

# Estimates of methane emissions from Chinese rice paddies by linking a model to GIS database

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**Abstract:** Methane is one of the principal greenhouse gases. Irrigated rice paddies are recognized as contributing to atmospheric methane concentration. Methane emissions from rice paddies are among the most uncertain estimates in rice-growing countries. Efforts have been made over the last decade to estimate CH<sub>4</sub> emissions from Chinese rice paddies via the model method. However, these estimates are very vague due to different models and upscaling methods. A reduction in these uncertainties may be achieved by coupling field-scale models with regional databases. The objective of this article is to develop a methodology of coupling a CH<sub>4</sub> emission model with regional databases by which CH<sub>4</sub> emissions from Chinese rice paddies can then be estimated. CH4MOD, a model for simulating CH<sub>4</sub> emissions from rice paddies with minimal input by using commonly available parameters, is of great potential in terms of upscaling as it has provided a realistic estimate of the observed results from various soils, climates and agricultural practices. By linking spatial databases to CH4MOD, CH<sub>4</sub> emissions from Chinese rice paddies in the 2000 rice-growing season were simulated on a day-by-day basis. The spatial databases were created by GIS with a spatial resolution of 10km×10km, including soil sand percentage, amounts of crop straw and roots from the previous season and farm manure, the water management pattern, dates of rice transplanting and harvesting, acreage of rice planted, rice grain yield and daily air temperature. ARCGIS software was used to meet all GIS needs, including data access, projection definition, overlaying of different vector layers, creation of grids (a raster format of ARCGIS software) by converting vector data, and the data conversion between grids and ASCII formats. Methane emissions from rice paddies in mainland China in the 2000 rice-growing season were estimated to be 6.02 Tg (1 Tg = 10<sup>9</sup> kg). Of the total, approximately 49% (2.93Tg) is emitted during the single rice-growing season, and 27% (1.63Tg) and 24% (1.46Tg) are from the early and late rice-growing seasons respectively. It was concluded that regional CH<sub>4</sub> emissions from rice paddies could be estimated by coupling CH4MOD with regional databases with a high spatial resolution. A further effort should be made to improve the quality of the spatial databases, especially in terms of the amount of added organic matter and the water regime. It is also necessary to evaluate the uncertainties of the present estimates in order to improve the overall accuracy.

**Key Words:** CH4MOD; GIS; model; rice paddy; methane

## 1 Introduction

Global warming caused by the increase of atmospheric greenhouse gases has become an issue of global concern. Methane is one of the principal greenhouse gases and its global warming potential is thought to be 23 times on a mass basis as that of CO<sub>2</sub> over a 100-year time horizon<sup>[1]</sup>. Irrigated rice paddies have been well recognized as contributing to atmospheric methane. The Intergovernmental Panel on Climate Change made great efforts to guide the practice in national greenhouse gas inventories. China has the world's second-lar-

gest area of rice paddies and the highest rice production, accounting for 22% of the world's rice area and 34% of the global rice grain production (FAO, <http://apps.fao.org>). Due to the role of rice paddies in the regional and/or global methane budget, a reliable estimate of methane emissions from Chinese rice paddies is of great significance in understanding the contribution that irrigated rice cultivation makes to the global methane pool.

Early efforts were made to estimate methane emissions from Chinese rice paddy soils by extrapolating field measurements to a national scale<sup>[2]</sup>. With growing knowledge of

methane production, oxidation and emissions, models have been developed to estimate regional and/or global methane emissions from rice fields<sup>[3]</sup>. Nevertheless, a wide range exists in the model estimates, mainly due to the models used and the methods of upscaling. By linking the statistical model to a soil map from the FAO, Bachelet *et al.*<sup>[4]</sup> estimated Chinese rice fields' methane emissions as 9.33–21.33 Tg a<sup>-1</sup>. Linking the MERES model to a soil database and rice-planted areas on a provincial scale, as well as daily climate up-scaled from 10 sites across China, produced estimates ranging from 3.35 to 8.64 Tg a<sup>-1</sup> under four scenarios of added organic matter and water regimes<sup>[5,6]</sup>. Li *et al.*<sup>[7]</sup> used their DNDC model on a county scale and estimated methane emissions from Chinese rice paddies as 8.53–16.00 Tg a<sup>-1</sup> under continuous flooding, and 2.27–10.53 Tg a<sup>-1</sup> under mid-season drainage.

