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**DNDC simulations of
CH₄**

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Quantifying methane emissions from rice fields in Tai-Lake region, China by coupling detailed soil database with biogeochemical model

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Abstract

China's paddy rice accounts for about 22% of the world's rice fields, therefore it is crucial to accurately estimate the CH₄ emissions at regional scale to gauge their contribution to global greenhouse gas effect. This paper reports an application of a biogeochemical model, DeNitrification and DeComposition or DNDC, for quantifying CH₄ emissions from rice fields in Tai-Lake region of China by linking DNDC to a 1:50 000 soil database, which was derived from 1107 paddy soil profiles in the Second National Soil Survey of China in the 1980s–1990s. The modeled results estimate that the 2.34 M ha of paddy rice fields in Tai-Lake region emitted about CH₄ of 5.67 Tg C for the period of 1982–2000, with the average CH₄ flux ranged from 114 to 138 kg C ha⁻¹y⁻¹. The highest emission rate (659.24 kg C ha⁻¹y⁻¹) occurred in the subgroup of “gleyed paddy soils”, while the lowest (90.72 kg C ha⁻¹y⁻¹) were associated with the subgroup “degleyed paddy soils”. The subgroup “hydromorphic paddy soils” accounted for about 52.82% of the total area of paddy soils, the largest of areas of all the soil subgroups, with the CH₄ flux rate of 106.47 kg C ha⁻¹y⁻¹. On a sub-regional basis, the annual average CH₄ flux in the Tai-Lake plain soil region and alluvial plain soil region was higher than that in low mountainous and hilly soil region and polder soil region. The model simulation was conducted with two databases using polygon or county as the basic unit. 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 CH₄ emissions in Tai-Lake region. However, discrepancies exist between the results from the two methods, the relative deviation is –42.10% for the entire region, and the relative deviation ranged from –19.53% to 97.30% for most counties, which indicates that the more precise soil database was necessary to better simulate CH₄ emissions from rice fields in Tai-Lake region using the DNDC model.

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1 Introduction

With the development of economy, the environmental problems are becoming increasingly serious. And the enhancement of greenhouse effects and global warming are two important aspects arousing have aroused wide attention. Methane (CH_4) is an important greenhouse gas and playing a great role in these processes. Since the 1990, CH_4 emission is responsible for approximately 15%–20% of the GHG emissions on the global (IPCC, 1996). At present, the atmospheric CH_4 concentration is 1774 ppb, it increased rapidly at a rate of $1.0\% \text{ yr}^{-1}$ (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 (Lelieveld et al., 1993; Cicerone et al., 1988). China has approximately 22% of the world's rice paddies and 38% of the world's rice production, and CH_4 emission is responsible for approximately 28% of the total CH_4 emission of the world's rice fields (Jiang et al., 2004; Wang et al., 1993). Therefore, accurate estimates of CH_4 emissions from the rice field in China are vitally important to evaluate atmospheric on of agricultural production.

Recently, using models for estimating CH_4 emissions from rice field has become popular. These models can be grouped into empirical/semi-empirical, regression, and process model, the latter gives the more intricate description of the various factors involved. Several empirical and semi-empirical models have also been developed to estimate CH_4 emissions from rice fields (e.g., Huang et al., 1998). Matthews et al. (2000a) developed a process-based Methane Emissions from Rice EcoSystems (MERES) model for simulating CH_4 emissions from rice fields. Using this MERES model integrated with daily weather data, spatial soil data, and rice-growing statistics, they estimated CH_4 emissions from rice fields in China, India, Indonesia, Philippines, and Thailand (Matthews et al., 2000b). Cao et al. (1995a) developed a process-based Methane Emission Model (MEM), which was then applied to estimate CH_4 emissions from rice fields in China (Cao et al., 1995b) and at the global scale (Cao et al., 1996, 1998).

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The DeNitrification-DeComposition (DNDC) model developed by Li and his colleagues is a process-based model that focused on trace gas emissions from agroecosystems (Li et al., 1992a, b, 1994). Using this model, environmental impacts such as climate change, land-use change and agricultural activities including alternative farming management practices, on CH₄ emissions can be assessed in a comprehensive way. At present, DNDC has demonstrated good performance through its long-term applications in North America, Europe, Asia and Oceania. For instance, Li et al. (2000) reported the model tests against observed CH₄ emissions from a rice-winter wheat rotated field in Wu County, Jiangsu Province, China, a maize field at La Selva Biological Station in Costa Rica, two rice plots at Beaumont, Texas, USA and a rice field in Fengqiu County, Henan Province, China with encouraging results. The results demonstrate DNDC robustness in capturing patterns and magnitudes of CH₄ emissions measured at the sites which were across a wide range of climate zones, soil types and management regimes. Jagadeesh et al. (2006) simulated CH₄ and N₂O emissions from rice fields at different geographical 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.

In China, the scientists have studied trace gas emissions using the DNDC model for many years. At the dry-land, Wang et al. (1999) simulated nitrogen circulation and N₂O emissions of soybean field in Sanjiang Plain of China using the DNDC model. Wang et al. (2002) studied soil respiration of summer-corn field in Huanghuaihai Plain with the DNDC model. Wang et al. (2004) simulated the soil carbon cycle of agro-ecosystem in High-yield Huabei Plain of China using the DNDC model with the support of GIS regional database. At the paddy field, Zheng et al. (1997) simulated CH₄ emissions at rice field of Wu County in the Jiangsu Province of China with the DNDC model, results showed that the model simulated results were in agreement with CH₄ emissions from rice fields. Cai et al. (2003) simulated CH₄ from rice fields at different region in China using the DNDC model and found that that simulated seasonal CH₄ emissions from paddy soils were in well agreement with field studies.

