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Quantifying methane emissions from rice fields in the Taihu Lake region, China by coupling a detailed soil database with biogeochemical model

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Abstract. As China has approximately 22% of the world's rice paddies, the regional quantification of CH_4 emissions from these paddies is important in determining their contribution to the global greenhouse gas effect. This paper reports the use of a biogeochemical model (DeNitrification and DeComposition or DNDC) for quantifying CH_4 emissions from rice fields in the Taihu Lake region of China. For this application, the DNDC model was linked to a 1:50 000 soil database derived from 1107 paddy soil profiles compiled during the Second National Soil Survey of China in the 1980s–1990s. The simulated results showed that the 2.3 Mha of paddy rice fields in the Taihu Lake region emitted the equivalent of 5.7 Tg C from 1982–2000, with the average CH_4 flux ranging from 114 to 138 kg C ha^{-1} y^{-1}. As for soil subgroups, the highest emission rate (660 kg C ha^{-1} y^{-1}) was linked to gleyed paddy soils accounting for about 4.4% of the total area of paddy soils. The lowest emission rate (91 kg C ha^{-1} y^{-1}) was associated with degleyed paddy soils accounting for about 18% of the total area of paddy soils. The most common soil in the area was hydromorphic paddy soils, which accounted for about 53% of the total area of paddy soils with a CH_4 flux of 106 kg C ha^{-1} y^{-1}. On a regional basis, the annual averaged CH_4 flux in the Taihu Lake plain soil region and alluvial plain soil region were higher than that in the low mountainous and hilly soil region and the polder soil region. The model simulation was conducted with two databases using polygons or counties as the basic units. The county-based database contained soil information coarser than the polygon system built based on the 1:50 000 soil database. The modeled results with the two databases found similar spatial patterns of CH_4 emissions in the Taihu Lake region. However, discrepancies exist between the results from the two methods. The total CH_4 emissions generated from the polygon-based database is 2.6 times the minimum CH_4 emissions generated from the county-based database, and is 0.98 times the maximum CH_4 emissions generated from the county-based database. The average value of the relative deviation ranged from −20% to 98% for most counties, which indicates that a more precise soil database is necessary to better simulate CH_4 emissions from rice fields in the Taihu Lake region using the DNDC model.

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1 Introduction

With economic development, environmental problems are becoming increasingly serious. The enhancement of the greenhouse effects is important aspect which has caused global concern. Methane (CH_4) is an important greenhouse gas and plays a large role in atmospheric processes. Since 1990, CH_4 emissions are responsible for approximately 15%–20% of the greenhouse gas (GHG) emissions globally (IPCC, 1996). Presently, atmospheric CH_4 concentration is 1774 ppb, and it is increasing rapidly at a rate of 1.0% yr^{-1} (IPCC, 2007). Rice paddies have been identified as one of the major sources of atmospheric CH_4, contributing about 12% to global CH_4 emissions (Cicerone et al., 1988;

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Lelieveld et al., 1993). China has approximately 22% of the world's rice paddies and 38% of the world's rice production, and CH_4 emissions are responsible for approximately 28% of the total CH_4 emission of the world's rice fields (Jiang et al., 2004; Wang et al., 1993). Over the past two decades, midseason drainage has been adopted throughout China as an alternative water management approach (Li et al., 2006). Field measurements in China indicate that midseason drainage significantly reduces CH_4 emissions (Cai et al., 1999). Therefore, accurate estimates of CH_4 emissions from the rice fields in China are vitally important for a comprehensive understanding of global GHG dynamics.

Recently, scientists have used models to estimate CH_4 emissions from cropping systems (Cao et al., 1995a, b, 1996, 1998; Huang et al., 1998; Matthews et al., 2000a, b). The DeNitrification-DeComposition (DNDC) model developed by Li et al. is a process-based model focused on trace gas emissions from agroecosystems (Li et al., 1992a, b, 1994). Using this model, environmental impacts on CH_4 emissions such as climate change, land-use change, and agricultural activities including alternative farming management practices, can be assessed in a comprehensive way. Presently, the DNDC model has demonstrated good performance through its long-term applications in North America, Europe, Asia and Oceania. For instance, Li et al. (2000) tested the model against observed CH_4 emissions from a rice field in Beaumont, Texas, USA. The simulated and measured relative deviation of CH_4 emissions was 5.4%, which demonstrated that the DNDC model could accurately simulate CH_4 emissions. Jagadeesh et al. (2006) simulated CH_4 and N_2O emissions from rice fields at different locations in India using the DNDC model and found that most discrepancies between simulated and observed seasonal fluxes were less than 20% of the field estimate of the seasonal flux.

The DNDC model has also been utilized to upscaling CH_4 emissions from local site to regional scales. So far, most of the DNDC modeling conducted at regional scale has used counties as the basic geographic unit. However, regional estimates of CH_4 fluxes cannot be derived simply from the extension of results from field-plot measurement of CH_4 fluxes because of the spatial variations in climate, soil, and management practices (Jagadeesh et al., 2006). As such, county scale model simulations can have great uncertainties as soil properties are averaged for each county, largely ignoring the nonlinear impacts of soil heterogeneity within a county (Pathak et al., 2005; Li et al., 2004; Cai et al., 2003).