The reliability of model estimates on a regional scale relies generally on two aspects: the validity of the model and the quality of the spatialized database for model input. Model validity should be characterized by its performance under various climates, soils and agricultural practices. With respect to the quality of the spatialized database, the quality of site scale datasets (e.g., rates of organic matter addition) used to upscale is essential. When upscaling is performed, the representative for each grid determines the quality of the spatialized database. With an understanding of the processes of methane production, oxidation and emissions, CH4MOD was developed and further modified to simulate methane emissions from rice fields<sup>[8,9]</sup>. Model validation based on 94 independent observations demonstrated that CH4MOD is capable of simulating CH<sub>4</sub> emissions from irrigated rice fields with a minimal amount of inputs and parameters, thus showing great potential in terms of upscaling as it has provided a realistic estimate of the observed results from various soils, climates and agricultural practices<sup>[9]</sup>. GIS is a principal technology for acquiring, processing, analyzing, managing and mapping spatial datasets, which provides an ideal tool to upscale CH4MOD. The objective of this article is to develop a methodology of linking CH4MOD to spatialized databases via GIS by which CH<sub>4</sub> emissions from Chinese rice paddies can then be estimated.

## 2 Methodology

### 2.1 Integration of CH4MOD with GIS

CH4MOD consists of two modules including the derivation of methanogenic substrates and the processes of methane production and emissions. The former simulates methanogenic substrates which are primarily derived from rice root exudation and added organic matter such as crop residues and manure. The latter simulates the rates of methane production regulated by the availability of methanogenic substrates and the rates of emissions via rice plants and bubbles. The processes involved in methane production and emissions are regulated by plant growth and environmental factors. Key factors

controlling these processes are soil texture, temperature and redox potential<sup>[9]</sup>.

Upscaling a model to a national scale was usually fulfilled by adopting the administrative area of provinces or counties as a basic cell<sup>[6,7]</sup>. A disadvantage of this approach is the different size of each administrative cell. For example, the acreage of China's largest province is about 100 times that of the smallest province. It is therefore difficult to quantify the spatial heterogeneity. A square grid measuring 10km×10km was adopted in order to get rid of the potential spatial heterogeneity. Each grid took values of input parameters and variables for running the CH4MOD. CH<sub>4</sub> emissions were estimated by running the CH4MOD in each grid across the rice-planted region. The input parameters include soil sand percentage, grain yields of single, early and late rice, and the amount of added organic matter (i.e. roots and stubble from previous crops, as well as straw and manure). Dynamically driven variables include soil temperature, redox potential (Eh) and rice biomass with a daily step. Above-ground biomass was simulated with a logistic function. Soil temperature was computed from air temperature<sup>[8]</sup>. Soil Eh was determined from field water management. Water management over the rice-planted area was categorized as five water patterns<sup>[9,10]</sup>. Fig. 1 shows the flowchart of the methodology.

### 2.2 Scheme of the spatialization

Different from the polygons based on administrative provinces or counties, a 10km×10km square grid was used as the basic cell. To minimize the distortion of areas, the area of China was projected into the Albers Equal Area Conic coordinate system with the parameters of the 1<sup>st</sup> Standard Parallel at 25°N, the 2<sup>nd</sup> Standard Parallel at 47°N, the Central Meridian at 105°E, the Latitude of Origin at 0°N, a Krasovsky Spheroid and no false easting or false northing. In the projected coordinate system, China is aptly confined by a rectangular region from the low-left corner ( $X_{LL}, Y_{LL}$ )=(−2838000.0 m, 1875000.0 m) to the upright corner ( $X_{UR}, Y_{UR}$ )=(2472000.0 m, 6075000.0 m). The area of interest (AOI) for the CH<sub>4</sub> estimation covers mainland China. Of the total 223020 grids, 97182 grids latticed the rectangular region spanned by the AOI.

To create a spatial database of the model parameters, the administrative boundary map of China (1 : 100000) was used as the spatial index of statistical datasets such as grain yield, while DEM (digital elevation model) data with the same spatial resolution of 10km×10km was used to make altitude corrections for daily air temperature. DEM data was generated from contour line maps (1 : 250000) from China's State Bureau of Surveying and Mapping.