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The DNDC model has been utilized for upscaling CH₄ emission from site to regional scale. So far, most of the DNDC modeling conducted at regional scale adopted county as the basic geographic unit. Since regional estimates of CH₄ fluxes cannot be derived simply from the extension of results from field-plot measurement of CH₄ because of the spatial variations of the drivers including climate, soil and management (Jagadeesh et al., 2006). The county scale model simulations can have great uncertainties as the soil properties averaged or unified for each county that largely ignore the nonlinear impacts of the soil heterogeneity within a county (Pathak et al., 2005; Li et al., 2004; Cai et al., 2003).

In this study for the selected rice-dominating region, Tai-Lake Region, we shifted the regional database linked to DNDC from county-based to a new grid system which was built upon a new soil map that was lately 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, we tried improving the model performance. The objectives of this study were to (1) estimate CH₄ emissions from rice paddy fields in Tai-Lake region, China in 1982–2000; (2) understand impact of crop system change, and of different agricultural management skills on CH₄ emissions; and (3) improving the accuracy of the estimates of CH₄ emissions with the DNDC model at regional scale.

2 Materials and methods

2.1 Study area

The Tai-Lake region (118°50′–121°54′ E, 29°56′–32°16′ N), an area of extensive rice cultivation, is located in the middle and lower reaches of the Yangtze River paddy soil region of China, including the entire Shanghai City administrative area and a part of Jiangsu and Zhejiang provinces, covering about a total area of 36 500 km² (Fig. 1) (Li, 1992). It mainly consists of plains formed on the 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 the mean temperature is around 16°. The frost-free period is over 230 days (Xu et al., 1980).

The study area is one of the oldest agricultural regions with a long history of rice cultivation for several centuries (Xu et al., 1980). Approximately 66% of the total land area is covered with paddy soils. 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) (Soil Survey Staff, 1994): Hydromorphic (Typic Epiaquepts), Submergenic (Typic Endoaquepts), Bleached (Typic Epiaquepts), Gleyed (Typic Endoaquepts), Percogenic (Typic Epiaquepts), and Degleyed (Typic Endoaquepts) (Shi et al., 2006). 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 in the region.

2.2 Description of the DNDC model

The DNDC (DeNitrification and 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, it is one of the more widely accepted biogeochemical models in the world (Li et al., 1992a, b, 1994, 1996; Li, 2000, 2007). The model contains six interacting sub-models which describe the generation, decomposition and transformation of organic matter, and outputs the dynamics of components of SOC and fluxes of greenhouse gases.

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 fed to the other sub-models; (2) nitrification sub-model; (3) denitrification sub-model, which calculate hourly denitrification rates and N₂O, NO and N₂ production during periods when the soil Eh decreases due to the rainfall, irrigation, flooding or soil freezing; (4) decomposition sub-model simulating decomposition of the SOC pools and

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CO₂ production through soil microbial respiration; (5) plant growth sub-model, which calculates daily root respiration, water and N uptake by plants, and plant growth; and (6) fermentation sub-model, which calculates daily methane (CH₄) production and oxidation.

5 The DNDC model can simulate C and N biogeochemical cycles in paddy rice ecosystems, whereby the model has been modified 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 the water management. During these changes in soil water content, the soil Eh is subject to substantial
10 changes between +600 and -300 mV. The soil Eh dynamics is one of the key processes controlling CH₄ and N₂O production/consumption in the paddy soils. CH₄ and N₂O are produced under certain Eh conditions (-300 to -150 mV for CH₄, and 200–500 mV for N₂O), so variation in soil Eh determines the dominant greenhouse gas emitted from the paddy soil.

15 DNDC allocates substrates (e.g., DOC, NO₃⁻, NH₄⁺ etc.) to reductive reactions (e.g., denitrification, methanogenesis) and oxidative reactions (e.g., nitrification, methanotrophy) based on relative fractional volumes of the oxidizing and reducing zones, and the potential oxidation and reduction reactions are determined by Eh and pH (Yu et al., 2001, 2004; Li, 2007). By tracking the formation and deflation of a series of Eh volume
20 fractions driven by depletions of O₂, NO₃⁻, Mn⁴⁺, Fe³⁺, and SO₄²⁻ consecutively, DNDC estimates soil Eh dynamics as well as rates of reductive/oxidative reactions, which produce and consume CH₄ or N₂O in the soil. The tracking links the soil water regime to trace gas emissions for rice paddy ecosystems. Temporally, DNDC predicts daily CH₄ and N₂O fluxes from rice fields through the growing and fallow seasons, during
25 extended flooded periods or shifts between flooded and drained states.

2.3 Database development

A major challenge for using an ecosystem model at a regional scale is to assemble adequate data sets needed to initialize and run the model. DNDC modeling of CH₄ emis-

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sion from rice paddy fields requires data describing the soil properties, daily weather, cropping systems and agricultural management practices.