For the rice-dominated Taihu Lake Region, we shifted the regional database linked to the DNDC model from a county-based to a grid-basd system which was built upon a new soil map that was recently developed in China. The 1:50 000 soil map was derived from 1107 paddy soil profiles summarized in the Second National Soil Survey of China in the 1980s–1990s. By linking the detailed soil database to DNDC model, we attempted to improve the performance of the model. The goals of this study were to (1) estimate the inter-annual variation in CH_4 emissions from rice paddy fields in the Taihu Lake region of China from 1982 to 2000; (2) display the CH_4 emissions patterns in different paddy soil subgroups as well as different soil sub-regions; and (3) compare CH_4 emissions modeled with polygon- and county-based databases.

Fig. 1. Geographical location of the study area in China.

2 Materials and methods

2.1 Study area

The Taihu Lake region (118°50′–121°54′ E, 29°56′–32°16′ N), an area of intensive rice cultivation, is located in the middle and lower reaches of the Yangtze River paddy soil region of China, includes the entire Shanghai City administrative area and a part of Jiangsu and Zhejiang provinces, and covers a total area of 36 500 km^2 (Fig. 1) (Li, 1992). It mainly consists of plains formed on deltas with numerous rivers and lakes within the region. The climate is warm and moist with plenty of sunshine and a long growing season. Annual rainfall is 1100–1400 mm, and with a mean temperature of 16°, and average annual sunshine of 1870–2225 h. The frost-free period is over 230 days. The study area is one of the oldest agricultural regions in China, with a history of rice cultivation for several centuries. Approximately 66% of the total land area is covered with paddy soils (Xu et al., 1980).

The paddy soils are derived mostly from loess, alluvium and lacustrine deposits and are classified in the following subgroups according to US Soil Taxonomy (ST) or the World Reference Base Soil Taxonomy (WRB) (Soil Survey Staff, 1994; Shi et al., 2006): Hydromorphic (Typic Epiaquepts or Hydragric Anthrosols), Submergenic (Typic Endoaquepts or Hydragric Anthrosols), Bleached (Typic Epiaquepts or Hydragric Anthrosols), Gleyed (Typic Endoaquepts or Gleyic-hydragric Anthrosols), Percogenic (Typic Epiaquepts or Hydragric Anthrosols), and Degleyed (Typic Endoaquepts or Gleyic-hydragric Anthrosols). Most of the croplands are managed with rice and winter wheat rotation systems. Rice is planted in June and harvested in October and wheat is planted in November and harvested in May.

2.2 Description of the DNDC model

The DNDC (DeNitrification & DeComposition) model, under development at the University of New Hampshire since 1992, is a process-orientated simulation tool for soil carbon and nitrogen biogeochemistry cycles (Li et al., 1992 a, b, 1994, 1996). Presently, the DNDC model is one of the more widely accepted biogeochemical models in the world (Li, 2000, 2007). The model contains six interacting sub-models which describe the generation, decomposition, and transformation of organic matter, and outputs the dynamics components of SOC and greenhouse gases fluxes.

The six sub-models include: (1) soil climate sub-models, which use soil physical properties, air temperature, and precipitation data to calculate soil temperature, moisture and redox potential (Eh) profiles and soil water fluxes through time. The results of the calculation are then fed to the other sub-models; (2) a nitrification sub-model; (3) a denitrification sub-model, which calculates hourly denitrification rates and N_2O, NO and N_2 production during periods when the soil Eh decreases due to rainfall, irrigation, flooding or soil freezing; (4) a sub-model simulating the decomposition of SOC pools and CO_2 production through soil microbial respiration; (5) a plant growth sub-model, which calculates daily root respiration, water and N uptake by plants, and plant growth; and (6) a fermentation sub-model, which calculates daily methane (CH_4) production and oxidation.

The DNDC model can simulate C and N biogeochemical cycles in paddy rice ecosystems, whereby the model has been implemented by adding a series of anaerobic processes (Li et al., 2002, 2004; Li, 2007; Cai et al., 2003). Paddy soil is characterized by frequent changes between saturated and unsaturated conditions driven by water management. During changes in soil water content, the soil Eh is subject to substantial changes between +600 and −300 mV.

The DNDC model allocates substrates (e.g., DOC, NO_3^-, NH_4^+ etc.) to reductive reactions (e.g., denitrification, methanogenesis) and oxidative reactions (e.g., nitrification, methanotrophy) based on the relative fractional volumes of the oxidizing and reducing zones, and the potential oxidation and reduction reactions determined by Eh and pH (Yu et al., 2001, 2004; Li, 2007). By tracking the formation and deflation of a series of Eh volume fractions driven by depletions of O_2, NO_3^-, Mn^{4+}, Fe^{3+}, and SO_4^{2-} consecutively, the DNDC model estimates soil Eh dynamics as well as rates of reductive/oxidative reactions, which produce and consume CH_4 or N_2O in the soil. This tracking links the soil water regime to trace gas emissions for rice paddy ecosystems. Temporally, the DNDC model predicts daily CH_4 and N_2O fluxes from rice fields during periods of extended flooding or shifts between flooded and drained states through the growing and fallow seasons.