### 2.3 Data sources and rasterization algorithms

#### 2.3.1 Daily air temperature

Daily air temperature sets in 381 meteorological stations across China were acquired from the National Meteorological Informa-

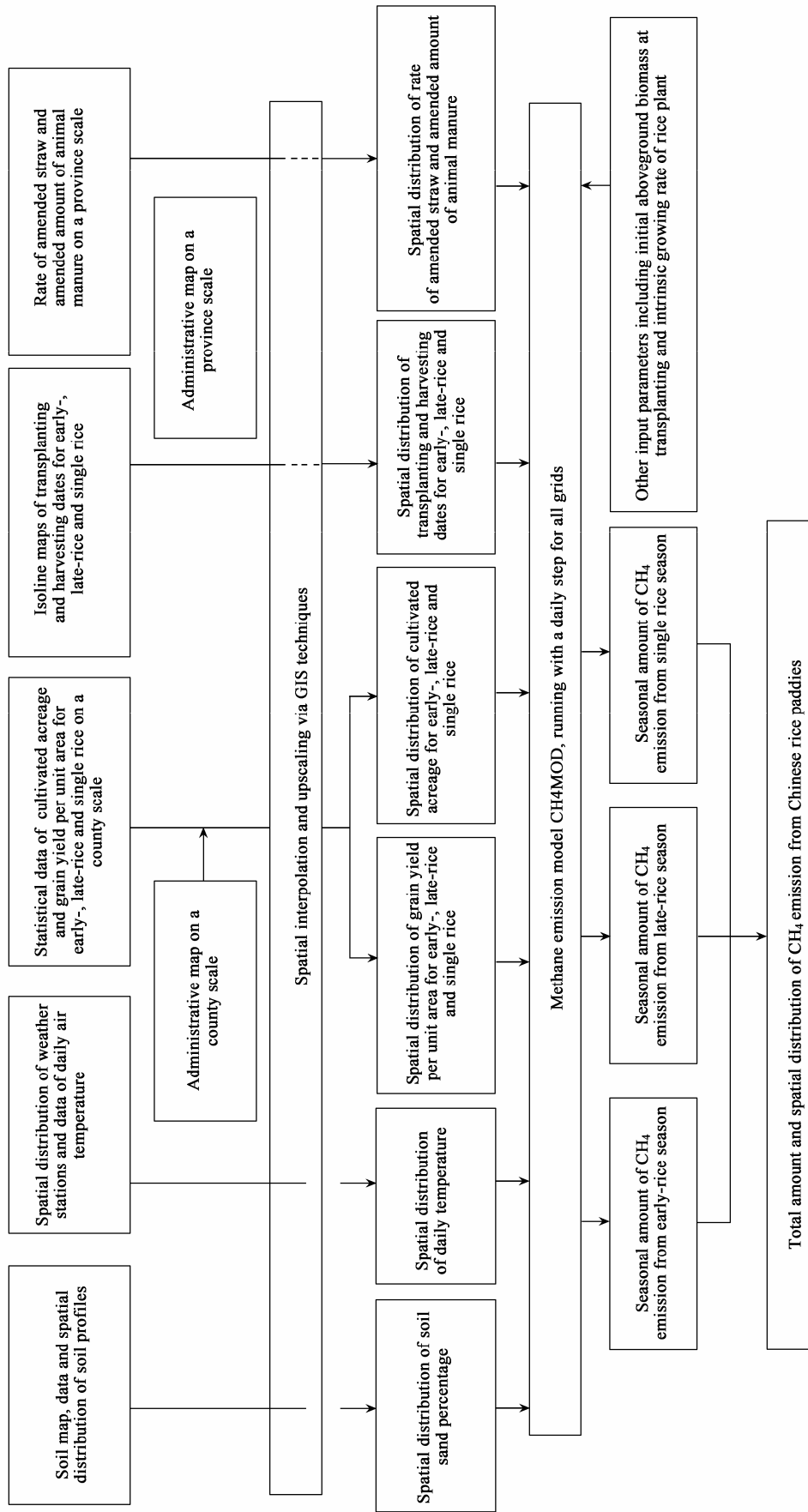


Fig. 1 Working routine of coupling CH4MOD with GIS for estimating CH4 emission from Chinese rice paddies

tion Center (NMIC), and China Meteorological Administration (CMA). By applying the interpolation algorithm of Thornton *et al.*<sup>[11]</sup>, these datasets were utilized to build thematic raster layers of daily air temperature. The core of the interpolation algorithm is the distance weight factor defined in Eq. (1).

