

2.4 Regional database

A geographic information system (GIS) database was constructed to hold all the input information required for upscaling DNDC simulations to the Sanjinag Plain. The database included a rice field map, soil properties, daily weather data, and farming management practices. The rice map was obtained through remote sensing analysis.

To estimate the CH_4 emissions from the target domain, it is necessary to acquire detailed and accurate spatial distribution of paddies. Remotely sensed data were often classified to map the spatial pattern of rice paddies and calculate the rice areas. In this study the Landsat thematic mapper (TM) imagery acquired from the EarthExplorer Interface (http://edcsns17.cr.usgs.gov/EarthExplorer/) were processed to extract the spatial distribution of rice paddies in the Sanjiang Plain (Table 1). Total of 9 clear TM images covering the target domain acquired in the near-maturing stage of rice in 2006 were selected to extract a single class paddy rice with elaborately image preprocessing such as mosaicking, subsetting and geometric correction at stepwise. Visual interpretation was applied for ensuring accurate delineation of rice paddies at the processing software environment of ArcGIS 9.0, although time-expensive. The vectorized rice paddy polygons then were segmented by soil data with cell size of 10 km × 10 km. Within each cell, rice area was calculated for estimating CH_4 emissions seasonally conducted in following sections. Due to the clear weather conditions and the distinguished phenology features, the rice fields were successfully extracted from remote sensing data. The formed rice map had a high spatial resolution of 30 m. The data set provided a sound basis for delineating the rice paddies in the study region with a high accuracy and a high precision.

Daily climate data (maximum and minimum air temperature, precipitation and mean wind speed) were acquired for 2004 and 2006 from seven weather stations (China

Meteorological Data Sharing Service System at http://data.cma.gov.cn/) within the target domain. Soil data were derived from the soil dataset developed by the Institute of Soil Science, Chinese Academy of Sciences, which was compiled based on the second national soil survey conducted in 1980–1990s. The soil dataset contains multi-layer soil properties (e.g. organic matter, pH and bulk density), soil texture (sand, silt and clay) and other spatial information (Shi et al., 2004; Yu et al., 2007) with a resolution of 10 km × 10 km. In this study, we adopted the top (0–10 cm) soil data derived from 805 paddy profiles within the domain to serve the DNDC simulations. Detailed management practices on rice cultivation were investigated by communicating with a number of local agronomists and farmers. All the spatially differentiated input information was composed in the GIS database, which was then linked to DNDC through the DNDC's regional mode interface.

DNDC was run for the Sanjiang Plain twice with 2004 and 2006 climate data, respectively. During the model runs, DNDC performed simulation for each grid cell twice with the maximum and minimum values of the soil properties, respectively. The two simulations produced a pair of CH_4 fluxes for each grad cell, which formed a range of CH_4 emission that was later used for quantifying the uncertainty generated from the upscaling (please refer Li et al., 2004 for details of the Most Sensitive Factor method). Based on the modeled CH_4 emission rate and the rice field acreage for each grid cell, the total CH_4 emissions from the cell could be calculated. The regional emission was calculated by summing up the CH_4 emissions from all the grid cells within the domain. The Sanjiang Plain contains 23 counties; the county-level CH_4 emissions were also calculated for evaluating the spatial patterns of CH_4 emissions in the plain.

3 Results

With visual interpretation technique, the rice paddy cover in the domain in 2006 was mapped based on 9 clear TM images (Fig. 1). The rice paddies were mainly distributed in the lowland areas along with the major rivers. The total area of paddy fields was 1.44

million ha in 2006, which was approximately 35% higher than that in 2000. This result confirmed the census reports that rice paddies rapidly increased in the Sanjiang Plain in the years. Driven by the market demand for high quality rice in China, more upland croplands planted with corn or soybeans were converted to wetland crops (mainly rice) in Northern China during the past decade. This kind of rapid land-use transformation could alter the national GHG inventory now and in the near future. Mapping the new land-use as well as the consequent GHG emissions should be an urgent task for the researchers.

Linked to the GIS database, DNDC was run across the entire 1.44 million ha of rice fields in the Sanjiang Plain. The modeled results were summed up to produce regional CH_4 emissions. The spatial and temporary patterns of CH_4 emissions in the domain are discussed as follows.