2.3 Database development

A major challenge for using an ecosystem model at a regional scale is to assemble adequate datasets required to initialize and run the model. DNDC modeling of CH_4 emissions from rice paddy fields requires data describing the soil properties, daily weather, cropping systems, and agricultural management practices.

In this study, two types of spatial soil databases, polygon-based and county-based, were used to support the DNDC regional simulations. The polygon-based soil database contained 52 034 polygons of paddy soils representing 1107 paddy soil profiles extracted from the latest national soil map (1:50 000), which was compiled using the Pedological Knowledge Based (PKB) method (Shi et al., 2004). The soil dataset covered 37 counties in the Taihu Lake region. The mapping units are based on the soil types as defined in Genetic Soil Classification of China (GSCC). The soil dataset consisted of many soil attribute fields, including profile code, soil name (in GSCC), profile thickness, bulk density, organic matter content, texture, pH, etc. The county-based soil database was built from the default method developed for DNDC, in which the maximum and minimum values of soil texture, pH, bulk density, and organic carbon content were recorded for each county. The maximum and minimum values of the soil parameters were also induced from the 1:50 000 soil database with relatively coarse source data. During the regional runs with the county-based database, the DNDC produced two CH_4 fluxes resulting from two runs with the maximum and minimum soil values, respectively. The two flux values formed a range to define the uncertainty induced from upscaling each county (see detail in Li et al., 2004). For comparison in this study, both the polygon-based and county-based soil databases were run concurrently so the DNDC model could generalize regional CH_4 emissions for the Taihu Lake region.

The crop dataset included physiological data of summer rice and winter wheat. The agricultural management dataset included sowing acreages, nitrogen fertilizer application rates, livestock, planting and harvest dates, and agricultural population at the county level from 1982 to 2000 (from the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences). The climate dataset included daily weather data (precipitation, maximum and minimum air temperature) from 1982–2000, which was acquired from 13 weather stations in the Taihu Lake region (from Institute of Atmospheric Physics, Chinese Academy of Sciences). Each of the counties in the simulation was assigned to a weather station nearest to the evaluated county.

Farming management scenarios were compiled based on the assumptions as follows (Tang et al., 2006; Qiu et al., 2004): (1) Nitrogen fertilizer consisted of 40% urea, 40% NH_4HCO_3, and 20% $NH_4H_2PO_3$; (2) 15% of aboveground crop residue was returned to the soil; (3) 20% livestock

Table 1. The CH_4 emission from rice fields of the Tai-Lake region in China.

Author	Location	year	Treatment and fertilizing amount	Emission
			$kg\,N\,ha^{-1}\,y^{-1}$	$kg\,C\,ha^{-1}\,y^{-1}$
Cai et al. (1994)	Wu County [a]SOM 3.20%	1992–1993	no fertilizer	122.3
			ammonium sulfate 223	73.7
			ammonium sulfate 223+ manure	135.0
			ammonium sulfate 223+nitrification inhibitor	99.0
			ammonium sulfate 223continuous flooding	143.3
Cai et al., 1995	[b]JASS SOM 1.85%	1994	contrast	59.3
			ammonium sulfate 100	34.5
			ammonium sulfate 300	24.0
			urea 100	55.5
			urea 300	51.0
Li et al., 1993	Jiangning SOM 2.29%	1990–1992	manure+urea 100	195.0
			manure	171.0
			ammonium sulfate 140	47.3
			manure+urea 100 half of dry farming	119.3
Xiong et al. (1999)	Wu County SOM 3.5%	1994–1996	urea 191	82.5
			ammonium hydrogen carbonate 191	52.5

[a] SOM: *S*oil *O*rganic *M*atter;
[b] JASS: *J*iangsu *A*cademy for *A*griculture *S*cience.

wastes and 10% human wastes were added as manure to the soil; (4) One midseason drainage and shallow flooding were applied to summer rice; and (5) For the rice-wheat rotation, tillage was conducted twice before 1990 at 20 cm for rice and 10 cm for wheat on the planting dates; No-till was applied for wheat after 1990.

3 Results and discussion

3.1 Model validation

At present, the DNDC model has been tested against several CH_4 flux datasets from wetland rice sites in the United States, Italy, China, Tailand, and Japan (Li et al., 2002; Cai et al., 2003). For sites in East Asia, simulated seasonal CH_4 emissions from paddy soils were in good agreement with field studies (r^2=0.96, regression slope=1.1, n=23) (Cai et al., 2003). Results showed that if the site soil characteristics, fertilization rate, fertilization type, crop and water management were well described, simulated fluxes were similar to observation (Fig. 2) (Zheng et al., 1997).