$$W_{(r)} = \begin{cases} 0 & r > R_p \\ \exp\left[-\left(\frac{r}{R_p}\right)^\alpha\right] e^{-\alpha} & r \leq R_p \end{cases} \quad (1)$$

where  $W_r$  defines the contribution weight value of the observation to the interpolated temperature at the point of the meteorological station with a distance of  $r$ .  $R_r$  is a criteria value for the variable  $r$ . The value of  $\alpha$  represents the characteristic of spatial correlation of the interpolated parameters (in this instance it is air temperature). When the spatial correlation of the parameter decreases more rapidly with the distance  $r$ ,  $\alpha$  would be a larger value. For air temperature,  $\alpha=3.0$ <sup>[11]</sup>. Instead of being a constant, the value of  $R_r$  was calculated with the spatial distribution density of the observations in neighborhood of the specific sites. The greater the observations in the neighborhood, the smaller the value of  $R_r$ . Altitude correction facilitated by establishing a linear equation between air temperature and surface elevation. The coefficients of the linear equation were calculated on a daily basis.

**2.3.2 Soil sand percentage**

Sand (0.2–2 mm) percentage in the cultivation soil layer was included in the database. Site-specific values of the sand percentage, from the Second National Soil Survey, were located and projected into the coordinate system defined in section 1.2. The spatial layer of soil sand percentage was created by overlaying the site-specific values on the soil type map (1:4000000) via GIS technique.

**2.3.3 Phenology of rice**

The phenology of rice transplanting and harvesting came from the Atlas of Agricultural Climate in China, an iso-line map edited by Zhang *et al.*<sup>[12]</sup> The TIN (Triangular Irregular Net) algorithm of GIS was applied to spatially create continuous rice phenological raster layers.

**2.3.4 Acreage of rice planted and grain yield**

Acreage and grain yield per unit area of rice paddies on a county scale were assigned in corresponding grids. Along the processing route in Fig. 1, the county-scale records of acreage and grain yield were first linked to a map of Chinese administrative boundaries (1:100000), and then the boundary map was overlaid with the thematic raster data of Chinese land-use to complete the allocation into each grid in the AOI. Land-use data was obtained from Resources and Environmental Scientific Data Center (RESDC) of the Chinese Academy of Sciences (CAS).

**2.3.5 Organic matter addition**

Organic matter added into the rice fields includes crop roots

and stubble, as well as straw and farm manure. According to Zhao and Li<sup>[13]</sup>, stubble accounts for approximately 13% of the total straw in dry weight, and the average ratio of roots to shoots at the harvest is about 0.1. The total amount of straw was calculated from the straw/grain ratio and the grain yield. The straw/grain ratio for different crops was adopted by Zhang and Zhu<sup>[14]</sup>. The values for each sector were then derived as: straw = ratio<sub>straw/grain</sub> × grain, root = ratio<sub>root/shoot</sub> × (straw+grain), and stubble = straw × 13%. In a practical sense, harvested straw that accounts for 87% of the total straw was generally added into rice fields as organic fertilizer. The percentage of harvested straw and the amount of farm manure added into the soils were obtained in a survey of local farmers, which was conducted by the Institute of Atmospheric Physics (IAP) of the Chinese Academy of Sciences. More than 300 survey samples were pooled on a provincial scale (Table 1).

Table 1 Addition of previous crop straw and farm manure

Administrative provinces	Rate of straw added (%)	Farm manure (kg C hm <sup>-2</sup> )	Administrative provinces	Rate of straw added (%)	Farm manure (kg C hm <sup>-2</sup> )
Beijing	14	60	Hubei	15	700
Tianjin	14	60	Hunan	27	470
Hebei	14	340	Guangdong	25	310
Shanxi	14	340	Guangxi	30	590
Inner Mongolia	4	260	Hainan	33	220
Liaoning	4	260	Chongqing	17	500
Jilin	3	120	Sichuan	8	480
Heilongjiang	33	300	Guizhou	24	780
Shanghai	15	1000	Yunnan	9	610
Jiangsu	15	1000	Tibet	9	610
Zhejiang	25	450	Shaanxi	10	890
Anhui	14	330	Gansu	10	890
Fujian	15	130	* Qinghai	—	—
Jiangxi	27	460	Ningxia	10	890
Shandong	14	340	Xinjiang	10	890
Henan	14	340			

\* No rice planted in Qinghai

Analogous to the method used in spatializing grain yields, the amount of organic matter addition was assigned in corresponding grids.