Results from the regional simulations indicated that the total CH_4 emissions from the Sanjiang Plain ranged from 0.43 to 0.58 (or 0.51 ± 0.07) Tg CH_4-C/year. Figure 4 show CH_4 emission rates and total emissions at the grid-cell scale. The two maps showed clear spatial variations in CH_4 emissions across the domain region. The emission rates varied between <40 and >900 kg CH_4-C/ha mainly driven by the spatial variation in the soil properties (Fig. 4a; Table 6). The regional average was around 400 kg CH_4-C/ha/year, which was higher than that (15–198 kg CH_4-C/ha/year) observed in the Southeast China such as Taihu Lake region (Zhang et al., 2009a) and also higher than the default emission factors of 200 kg CH_4/ha/season suggested by the IPCC guidelines (IPCC, 1997). The simulated data attributed the high CH_4 emission rates to the SOC rice soils (averagely 0.31 kg C/kg soil) in combination with the continuous flooding management in the Sanjiang Plain. Following the SOC content trend, the modeled CH_4 emission rates gradually decreased from the southwest to the northeast of the region. The maximum CH_4 emission rates (about 930 kg CH_4-C/ha) were shown in five grid cells in the southwestern part of the domain apparently related to the higher SOC contents in the region (Table 6). Differing from the CH_4 emission rate, the total CH_4 emission flux for each grid cell was not only related to the emission rate but also the total rice area. In general, the mid-northern and southeastern parts of the Sanjiang Plain had more expansive rice paddies and hence possessed higher CH_4 emissions (Fig. 4b). The regional simulations indicated that the change in fertilizer application rate did not affect the regional CH_4 emissions very much although it did increased the crop yields that could indirectly enhanced the CH_4 production. The regional CH_4 emissions were 0.49 and 0.53 Tg CH_4-C/year for 2004 and 2006, respectively (Table 6). The 10% difference was apparently related to the climate data of the two years. By comparing the daily mean temperatures during the rice-growing seasons in 2004 and 2006, we found the average temperature in the 2006 growing season was 0.26 °C higher that that in 2004.

The Sanjiang Plain contains 23 administrative counties. The county-level CH_4 emissions are shown in Fig. 5. The high emission counties such as Fujin (FJ), Huachuan (HC) and Hulin (HL) are located either in mid-northern or southeastern parts of the domain. In contrast, the low emission counties such as Shuangyashan (SYS), Youyi (YY), Qitaihe (QTH), Jixi (JX), Muling (ML) and Hegang (HG) are located in either the central-southern or the northwestern areas of the plain (Fig. 5a–c). The highest CH_4 emission (>150 000 t CH_4-C) was in the HC and HL Counties, and the lowest (<4000 t CH_4-C) was in the ML County. Statistic results showed that the highest emission county emitted over 40 times higher than the lowest one per season (Fig. 5d). Such a huge difference in CH_4 emission was due to the variations in the total paddy cultivation acreage as well as the CH_4 emission rate determined by the soil properties (e.g. SOC content, clay fraction in soil, etc.).

4 Discussions

The Sanjiang Plain possesses 1.44 million ha of paddy rice in the very northeastern part of China where the annual mean temperature is 2.2 °C, which is 10–15°C lower than that in the majority rice producing areas in the southeastern or southwestern part of the country. DNDC was first utilized to estimate CH_4 emissions from this high latitude rice fields. After the calibration and validation against local observations, DNDC simulated CH_4 fluxes across the target domain. The modeled CH_4 emission rates varied in a range of 100–800 kg C/ha per year, which is consistent with the CH_4 emission rates observed or modeled in the southern rice regions in China. Our modeled results are supported by observations conducted in a number of high latitude wetlands where the researchers measured high fluxes of CH_4 from the cold, even frozen, wetland ecosystems. Our results confirmed the hypothesis that the high latitude wetlands could be an important CH_4 source maybe due to adaptation of the methanogens to the low temperatures.

In this study, we utilized a remote sensing-derived crop map to drive a process-based biogeochemistry model to realize the regional quantification. The uncertainty produced from the upscaling has been estimated with the Most Sensitive Factor method developed by Li and his colleagues (Li et al., 2004). By including the maximum and minimum values of the most sensitive factors (i.e., soil texture and SOC content) into the GIS database, DNDC calculated two CH_4 fluxes for each grid cell. The two extreme CH_4 fluxes formed a range, within which the "real" flux should be located with a high probability. With this methodology, we concluded that the regional CH_4 emission ranged between 0.43 and 0.58 Tg CH_4-C; i.e., the standard deviation was ±14%.