Previous field measurement of CH_4 emissions from the rice fields in the Taihu Lake region of China ranged from 20 to 200 $kg\,C\,ha^{-1}\,y^{-1}$ (Table 1) (Wang et al., 2001). In our study, DNDC-modeled CH_4 emissions from the majority paddy soils were in the range of 20 to 200 $kg\,C\,ha^{-1}\,y^{-1}$ (Fig. 3), indicating that the modeled results are consistent with observations for the Taihu Lake region. Table 1 shows that plots with no-fertilizer application yielded higher CH_4 fluxes than those receiving only mineral fertilizer nitrogen

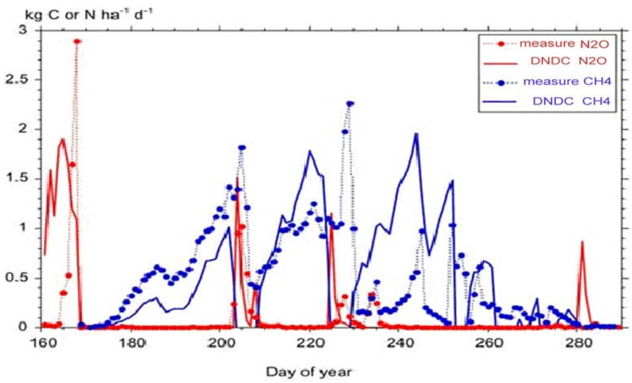

Fig. 2. Comparison between observed and DNDC-modeled CH_4 and N_2O fluxes from a paddy rice field applied with midseason drainage in Wu County, the Taihu Lake region, China, in 1995.

(Cai et al., 1994). This was consistent with the general belief that alternating flooding and drainage (treatment of "ammonium sulfate 223") should be beneficial in reducing CH_4 emissions from rice paddy soils (Li et al., 2002). Under the same water regime conditions, addition of $(NH_4)_2SO_4$ depressed CH_4 fluxes from rice fields, and the depressing effect of $(NH_4)_2SO_4$ on CH_4 fluxes seemed to be alleviated by the addition of a nitrification inhibitor.

The simulated CH_4 emission using the DNDC model closely reflected field observations in Nanjing, Jiangning, Wu County, Hangzhou, Jurong, and Suzhou of the Taihu Lake region (Table 2) (Wang et al., 2001; Cai

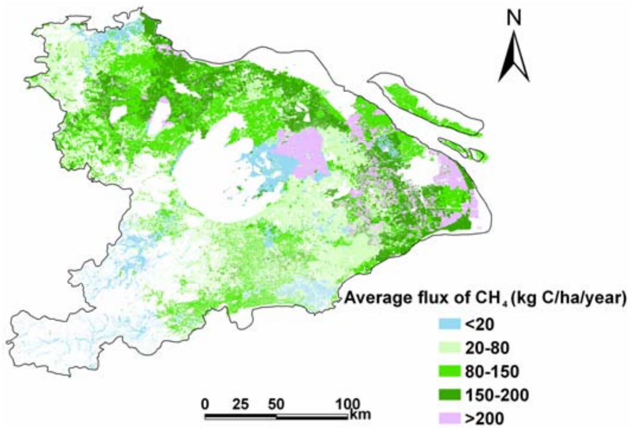

Fig. 3. Distribution of the average CH_4-C flux from 1982 to 2000 in the Taihu Lake region, China.

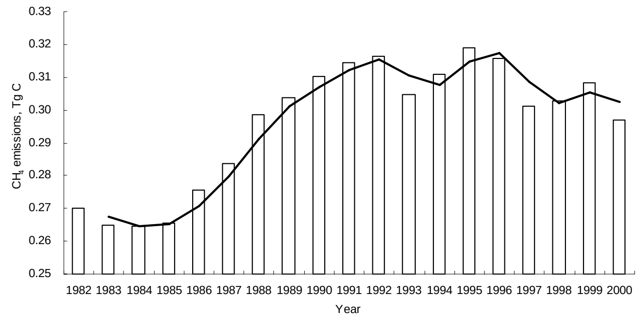

Fig. 4. Distribution of CH_4 emission from 1982 to 2000 in the Taihu Lake region, China.

et al., 2003). Total CH_4 emissions ranged from 14 to 180 kg C ha^{-1} y^{-1}, while simulated emissions ranged from 15 to 198 kg C ha^{-1} y^{-1}. The difference between the observed and simulated emissions in all sites ranged from −12 to 51 kg C ha^{-1} y^{-1}. The highest percentage of relative deviation was found at the Nanjing site while the lowest was recorded at the Suzhou site. Most discrepancies between the simulated and observed yearly fluxes were less than 10%, which showed that the CH_4 emissions from paddy soil in the Taihu Lake region were well simulated by the DNDC model.