In the study, two types of spatial soil databases, polygon-based and county-based, were utilized 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 were compiled in the spatial database using the Pedological Knowledge Based (PKB) method (Shi et al., 2004). The soil dataset covered 37 counties in Tai-Lake region. The basic mapping units are based on the soil types as defined in Genetic Soil Classification of China (GSCC). The soil dataset consisted of 81 soil attribute fields, including profile code, soil name (in GSCC), profile location, horizon name, thickness of profile, bulk density, organic matter content, texture and pH, etc. The county-based soil database was built up based on the default method developed for DNDC, with 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, DNDC produces two CH₄ fluxes resulting from two runs with the maximum and minimum soil values, respectively. The two flux values will form a range to define the uncertainty induced from the upscaling for each county (see detail in Li et al., 2004). In a purpose for comparison in this study, both the polygon-based and county-based soil databases were used in parallel to run DNDC to generalize the regional CH₄ emissions for the Tai-Lake region.

The cropping dataset included crop types, physiological data of summer rice and winter wheat, and planting and harvest dates, etc. The agricultural management dataset included sowing acreages, nitrogen fertilizer application rates, livestock and agricultural population at county level from 1982 to 2000 (from 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) for the period of 1982–2000, which were acquired from 13 weather stations in

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Tai-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 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% $\text{NH}_4\text{H}_2\text{PO}_3$; (2) 15% of aboveground crop residue was returned to the soil; (3) 20% of livestock wastes and 10% of human wastes were added as manure to the soil; and (4) Tillage was applied twice before 1990 for the rice-wheat rotation with 20 cm tilling depth for rice and 10 cm for wheat on the planting dates; and 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 data sets from wetland rice sites in the United States, Italy, China, Thailand, 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). If the site soil characteristics and 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 Tai-Lake region of China ranged from 20 to 200 $\text{kg C ha}^{-1}\text{y}^{-1}$ (Table 1) (Wang et al., 2001). In the present study, DNDC-modeled CH_4 emission from the majority paddy soils are in the range of 20 to 200 $\text{kg C ha}^{-1}\text{y}^{-1}$ (Fig. 3), indicating that the modeled results are encouragingly consistent with observations for the Tai-Lake region.

The simulated CH_4 emission using DNDC was greatly in accordance with field measurement values in Nanjing, Jiangning, Wu County, Hangzhou, Jurong and Suzhou of

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Tai-Lake region (Table 2) (Wang et al., 2001; Cai et al., 2003). Total CH₄ emissions ranged from 14.0 to 180.0 kg C ha⁻¹y⁻¹, while the simulated emissions were in the range of 14.7–197.6 kg C ha⁻¹y⁻¹. The difference between the observed and simulated emissions in all sites ranged from –11.6 to 50.6 kg C ha⁻¹y⁻¹. The highest percentage of relative deviation was found in Nanjing site while the lowest was recorded in Suzhou site. Most discrepancies between simulated and observed fluxes per year were less than 10% of the field estimate of flux per year.

3.2 Inter-annual variation in CH₄ emissions

Based on modeled results, the 2.34 Mha of paddy soils in Tai-Lake region emitted about CH₄ of 5.67 Tg C for the period of 1982–2000, with the average CH₄ flux ranged from 114 to 138 kg C ha⁻¹y⁻¹. However, the modeled annual CH₄ emissions highly varied from year to year (Fig. 4). Before 1985, the CH₄ emissions of the entire area were very low, those four years from 1982 to 1985 were account for 18.93% of the total CH₄ emissions. The main reason that input of chemical fertilizer and manure was low. During the period of 1986–1992, the magnitude of applied chemical fertilizers and livestock was greatly increased. The increase in livestock number provided more manure, which in turn enhanced substrates for methanogens (Sass et al., 1991; Zheng et al., 1999; Sun et al., 2007). In addition, increase in the magnitude of applied fertilizer could lead to an increase in CH₄ emissions due to an increase in rice plant productivity and biomass, or to a decrease due to soil Eh elevation induced by fertilizers such as ammonium sulfate, those seven years from 1986 to 1992 were account for 37.37% of the total CH₄ emissions (Dunfield et al., 1995; Lindau et al., 1990; Denier van der Gon and Neue, 1994; Wassmann et al., 1994; Yao and Chen, 1994). However, the increasing rate of the modeled CH₄ emission decreased for the period of 1993–2000. The change could be related to the economic development in this region. According to statistics the amount of synthetic fertilizer use in the region decreased since 1993 (from Institute of Geographic Sciences and Natural Resources Research, Chinese Academy

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3.3 Impacts of paddy soil subgroups on CH₄ emissions