**3 Model inputs and performance**

The spatial data layers of model input parameters include daily air temperature (Section 1.3.1), soil sand percentage (Section 1.3.2), the rice transplanting and harvesting date (Section 1.3.3), acreage and grain yield (Section 1.3.4), organic matter addition (Section 1.3.5), initial above-ground biomass at rice transplanting, the intrinsic growth rate to

simulate rice growth and the water management pattern<sup>[9]</sup>. The initial above-ground biomass was set at a constant of  $15 \text{ g m}^{-2}$ <sup>[15]</sup>. The intrinsic growth rate was  $0.08 \text{ d}^{-1}$  for single rice and  $0.1 \text{ d}^{-1}$  for early and late rice<sup>[8]</sup>. Referring to the work by Gao and Li<sup>[10]</sup>, we cataloged five patterns of water management for rice cultivation in China, i.e., flood–drainage–re-flood–moist with intermittent irrigation for early rice, flood–drainage–moist with intermittent irrigation for late rice, flood–drainage–re-flood–moist with intermittent irrigation for single rice in northern China, flood–drainage–moist with intermittent irrigation for single rice in southern China, and continuous flooding for submerged rice fields. Continuously flooding rice fields were located in central and southwestern China, where fields generally remain submerged in the winter season and during the subsequent rice season due to a poorly developed drainage system.

CH4MOD was run grid-by-grid with a daily step for the single, early and late rice seasons from transplanting to harvesting across the entire AOI. The seasonal amount of CH<sub>4</sub> emissions per unit area was determined from the summation of daily values. By multiplying the seasonal amount per unit area by the cultivated acreage, the amount of CH<sub>4</sub> emissions was obtained for each grid. The total amount of CH<sub>4</sub> emissions in mainland China was obtained by adding the amounts for all grids in the AOI.

#### 4 Methane emissions from Chinese rice fields in 2000

In 2000, the acreage of irrigated rice was 30.1 million  $\text{hm}^2$  in mainland China—with 15.71 million  $\text{hm}^2$  for single rice, 6.82 million  $\text{hm}^2$  for early rice and 7.57 million  $\text{hm}^2$  for late rice. Approximately 70% of double rice (early/late rice rotation) was planted in Hunan, Guangdong, Guangxi and Jiangxi, China.

The spatial distribution of CH<sub>4</sub> emissions per unit area is shown in Fig. 2(a) for early rice, in Fig. 2(b) for late rice and in Fig. 2(c) for single rice. Higher CH<sub>4</sub> emission fluxes occurred in the southeastern region of Guangxi, China and the southwestern region of Guangdong, China for early rice (Fig. 2a) and late rice (Fig. 2b). In the eastern region of Hunan, the CH<sub>4</sub> emission flux was also higher for the early rice season (Fig. 2a). With respect to the CH<sub>4</sub> emission flux from the single rice season, higher values occurred in Hunan and Hubei (Fig. 2c). The total amount of CH<sub>4</sub> emissions from irrigated rice cultivation in mainland China was estimated to be 6.02 Tg in 2000 (Fig. 2d). Of the total, approximately 49% (2.93Tg) was emitted during the single rice-growing season, and 27% (1.63Tg) and 24% (1.46Tg) were from the early and late rice-growing seasons, respectively. Higher amounts of CH<sub>4</sub> emissions from single rice occurred in Jiangsu, Anhui, Hu'nan, Hubei and the eastern region of Sichuan, and those from double rice appeared in Hunan, Jiangxi, Guangdong and Guangxi.

Model estimates showed that the provinces where the majority of CH<sub>4</sub> (68% of the total) was emitted are Sichuan, Hunan, Hubei, Guangdong, Guangxi, Jiangsu and Jiangxi (Fig. 3). The acreage of irrigated rice cultivation in these provinces accounts for approximately 60% of the total in mainland China. Wide distribution of the submerged rice fields in Sichuan, Hunan and Hubei resulted in higher CH<sub>4</sub> emissions<sup>[16]</sup>.