3.2 Inter-annual variation in CH_4 emissions in the Taihu Lake region

Based on simulated results, the 2.3 M ha of paddy soils cultivated with summer rice and winter wheat in the Taihu Lake region emitted the equivalent of 5.7 Tg C from CH_4 from 1982–2000. The average CH_4 flux ranged from 114 kg C ha^{-1} y^{-1} to 138 kg C ha^{-1} y^{-1}. However, the modeled annual CH_4 emission was highly variable from year to year (Fig. 4). From 1982–1985, the CH_4 emissions of the entire area were very low, accounting for 19% of the total CH_4 emissions. This was mainly caused by the low input of chemical fertilizer and manure. The chemical fertilizer application rate ranged from 180 kg N ha^{-1} yr^{-1} to 210 kg N ha^{-1} yr^{-1}and the manure rate ranged from 230 kg C ha^{-1} yr^{-1} to 240 kg C ha^{-1} yr^{-1}. After that (from 1986 to 1992), the application rates of fertilizer tended to increase. Chemical fertilizers increased from 260 kg N ha^{-1} yr^{-1} to 400 kg N ha^{-1} yr^{-1} and manure went up from 230 kg N ha^{-1} yr^{-1} to 280 kg N ha^{-1} yr^{-1}. The increase in livestock number provided more manure, which in turn enhanced substrates for methanogenesis (Sass et al., 1991; Zheng et al., 1999; Sun et al., 2007). While additional fertilizer application could lead to an increase in CH_4 emissions due to an increase in rice productivity and biomass, a decrease due to soil Eh value induced induced by fertilizers such as ammonium sulfate is also plausible (Lindau et al., 1990; Denier van der Gon and Neue, 1994; Wassmann et al., 1994; Yao and Chen, 1994; Dunfield et al., 1995). The seven years from 1986 to 1992 accounted for 37% of the total CH_4 emissions. However, the increasing rate of modeled CH_4 emissions decreased from 1993 to 2000. Agricultural statistics show that the amount of synthetic fertilizers used in the region has decreased since 1993 (from the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences).

3.3 CH_4 emission pattern in different paddy soil subgroups in the Taihu Lake region

The hydromorphic subgroup is the most prominent paddy soil type in the Taihu Lake region, accounting for 53% of the total paddy soil area (Fig. 5a). This group contains a high organic carbon content (15 g kg^{-1}) and total nitrogen (2.0 g kg^{-1}) making it favorable for CH_4 production by providing more substrates (soluble C, ammonium, and nitrate) (Zheng et al., 1999; Yao et al., 1999).The modeled average CH_4 flux was 106 kg C ha^{-1} y^{-1} (Fig. 5a, b). In the Taihu Lake region, the total CH_4 emissions from this subgroup were equivalent to 2.5 Tg C, accounting for 44% of the total CH_4 emissions from the region.

The degleyed and percogenic subgroups cover 18% and 16% of the total paddy soil area in the region, respectively. The modeled CH_4 from the degleyed and percogenic subgroups were equivalent to 0.71 and 0.83 Tg C, and accounted for 12% and 15% of the regional CH_4 emissions, respectively. The CH_4 emission rate from the percogenic subgroup was higher than the degleyed subgroup. The main reasons were that the pH value of the former was close to neutral (6.9), and the clay content was only 22%. The latter was weakly acidic (6.5), and had a clay content of 30%. Some studies show that the optimum pH range for CH_4 production is 6.8–7.2 (Pacey et al., 1986), and soil texture has also been documented to affect CH_4 emissions from rice fields, increasing emissions with decreasing clay content (Cai et al., 1999).

Table 2. Comparison between observed and DNDC-modeled CH_4 fluxes from rice fields in the Taihu Lake region, China.

Location	Year	Observed ($kg\,C\,ha^{-1}\,y^{-1}$)	Simulated ($kg\,C\,ha^{-1}\,y^{-1}$)	Relative deviation (%)
Nanjing	1994	24.0–55.5 (39.8)	35.3–51.8 (43.5)	9.4
Jiangning	1990–1992	47.3–195.0 (121.1)	75.0–144.8 (109.9)	−9.3
Wu County	1992–1996	52.5–143.3 (97.9)	53.3–93.0 (73.1)	−25.2
Hangzhou	1987–1989	120.0–240.0 (180.0)	148.5–246.8 (197.6)	9.8
Nanjing	1994	57.8	41.3	−28.6
Jurong	1995	14.3	14.7	3.2
Jurong	1997	49.5	55.0	11.1
Suzhou	1993	122.3	122.9	0.6
Suzhou	1993	143.3	151.8	9.8

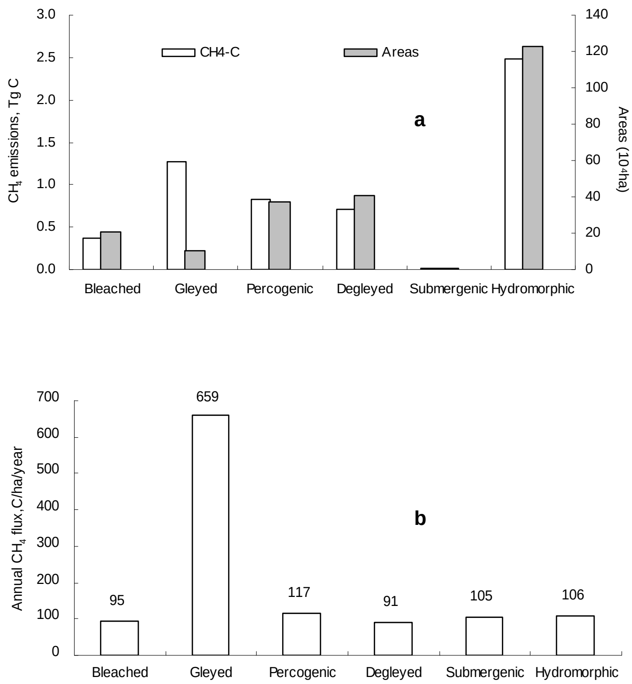

Fig. 5. **(a)** Comparison between areas and total CH_4 emissions in various paddy soil subgroups of the Taihu Lake region, China. **(b)** Comparison of the average CH_4 flux per year in various paddy soil subgroups of the Taihu Lake region, China.