Subgroup of “hydromorphic” is the most prominent paddy soil type in Tai-Lake region, accounting for 52.82% of the total paddy soil area (Fig. 5a). The modeled average CH₄ flux was as high as 106.47 kg C ha⁻¹y⁻¹ driven by the high organic matter contents and total nitrogen in the soils (Fig. 5b). Some researches report that the CH₄ emissions and organic matter content, total nitrogen in the soil had a positive correlation (Zheng et al., 1999; Yao et al., 1999). In Tai-Lake region, the total CH₄ emissions from the subgroup was 2.48 Tg C, accounted for 43.73% of the total CH₄ emissions from the region. The subgroups of “degleyed” and “percogenic” were distributed in 17.65% and 16.02%, respectively, of the total paddy soil area in the region (Fig. 5a). The modeled CH₄ emissions from the “degleyed” and “percogenic” subgroups were 0.71 and 0.83 Tg C, accounted for 12.45% and 14.60% of the regional CH₄ emissions, respectively. The CH₄ emission rate from subgroup “percogenic” was higher than that from subgroup “degleyed” (Fig. 5b). The main reason were that the pH value of the former was close to neutral state, and the average of clay content were only 21.51%; the latter was that not only mostly weak acidic, but also the average of clay content had reached a level of 29.88%. The research indicated that the optimum range of pH value was 6.8–7.2 on methane production (Pacey et al., 1986), and soil texture has also been documented to affect CH₄ emissions from rice fields, increasing emissions with decreasing clay content (Cai et al., 1999). In Tai-Lake region the area dominated by subgroup of “submergenic” had 0.0073 M ha of rice fields with a high emission rate of 105.41 kg C ha⁻¹y⁻¹ due to the neutral state of pH value, and a low clay content (14.76%) in the soil (Fig. 5a and b). The areas dominated by subgroups of “gleyed” and “bleached” had 4.38% and 8.81%, respectively, of the regional paddy soil area (Fig. 5a) with average CH₄ fluxes of 659.24 and 99.37 kg C ha⁻¹y⁻¹, respectively.

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3.4 Spatial distribution of CH₄ emissions in Tai-Lake region

The Tai-Lake region can be divided into four sub-regions based on the land-use characteristics: the rolling hills, the plains around the lake, the plain along the river, and the polders (Xu et al., 1980) (Fig. 6). In the sub-region of rolling hills and low mountains, there was 0.39 M ha of paddy fields distributed in the western and northern parts of the Tai-Lake plain. The soils in the sub-region were less fertile with relatively low fertilizer application rates and good drainage ability (Ma et al., 1999; Rashid et al., 2008). The modeled average CH₄ flux rate was 68.12 kg C ha⁻¹y⁻¹.

The sub-region of the Tai-Lake plain like an arc shape spreads northward and eastward from the centre, there were about 0.59 M ha of rice fields, which contained high organic matter contents and applied with high rates of fertilizers. The modeled average CH₄ flux was 173.04 kg C ha⁻¹y⁻¹.

The sub-region of the plain along the river is an alluvial plain with about 0.64 M ha of rice fields. The soils contained organic matter 23.20 g kg⁻¹, and the soil pH was 7.25 which is almost in the range (6.8–7.2) favorable for methane production (Pacey et al., 1986). Moreover, fertilizer input was also high in this sub-region. The modeled average CH₄ flux was 132.72 kg C ha⁻¹y⁻¹. The sub-region of polder is low in elevation, having 0.69 M ha of rice fields with a low crop production and pH value (6.52) in the soil. The modeled average CH₄ flux had reached 117.95 kg C ha⁻¹y⁻¹.

The spatial differentiation of CH₄ emissions was also shown at the county scale within the Tai-Lake region (Fig. 7). The average annual CH₄ fluxes were higher than 200 kg C ha⁻¹ for counties Wu County, Wujin, Chuangsha and Qingpu. In addition, the average annual CH₄ flux in Zhangjiagang, Changshu, Taicang, Jintan, Jinshan, Minhang and Fengxian were also comparatively higher, ranged from 150 to 200 kg C ha⁻¹. Most of the counties in the region had average annual CH₄ fluxes ranged from 50.0 to 200.0 kg C ha⁻¹. Two counties, Jurong and Anji, had the lowest CH₄ fluxes, 9.29 and 5.73 kg C ha⁻¹, respectively. The main reason that the pH value of the Anji county has a slight acidity, ranged from 5.4 to 6.7; Linan has not only mostly weak acidic soil, but

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also the low mean annual temperature. It has been demonstrated that CH₄ production and emissions are suppressed in acid soil and at low temperature (Jugsujinda et al., 1996; Yagi et al., 1998).

3.5 Comparison of CH₄ emissions modeled with polygon- and county-based databases

According to the default method for regional simulations with the of DNDC model, county is used as the basic simulation unit. The county-based database usually requires relatively less soil data. However, when DNDC is applied for a region with high heterogeneity is soil properties; the method would produce higher uncertainty due to missing the spatially differentiated soil information (Pathak et al., 2005; Cai et al., 2003; Li et al., 2004; R uth et al., 2008). The study carried out for the Tai-Lake region has provided a chance to test the uncertainty as there is detailed soil information available for the region. As above described, a polygon-based database was built up based on a 1:50 000 soil map for the Tai-Lake region. There are 52 034 polygons in the polygon-based database. In contrast, there are only 37 counties in the county-based database. However, the DNDC runs with the polygon-based database produced a single CH₄ flux for each polygon while the DNDC runs with the county-based database produced a range of CH₄ flux 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 8a shows the CH₄ emissions modeled with the county- and polygon-based databases for the Tai-Lake region. In the cart, the CH₄ emissions modeled with the county-based database are expressed with ranges defined by the minimum and maximum CH₄ fluxes; and the CH₄ emissions modeled with the polygon-based database are expressed with single values. The results from the two methods demonstrates the spatial patterns of CH₄ emissions across the simulated 37 counties; and most of the polygon-based CH₄ fluxes are located within the ranges produced by the county-based method. However, discrepancies exist between the results from the two methods. For

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the Tai-Lake region, the total CH₄ emissions modeled with the county-based database are ranged from 2.15 to 5.83 Tg C, with an average 3.99 Tg C; and the total CH₄ emissions modeled with the polygon-based database is 5.67 Tg C. The relative deviation (y) of two methods was calculated by the following equation: $y=(x_s-x_0)/x_0 \times 100$; where x_0 is the county level average CH₄ emissions with the county-based database, and x_s is the CH₄ emissions produced with the polygon-based database. In comparison between the two methods, the CH₄ flux generated with the polygon-based database is 1.42 times of the average CH₄ flux generated with the county-based database. The relative deviation is -42.10% for the entire region.