Statistical analysis of a total of 53311 grids where rice was planted in the AOI showed that more than 90% of these grids have a CH<sub>4</sub> emission flux ranging from 50 to 300  $\text{kg}/\text{hm}^2$  during the rice-growing season (Fig. 4). The statistical histogram distribution is consistent with the report by Wang *et al.*<sup>[17]</sup> who summarized 214 cases of *in situ* CH<sub>4</sub> emission observations in China.

## 5 Discussion

### 5.1 Model estimates of CH<sub>4</sub> emissions from Chinese rice paddies

Reliable estimates of CH<sub>4</sub> emissions on a national scale depend on the validity and/or interpretation of the models and the representatives of the spatialized input parameters. By linking a statistical model to soil map from FAO, Bachelet *et al.*<sup>[4]</sup> estimated methane emissions in Chinese rice fields from soil organic matter and crop residue addition. However, Huang *et al.*<sup>[18]</sup> reported that CH<sub>4</sub> emissions in rice-planted soils did not significantly correlate with soil organic matter, but the methanogenic substrates derived mostly from the root exudation of rice crops<sup>[19,20]</sup>. Climate and soil are main spatialized input parameters that have a wide spatial heterogeneity. Li *et al.*<sup>[7]</sup> adopted administrative counties as basic cells while Matthews *et al.*<sup>[6]</sup> used provinces as basic cells and only 10 meteorological stations to estimate CH<sub>4</sub> emissions from Chinese rice paddies<sup>[5]</sup>. Obviously, coarse spatial resolution may conceal the detailed spatial variation of climate and soil parameters to some extent. As a result, there may be great uncertainties in terms of the regional estimates.

The original version of CH4MOD<sup>[8]</sup> already provided a realistic estimate of the observed results from continuously flooding fields<sup>[3]</sup>. Focusing on the effect of the water regime on CH<sub>4</sub> production/emissions and CH<sub>4</sub> transport via bubbles, the model was further modified and validated based on a total of 94 *in situ* observations conducted in China's main rice cultivation areas. The computed seasonal CH<sub>4</sub> emissions by CH4MOD conformed well with the observations<sup>[9]</sup>. In addition to the model validity, a higher spatial resolution (10km×10km) of the model inputs was coupled in this study, and thus the present estimates may be more reliable compared with existing model estimates. Results made by this methodology of the methane emissions from rice fields of China in 1994 had been accepted by The People's Republic of China Initial National Communication on Climate Change<sup>[21]</sup>.