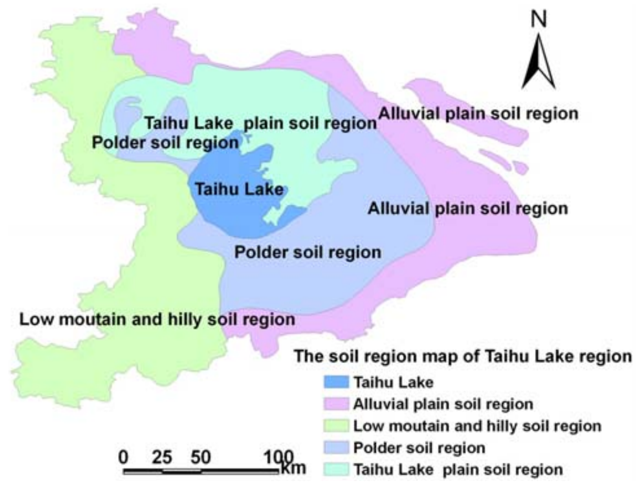

Fig. 6. The paddy soil region map of the Taihu Lake region, China.

In the Taihu Lake region, submergenic soils support 0.0073 Mha of rice fields with an emission rate of 105 $kg\,C\,ha^{-1}\,y^{-1}$. Although this subgroup has a neutral pH value (6.8) and a low clay content (15%), the organic carbon content was only 10 $g\,kg^{-1}$, leading to moderate CH_4 emissions (Fig. 5a, b). The areas dominated by gleyed and bleached soil account for 4.4 and 8.8% of the regional paddy soil area, with average CH_4 fluxes of 660 and 95 $kg\,C\,ha^{-1}\,y^{-1}$, respectively. The CH_4 emission rate from the gleyed subgroup was much higher than other soil subgroups due to continuous flooding and a high organic carbon content (25 $g\,kg^{-1}$) (Yagi and Minami, 1990; Wang et al., 1993). The CH_4 emission rate from the bleached subgroup was low due to low organic carbon content (10 $g\,kg^{-1}$).

3.4 CH_4 emission patterns in different paddy soil sub-regions in the Taihu Lake region

The Taihu Lake region can be divided into four sub-regions based on landscape characteristics: rolling hills, plains around the lake, plains along the river, and polders (Xu et al., 1980) (Fig. 6).

The rolling hills and low mountains sub-region was distributed in the western and northern extents with paddy fields of 0.39 Mha. Soils in this sub-region are weakly acidic (6.0), have low soil organic carbon content (13 $g\,kg^{-1}$) and are well drained (Ma et al., 1999; Rashid et al., 2008). The modeled average CH_4 flux rate for the region was equivalent to 68 $kg\,C\,ha^{-1}\,y^{-1}$.

The plain around the lake sub-region exists as an arc shape and spreads northward and eastward from the center. The 0.59 Mha of rice fields have high soil organic