As for most of the simulated counties, there are large amounts of difference in the CH₄ emissions modeled with the county- and polygon-based databases in Tai-Lake region (Fig. 8a and b). For example, for county Wu County, the CH₄ flux modeled with the polygon-based database is 0.85 Tg C, this is nearly 9.84 times higher than that with the county-based database. Correspondingly, the relative deviation of CH₄ emissions for Wu County is as high as 883.70%. With the county level CH₄ emissions as the baseline, the relative deviation ranged from -19.53% to 97.30% for most counties. Only seven counties had relative low deviations (<10%). The comparison indicates that utilizing more precise soil databases will substantially improve the accuracy of the estimates of greenhouse gas emissions modeled with process-based models such as DNDC at regional scale.

4 Conclusions

Quantifying CH₄ emissions from wetland ecosystems is a relatively new issue in the global climate change studies. Process-based models integrated with GIS databases can play an important role to biogeochemical cycles based on spatially differentiated information, and either target mitigation efforts to 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 CH₄ emissions from

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terrestrial ecosystems and has been applied in rice paddies with various purposes. The study reported in the paper showed that by linking with a detailed soil database, DNDC estimated 5.67 Tg C emitted from the 2.34 M ha of paddy rice fields in Tai-Lake region, China during the period of 1982–2000, the modeled annual CH₄ emissions highly varied from year to year. The trend is mainly attributed to the increase or decrease of N-fertilizer and livestock application.

Annual CH₄ emission rates in Tai-Lake region have a large difference in different paddy soil subgroups, sub-regions and county level, due to the high variation in soil properties. Therefore, uncertainty in soil properties introduces large uncertainty into CH₄ estimates. This result suggests that the government should adjust the proper policy to mitigate CH₄ emissions according to different soil types in Tai-Lake region.

At the regional scale for the Tai-Lake region, total CH₄ emission was estimated with DNDC by linking it to two different soil databases. The CH₄ emissions modeled with the two databases showed the similar spatial patterns of CH₄ fluxes across the counties. However, discrepancies exist between the results from the two methods, which indicate that utilizing more precise soil databases will substantially improve the accuracy of the estimates of greenhouse gas emissions modeled with process-based models.

Acknowledgements. We gratefully acknowledge support for this research from National Natural Science Foundation of China (No. 40621001), National Basic Research Program of China (2007CB407206) and The Frontier Project of the Chinese Academy of Sciences (No. IS-SASIP0715).

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Table 1. The CH₄ emission from rice field of 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.,	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 223, continuous flooding	143.3
Cai et al.,	^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.,	Jiangning SOM 2.29%	1990–1992	manure + urea 100	195.0
			manure	171.0
			ammonium sulfate 140	47.3
Xiong et al.,	Wu County SOM 3.5%	1994–1996	manure + urea 100, half of dry farming	119.3
			urea 191	82.5
			ammonium hydrogen carbonate 191	52.5

^a SOM: Soil Organic Matter;

^b JASS: Jiangsu Academy for Agriculture Science.

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Table 2. Comparison between observed and DNDC-modeled CH₄ fluxes from rice field in Tai-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

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Fig. 1. Geographical location of the study area.

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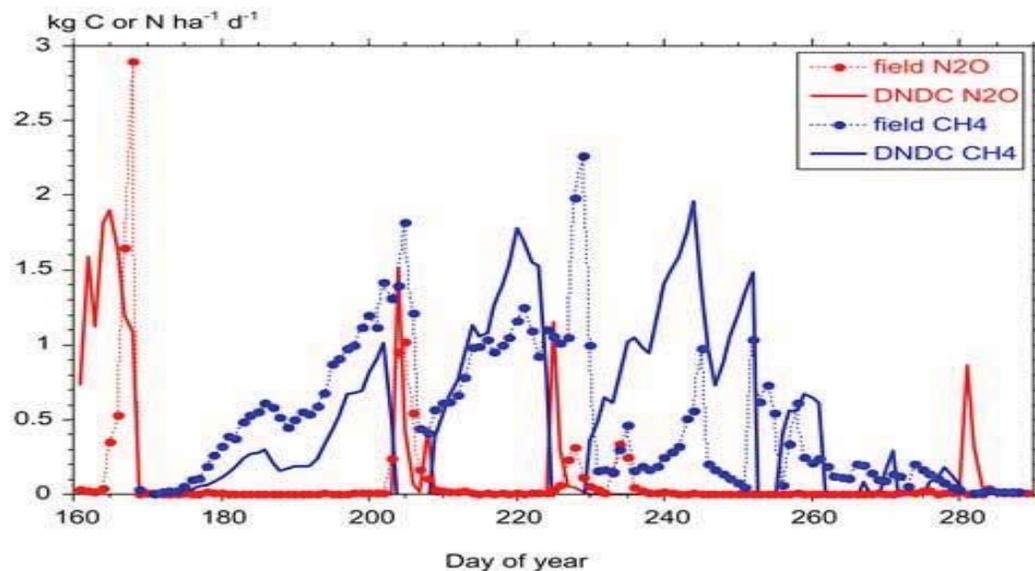


Fig. 2. Comparison between observed and DNDC-modeled CH₄ and N₂O fluxes from a paddy rice field applied with midseason drainage in Wu County of Tai-Lake region, China, in 1995.