### 5.2 Potential sources of errors and uncertainties

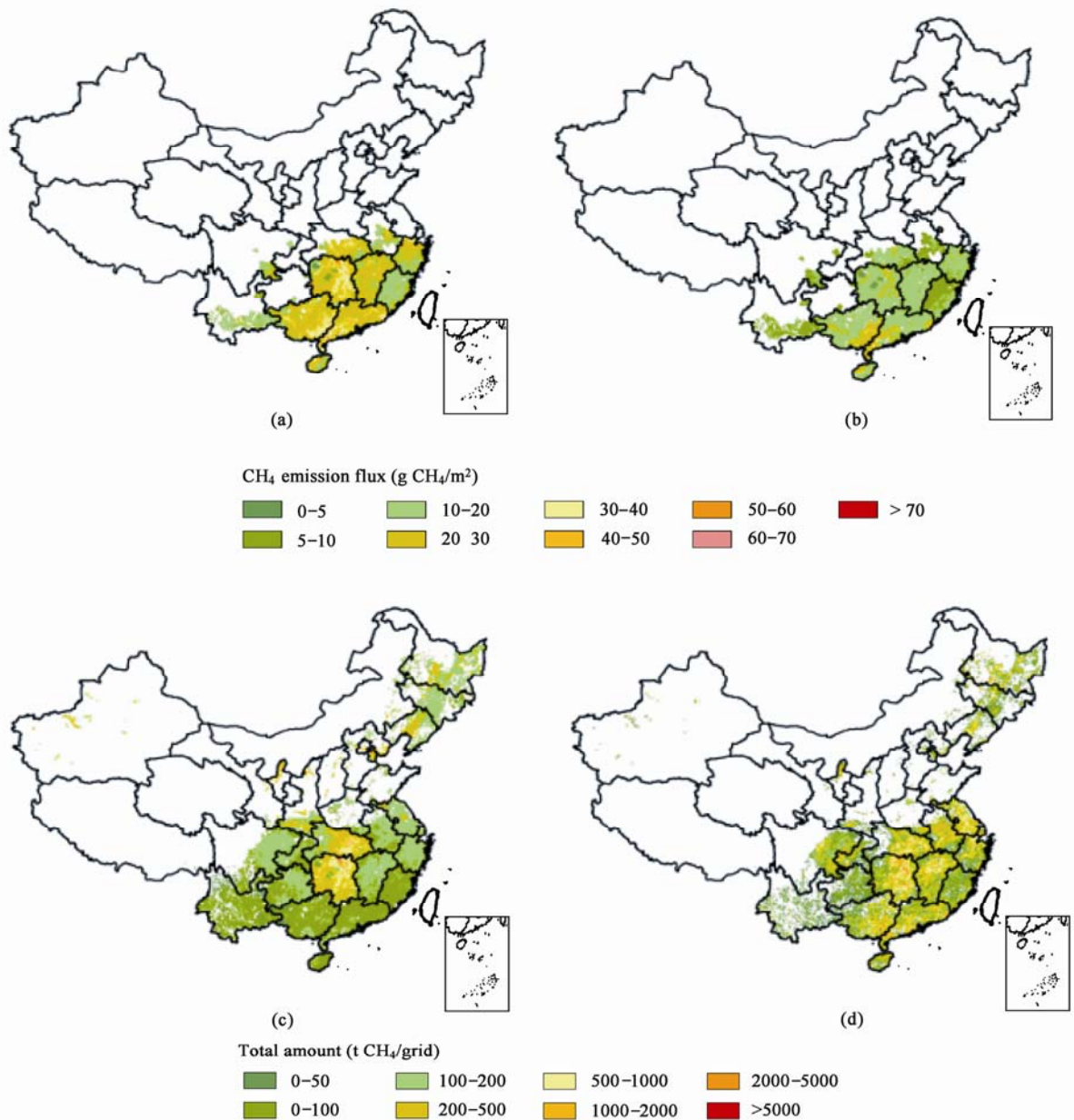


Fig. 2 Spatial distribution of CH<sub>4</sub> emission flux (g CH<sub>4</sub>m<sup>-2</sup>) from early rice (a) late rice (b) and single rice (c) and total amount (t CH<sub>4</sub> grid<sup>-1</sup>) in Chinese rice paddies (d)

While estimating regional CH<sub>4</sub> emissions from rice fields by integrating the model with GIS, there are usually cases in which some model parameters are unavailable on a regional scale. To fill this gap, assumptions are made with the best knowledge, which may still induce uncertainties in the model estimates on a regional scale. Potential sources associated with these uncertainties may include the following four aspects:

**Model performance.** Models in general combine available knowledge with the processes involved in CH<sub>4</sub> production, oxidation and emissions. It is difficult for modelers to guarantee that the processes can be simulated in great detail, and therefore some simplification is inevitable. Although CH4MOD

includes equations explaining key processes and has been validated based on field observations, the simplification may introduce some errors to the current estimates<sup>[9]</sup>. Generally speaking, the more detailed a model is, the more input data it requires and the less applicable it can be on a regional scale due to the unavailability of the input database.

**Model inputs.** The rates of organic matter addition and field water management are the key factors controlling CH<sub>4</sub> emissions from rice fields. By surveying local farmers, we obtained the percentage of the harvested straw and the amount of farm manure added into the soil on a provincial scale (Table 1) as model inputs. It appears that these sets of data (Table 1) are