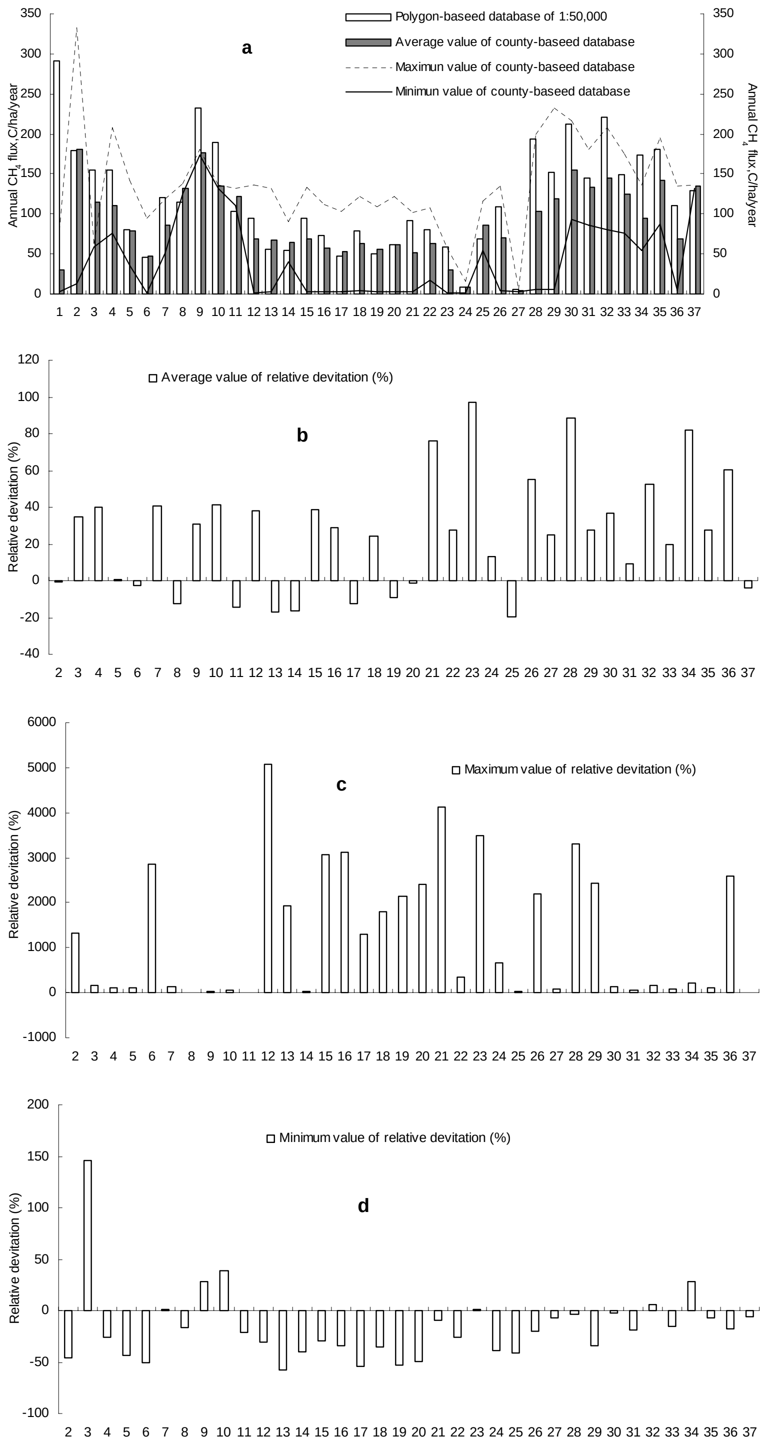

Fig. 7. (a) Comparison of the average CH_4 flux modeled with the county- and polygon-based database for the Taihu Lake region, China; and **(b, c** and **d)** average (maximum or minimum) value of the relative deviation of the average CH_4 flux modeled with the polygon-based database by county level as a baseline for the Taihu Lake region, China. (1. Wu County; 2. Zhangjiagang; 3. Changshu; 4. Taicang; 5. Kunshan; 6. Wujiang; 7. Wuxi; 8. Jiangyin; 9. Wujin; 10. Jintan; 11. Liyang; 12. Yixing; 13. Dantu; 14. Jurong; 15. Danyang; 16. Jiaxing; 17. Jiashan; 18. Pinghu; 19. Haiyan; 20. Haining; 21. Tongxiang; 22. Huzhou; 23. Changxing; 24. Anji; 25. Deqing; 26. Yuhang; 27. Linan; 28. Minhang; 29. Jiading; 30. Chuansha; 31. Nanhui; 32. Qingpu; 33. Songjiang; 34. Jinshan; 35. Fengxian; 36. Baoshan; 37. Chongming.)

carbon ($16\,g\,kg^{-1}$) and large amounts of fertilizers applied ($302\,N\,ha^{-1}\,yr^{-1}$). Moreover, gleyed soils cover an extensive area in this sub-region. So, the modeled average CH_4 flux was equivalent to $173\,kg\,C\,ha^{-1}\,y^{-1}$.

The alluvia plains along the river sub-region contains about 0.64 M ha of rice fields. The soil organic carbon is $23\,g\,kg^{-1}$ and the soil pH is 7.3. A reaction range of 6.8–7.2 is favorable for methane production (Pacey et al., 1986). Moreover, fertilizer application ($370\,N\,ha^{-1}\,yr^{-1}$) was high in this sub-region. The modeled average CH_4 flux was equivalent to $133\,kg\,C\,ha^{-1}\,y^{-1}$.

The polder sub-region is low in elevation, and contains 0.69 Mha of rice fields. Soils in this sub-region were mostly weakly acidic (6.5), and clay contents reach ∼30%. The modeled average CH_4 flux was equivalent to $118\,kg\,C\,ha^{-1}\,y^{-1}$.

3.5 Comparison of CH_4 emissions modeled with polygon- and county-based databases in the Taihu Lake region

According to the default method for regional simulations with the DNDC model, counties are used as the basic simulation unit. The county-based database usually requires relatively less soil data. However, when the DNDC model is used for a region with high heterogeneity in soil properties, the method produces higher uncertainty due to limited spatially differentiated soil information (Pathak et al., 2005; Cai et al., 2003; Li et al., 2004; Rüth et al., 2008). The study carried out for the Taihu Lake region has provided a chance to test the uncertainty as there is detailed soil information available for the region. The polygon-based soil database contains 52 034 polygons. By contrast, only 37 counties are found in the county-based database. However, DNDC model runs with the polygon-based database produced a single CH_4 flux for each polygon while runs with the county-based database produced a range of CH_4 fluxes to define the uncertainty. The results simulated by DNDC with the two types of databases were compared to assess the advantages of using the detailed, polygon-based soil dataset.