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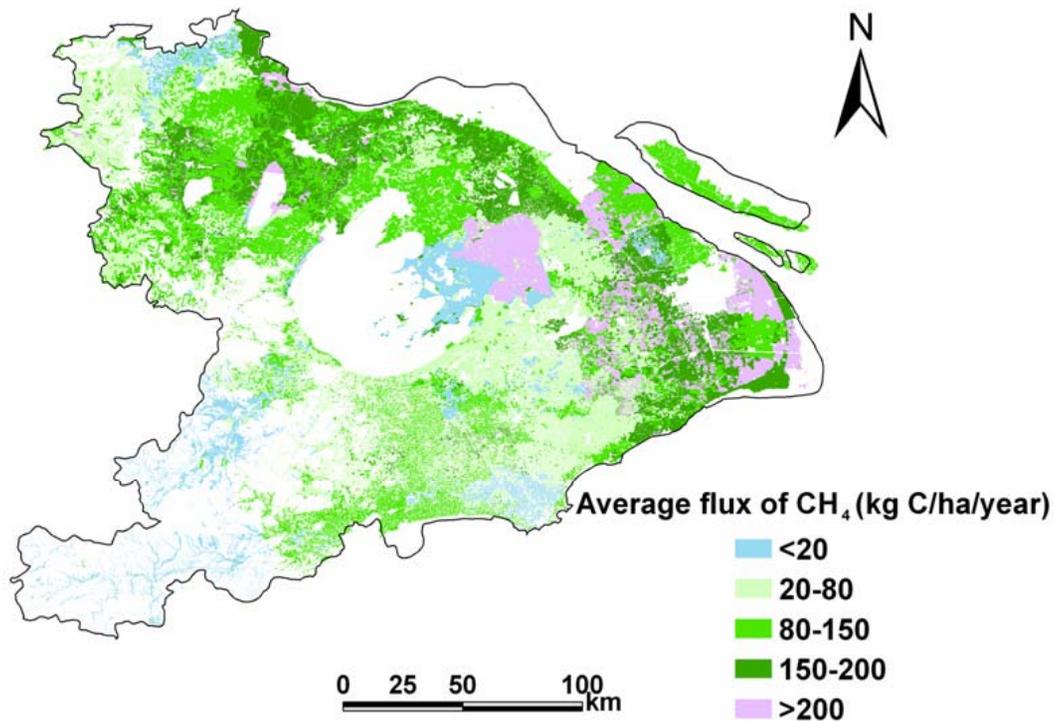


Fig. 3. Distribution of average CH₄ flux from 1982 to 2000 in Tai-Lake region.

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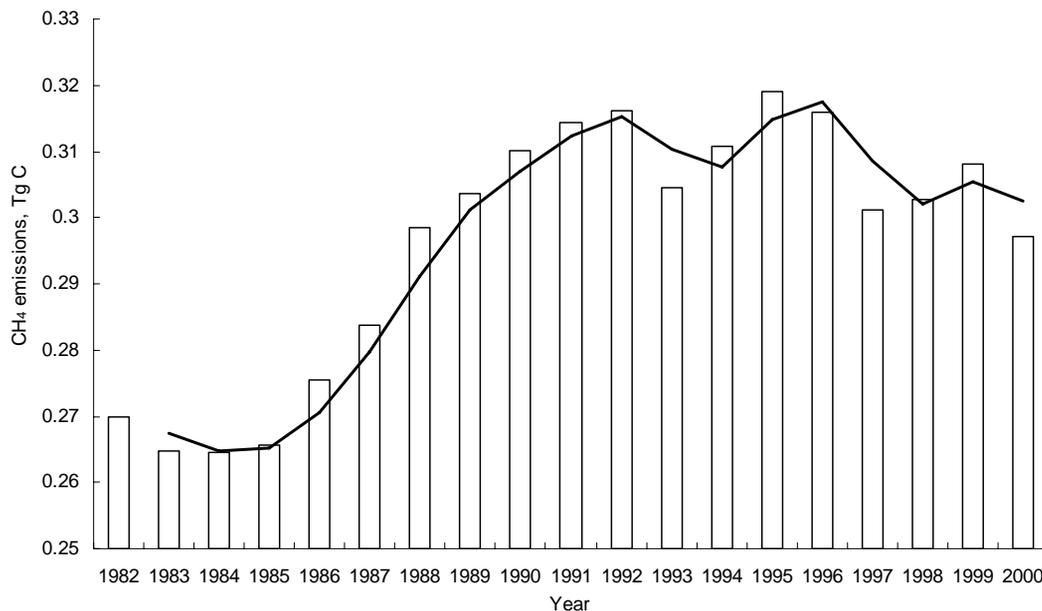


Fig. 4. Distribution of average CH₄ flux from 1982 to 2000 in Tai-Lake region.