Studies on greenhouse gas inventory and mitigation in China were started relatively later in comparison with some other countries. However, the new research campaigns in the direction are being rapidly developed in the country during the recent years driven by the social and research demands. The results reported in the paper is one of the attempts to try to absorb the world advanced techniques such as biogeochemical models, remote sensing mapping, uncertainty analysis to serve the national environmental issues in China.

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Table 1. Remotely sensed imagery used for mapping rice paddy.

Sensor	Path/row no.	Acquisition date
Landsat TM	114/26	30 Aug 2006
	114/27	30 Aug 2006
	114/28	30 Aug 2006
	114/29	30 Aug 2006
	115/27	22 Sep 2006
	115/28	22 Sep 2006
	115/29	22 Sep 2006
	116/27	31 Aug 2006
	116/28	31 Aug 2006

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Table 2. Management information on the rice paddies at study sites in SJP of Northeast China.

Year	Date	Management practices	
2004	25 May–29 Sep	Rice cultivation	
	13 Jun	Fertilization: 1. Synthetic fertilizer (24 kg N/ha); 2. Urea+synthetic Fertilizer (60 kg N/ha)	Fraction of residues left in fields: 20%;
	28 Jun	Fertilization: 1. Synthetic fertilizer (36 kg N/ha); 2. Urea (90 kg N/ha)	
	15 May–23 Aug	Flooding: Continuously flooding, water depth of 5–10 cm	No manure application;
	15 May	Tillage: Plow depth of 30 cm	
2006	24 May–24 Sep	Rice cultivation	Nitrogen content of synthetic fertilizer is 15%
	24 May	Fertilization: Urea+synthetic fertilizer (60 kg N/ha)	
	2 July	Fertilization: Urea (90 kg N/ha)	
	14 May–28 Aug	Flooding: Continuously flooding, water depth of 5–10 cm	
	14 May	Tillage: Plow depth of 30 cm	

Table 3. Inputs used to test the DNDC model and baseline values for sensitivity tests in the validated sites of rice paddies.

	Environmental factors	Baseline value	Range tested
Climate	Annual mean temperature (°C)	2.4	0.4–4.4
	Total annual precipitation (mm)	560	448–672
Soil property	Clay fraction (%)	0.41	0.1–0.6
	Field capacity (%)	0.57	Not varied
	Wilting point (%)	0.27	Not varied
	Porosity (%)	0.59	Not varied
	Initial soil C fraction (kg C/kg soil)	0.0277	0.01–0.07
	Bulk density (g/cm^3)	0.98	0.8–1.6
	Soil pH	5.61	5.0–9.0
Management practices	Depth of continuous flooding water (cm)	10	Not varied
	Drained days (d)	0	2–12
	Fraction of rice residue left in field (%)	20	0–100
	N-Fertilizer application (kg N/ha)	60	60.0–150.0

Table 4. The calibrated crop parameters of rice for regional simulation of DNDC.

Crop parameters	Value
Total biomass (kg C/ha)	4383.8
Grain fraction of total biomass (%)	47.0
Shoot fraction of total biomass (%)	43.0
Root fraction of total biomass (%)	10.0
C/N ratio for plant	58.3
C/N ratio for grain	55.0
C/N ratio for shoot (leaf+stem)	60.0
C/N ratio for root	70.0
Water demand (g water/g dry matter)	508.0
Maximum leaf area index	6.0
Maximum height of plant (m)	1.0
Temperature degree days for maturity (TDD) (°C)	2300.0
N fixation index	1.0
Valscularity index (0–1)	1.0

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Table 5. Statistical analysis for comparison of the simulated and observed CH_4 fluxes (kg CH_4-C/ha/day) in three case studies.

Mode	Measurement number	Slope	Intercept	RMSE	EF	CD
C04-N60	24	0.908	0.058	0.190	0.870	1.058
C04-N150	24	0.826	0.056	0.304	0.837	1.227
C06-N150	35	0.903	−0.109	0.344	0.844	1.041

Table 6. Simulated results of CH_4 emissions from paddies of the SJP.