Figure 7a shows the average CH_4 flux modeled with the county- and polygon-based databases for the Taihu Lake region. In the figure, the average CH_4 fluxes modeled with the county-based database are expressed with ranges defined by the minimum and maximum CH_4 fluxes. The average CH_4 flux modeled with the polygon-based database is expressed with single values. Results from the two methods demonstrate the spatial patterns of CH_4 emissions across the 37 simulated counties. Most of the polygon-based CH_4 fluxes are located within the ranges produced by the county-based method. However, discrepancies exist between results from the two methods. For the Taihu Lake region, the total CH_4 emissions modeled with the county-based database ranged from 2.2 to 5.8 Tg C; and the total CH_4 emissions modeled with the polygon-based database is equivalent to 5.7. The total CH_4 emissions generated from the polygon-based database are 2.6 times the minimum CH_4 emissions generated from the county-based database, and 0.98 times the maximum CH_4 emissions generated from the county-based database. The relative deviation of maximum and minimum is 60% and −2.0% for the entire region, respectively.

For most of the simulated counties, there are large differences in the average CH_4 flux modeled with the county- and polygon-based databases in the Taihu Lake region (Fig. 7). For example, in Wu County the CH_4 flux modeled with the polygon-based database database is equivalent to $290\,kg\,C\,ha^{-1}\,y^{-1}$. This is nearly 3.7 times the minimum CH_4emissions generated from the county-based database, and 130 times of the maximum CH_4 flux generated from the county-based database due to gleyed soils covering an extensive area in this county. Continuous flooding of gleyed soils can be set using the polygon-based database method, but the water management cannot be set using the county-based database method. This is because the simulation of county-based database cannot differentiate the difference of paddy soil type within a county, water management was usually set according to the conventional practice for the entire region, although different soil type have different water management practices. However, the simulation of polygon-based database can differentiate different water management of paddy soil type respectively. In this study, the water management of gleyed paddy soil, which is in a state of long-term waterflooding, is different from other paddy soil sub-region in the Taihu Lake region. All the gleyed paddy soil polygons were simulated separately by adopting water management of continuous flooding. The average value of the relative deviation for Wu County was as high as 880%. This also showed that smaller soil units or using different soil types would improve simulated CH_4 emissions from rice fields in the Taihu Lake region using the DNDC model.

On the basis of the DNDC method, the fraction of clay content is the most sensitive parameter in DNDC affecting CH_4 emissions (Li et al., 2004). The clay content in the county-based database for Yixing (10%–53%), Danyang (16%–53%), Jiaxing (20%–56%), Tongxiang (20%–52%), and Minhang (17%–46%) vary widely. The CH_4 flux modeled with the polygon-based database are nearly 0.7, 0.7, 0.7, 0.9 and 1.0 times that of the minimum, respectively, and are nearly 52, 32, 32, 42 and 34 times that of the maximum CH_4 flux generated with the county-based database, respectively. With the county level average CH_4 flux as the baseline, the average value of the relative deviation ranged from 30% to 89% for those counties. Only eight counties (Jiangyin, Wujin, Jintan, Liyang, Deqing, Linan, Chuansha, and Chongmig) had relatively low deviations. The CH_4 flux modeled with the polygon-based database were between 0.5 to 2.0 times the minimum and maximum CH_4 flux generated with the county-based database due to low discrepancy of soil properties. This comparison indicates that utilizing more precise soil databases will substantially improve the accuracy of the estimates of greenhouse gas emissions obtained with process-based models, such as the DNDC model, at regional scales.

4 Conclusions

Quantifying CH_4 emissions from wetland ecosystems is a relatively new issue in global climate change studies. Process-based models integrated with GIS databases can play an important role in the biogeochemical cycles based on spatially differentiated information, and either mitigation efforts in the most beneficial regions or evaluate spatial variability of greenhouse gas impacts. The biogeochemical model, DeNitrification and DeComposition or DNDC, is a powerful tool for estimating CH_4 emissions from terrestrial ecosystems and has been applied in rice paddies with various purposes. This study showed that by linking with a detailed soil database, the DNDC model estimated emissions equivalent to 5.7 Tg C from the 2.3 Mha of paddy rice fields in the Taihu Lake region of China for the period between 1982 and 2000. The modeled annual CH_4 emissions were highly variable from year to year. The trend is mainly attributed to the increase or decrease of N-fertilizer and livestock manure application.

Annual CH_4 emission rates in the Taihu Lake region are highly differentiated based on paddy soil subgroups, subregions, and county levels due to heterogeneity in soil properties. Therefore, uncertainty in soil properties introduces large uncertainty into CH_4 estimates. As such, using smaller soil units is preferable for defining implementation of government policies designed to reduce CH_4 emissions in the Taihu Lake region. Further, smaller soil units help to ensure that such policies can be implemented at the farm level successfully.

At the regional scale, total CH_4 emissions were estimated with the DNDC model by linking it to two different soil databases. The CH_4 emissions modeled with the two databases showed similar spatial patterns of CH_4 fluxes across the counties. However, discrepancies existed between the results from the two methods due to heterogeneity in soil properties (e.g. clay content). In addition, the simulation of county-based database of the default method with the DNDC model cannot differentiate the difference of paddy soil type within a county, water management was usually set according to the conventional practice for the entire region. However, polygon-based database can simulate different water management of paddy soil type respectively. Therefore, utilizing more precise soil databases will substantially improve the accuracy of the estimates of greenhouse gas emissions from process-based models.

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