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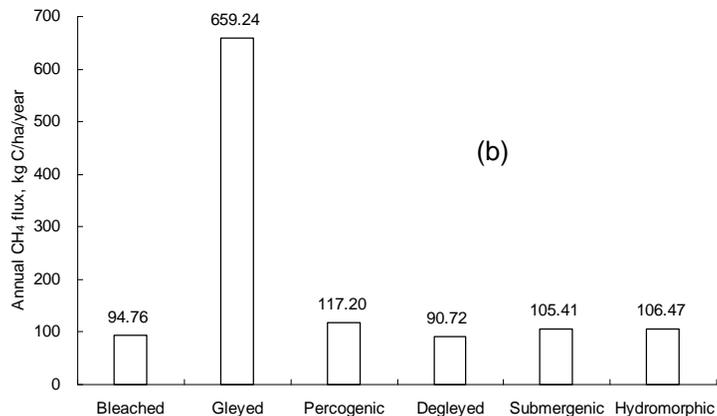
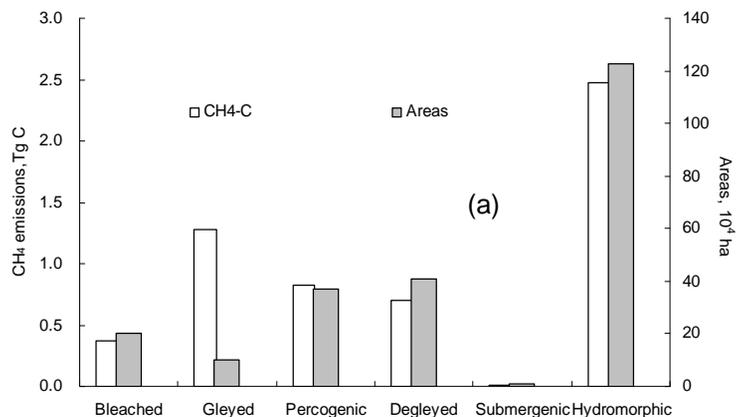


Fig. 5. (a) Comparison between areas and total CH₄ emissions of in various paddy soil subgroups and (b) comparison of the average CH₄ flux per year in various paddy soil subgroups.

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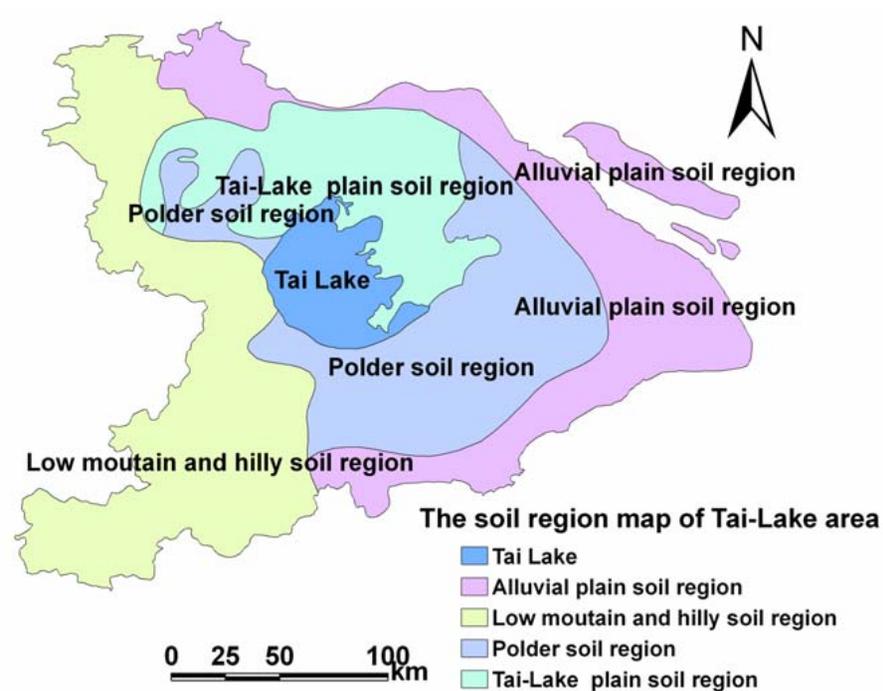


Fig. 6. The paddy soil region map of Tai-Lake area.

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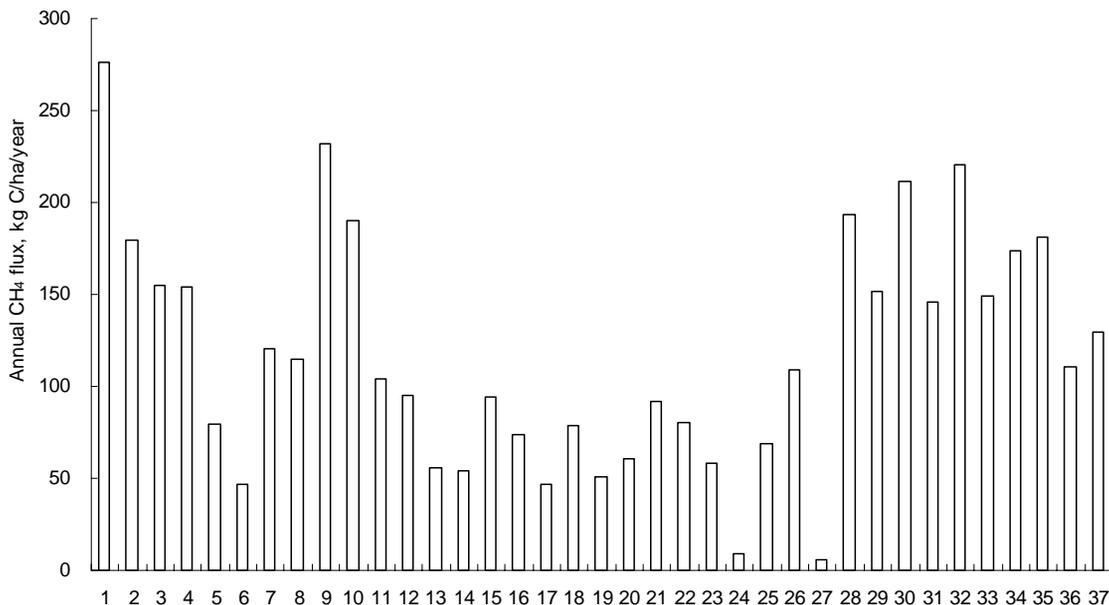