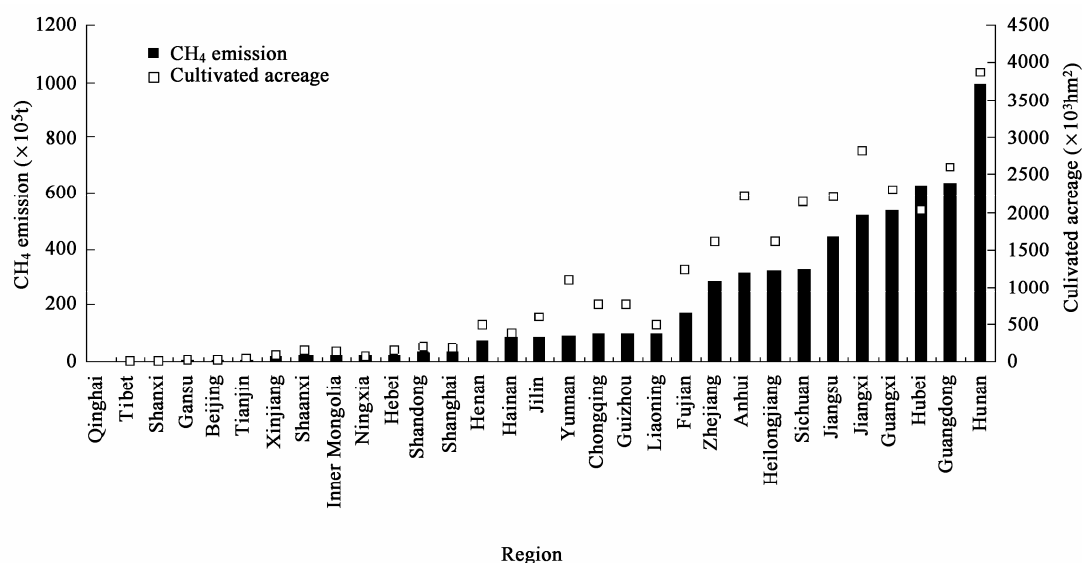


Fig. 3 CH<sub>4</sub> emissions and cultivated rice acreage on a provincial scale

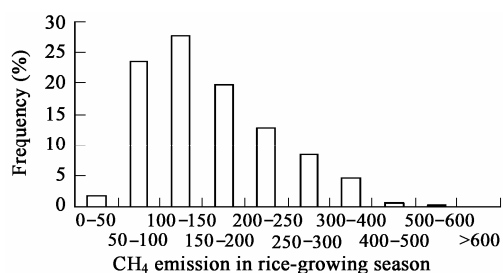


Fig. 4 Frequency distribution of CH<sub>4</sub> flux occurred at different levels

insufficient to comprehensively represent the regional variation. With respect to field water management, we simply took five patterns of water management into account. In fact, water management varies significantly from place to place, and the five patterns might not be sub-regionally representative. Errors from the rates of organic matter addition and field water management may introduce an element of uncertainty to the present estimates. In addition, the quality of other input parameters such as soil sand percentage and grain yield may also result in uncertainties.

**Aggregation errors.** To apply a model in a large-scale region, a common scheme is to divide the whole objective region into smaller sub-regions, where one set of model input parameters is assigned. This scheme assumes that the input parameters are homogeneous in a given sub-region, while it would not be true especially when the sub-regions are large (e.g. administrative counties or provinces). The heterogeneity that existed naturally in each sub-region would inevitably introduce an element of uncertainty to the regional estimates. A higher spatial resolution (e.g. the 10km×10km grid in this study) creates smaller sub-regions where the parameters would approach homogene-

ity. However, the dimensions of the sub-regions cannot be infinitely small, depending on the attributes of the parameters and the spatial density of the available datasets (e.g. the number of meteorological stations in the whole objective region).

Errors related to spatial transformation with GIS and interpolation methods. GIS and some other interpolation methods are usually used to create spatially continuous raster data from scattering datasets. These processes of spatialization would result in data errors. Consequently, the data errors are transferred to the estimates via model and yield uncertainties. The data errors induced in this way depend greatly on the attributes of datasets. For example, the interpolation error is 5.69% for air temperature in this study, while it is 45.8% for soil sand percentage. The explanation is that the air temperature in different sites correlates with each other across a large space, but intensive spatial variation exists in soils despite that there are more soil sampling sites than meteorological stations in the same region.

### 5.3 Future research requirements

The ultimate goal of this study is to accurately calculate CH<sub>4</sub> emissions on a regional or larger scale based on the available spatial database. In order to reduce uncertainties, more detailed information on the rates of organic matter addition and the field water management is required with a higher spatial resolution. In addition, it is necessary to quantify the uncertainties of the present estimates of CH<sub>4</sub> emissions from Chinese rice paddies.

## 6 Conclusions

It is possible to make regional estimates of CH<sub>4</sub> emissions from rice paddies by linking CH4MOD to a GIS database. Methane emissions from rice paddies in mainland China in the

2000 rice-growing season were estimated to be 6.02 Tg. Of the total, approximately 49% was emitted from the single rice-growing season, while 27% and 24% were from the early and the late rice-growing seasons, respectively. A further study should focus on quantifying the uncertainties of the current estimates, obtaining more detailed addition on the rates of organic matter addition and field-water management, and improving the quality of regional datasets.

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