Mode		C04-N60	C04-N150	C06-N150
Emission rates (kg CH_4-C/ha)	Mean	381.241	386.931	416.482
	Maximum	926.368	927.04	943.88
	Minimum	32.295	32.228	38.587
Total emissions (Tg CH_4-C)	Mean	0.476	0.485	0.529
	Maximum	0.522	0.53	0.577
	Minimum	0.431	0.44	0.482

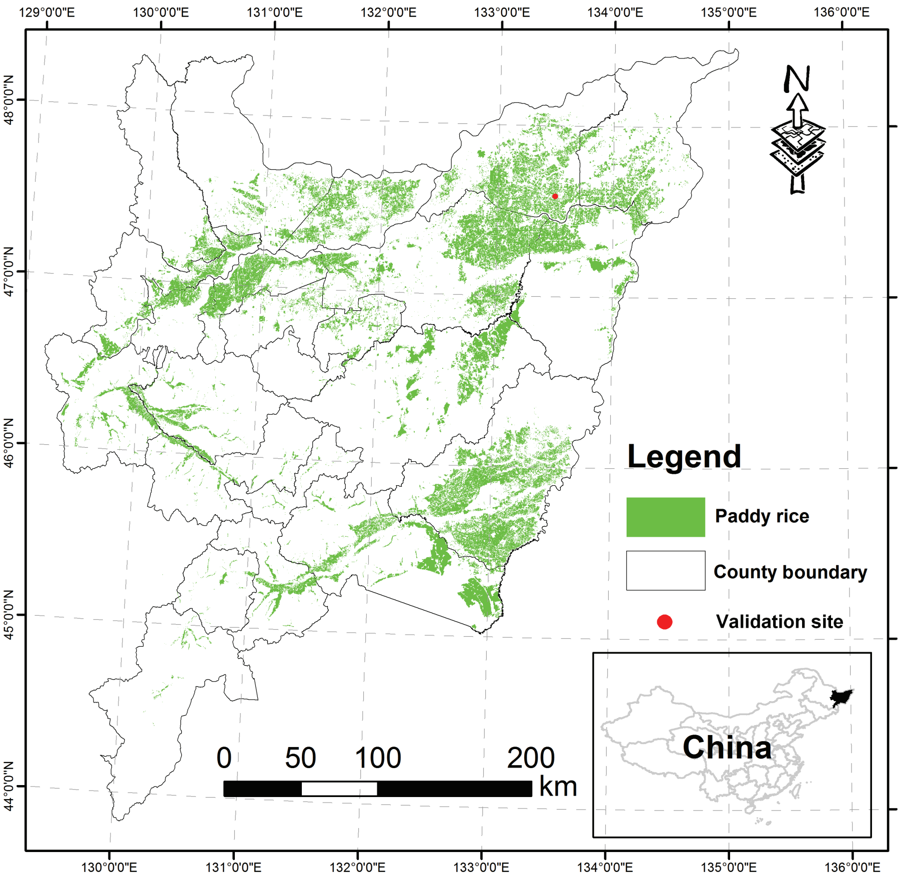

Fig. 1. Spatial distribution of paddy rice in the Sanjiang Plain in 2006.