Fig. 7. Comparison of the average annual CH₄ fluxes in different counties. (1. Wu County; 2. Zhangjiagang; 3. Changshu; 4. Taicang; 5. Kunshan; 6. Wujiang; 7. Wuxi; 8. Jiangyin; 9. Wujin; 10. Jintan; 11. Liyang; 12. Yixing; 13. Dantu; 14. Jurong; 15. Danyang; 16. Jiaxing; 17. Jiashan; 18. Pinghu; 19. 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.)

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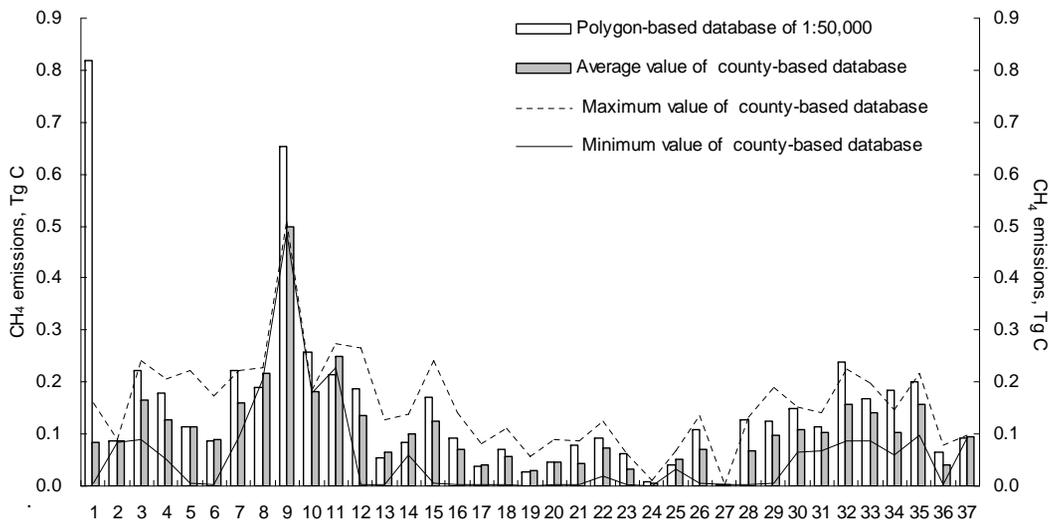


Fig. 8a. Comparison of the CH₄ emissions modeled with the county- and polygon-based database for the Tai-Lake region.

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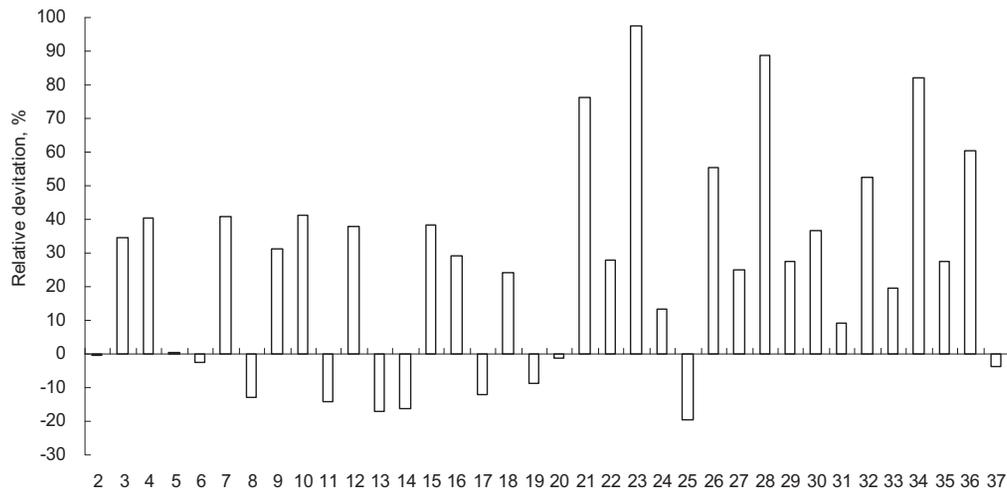


Fig. 8b. The relative deviation of CH₄ emissions modeled with the polygon-based database by the county level as the baseline for the Tai-Lake region. (1. Wu County; 2. Zhangjiagang; 3. Changshu; 4. Taicang; 5. Kunshan; 6. Wujiang; 7. Wuxi; 8. Jiangyin; 9. Wujin; 10. Jintan; 11. Liyang; 12. Yixing; 13. 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.)

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