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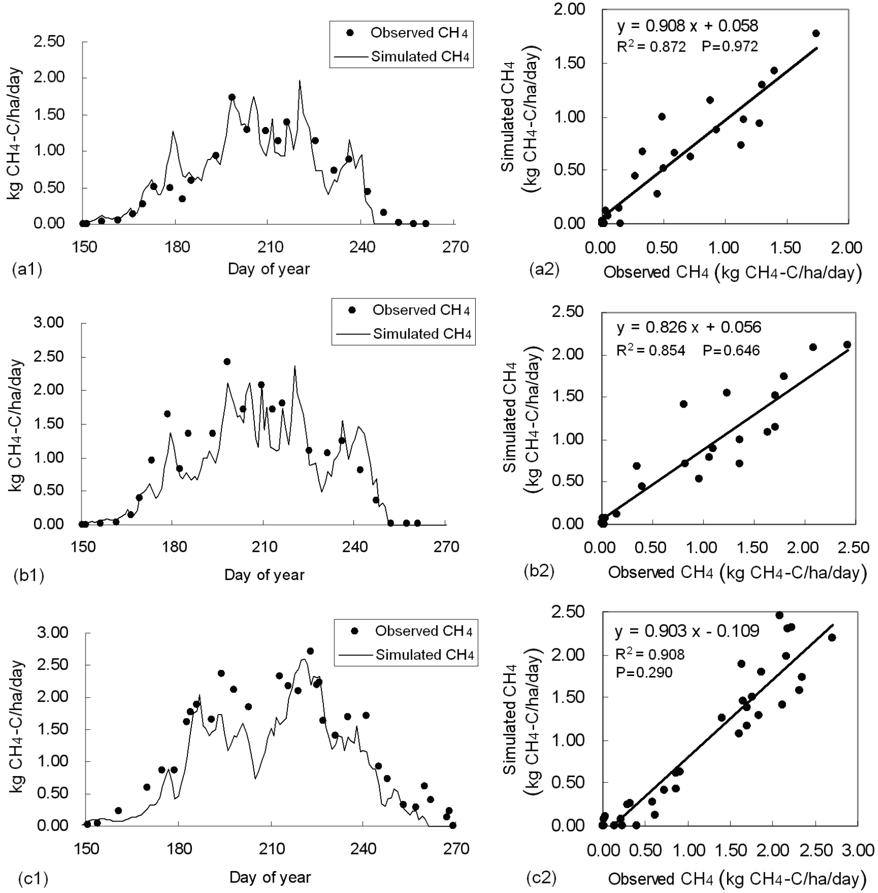

Fig. 2. Simulated vs. observed CH$_4$ fluxes in validation site with three N-fertilizer application scenarios: 60 N/ha (**a1** and **a2**) and 150 N/ha (**b1** and **b2**) in 2004, and 150 N/ha (**c1** and **c2**) in 2006, respectively.

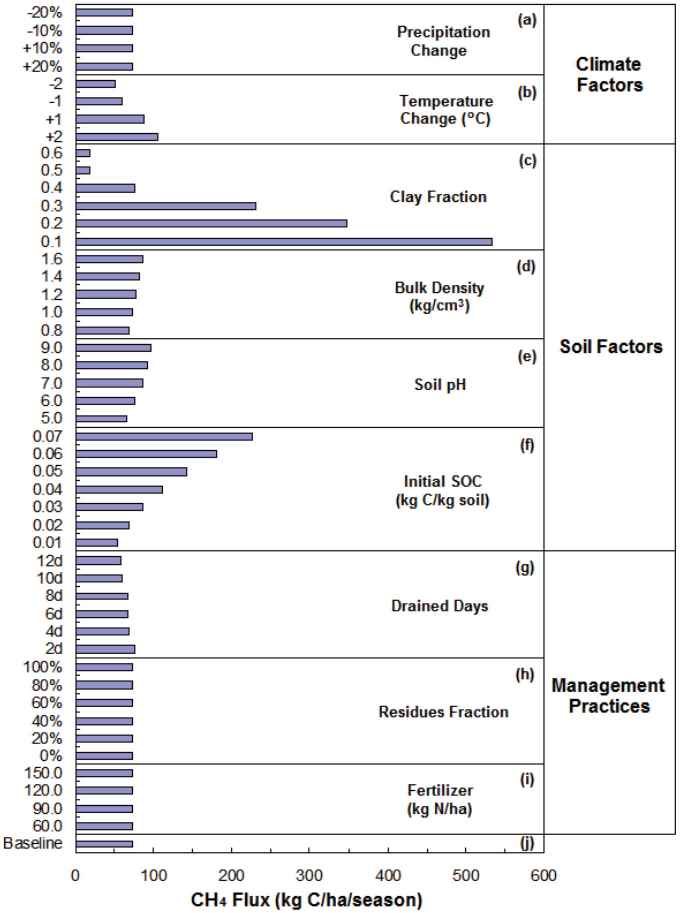

Fig. 3. Sensitivity tests of environment factors driving CH_4 emissions from rice paddies.

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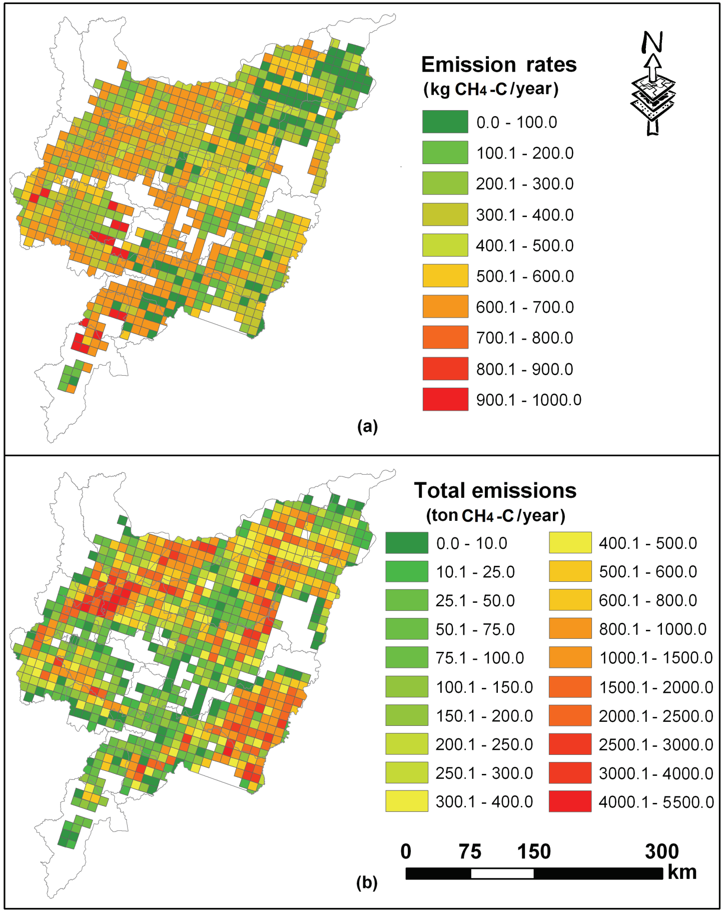

Fig. 4. Mean CH$_4$ emission rates **(a)** and total emissions **(b)** per year from paddy fields in the Sanjiang Plain at scale of 10 km×10 km grid-cell in 2006.

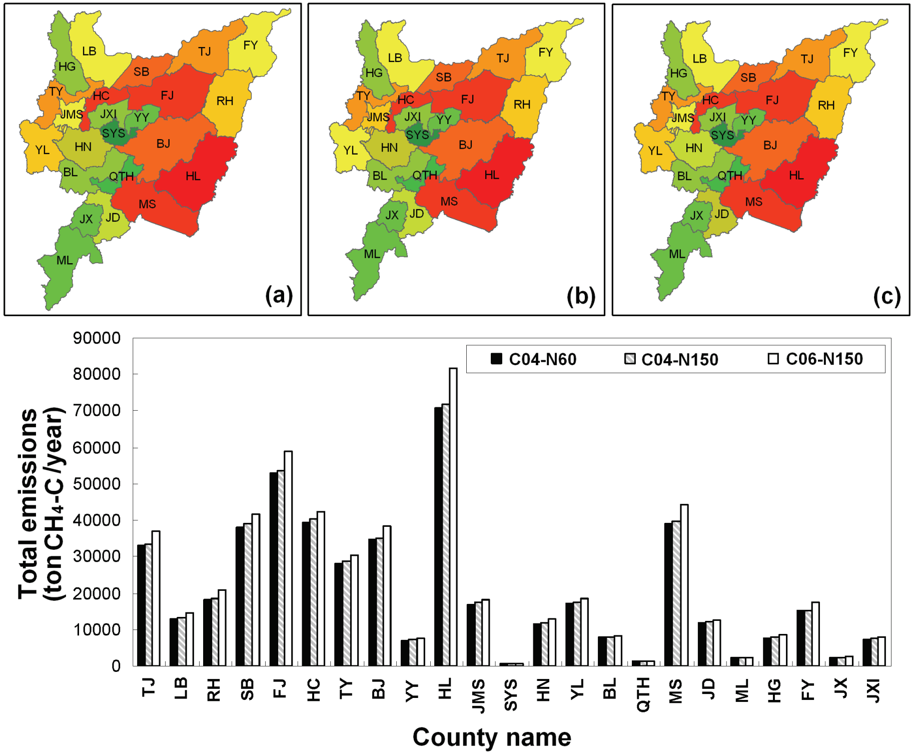

Fig. 5. Mean CH_4 emissions per year from rice paddies in the Sanjiang Plain at county-level scale in 2004 and 2006. Where, **(a)**, **(b)** and **(c)** denotes case study of C04-N60, C04N150 and C06N150, respectively.