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Simulation of global warming potential (GWP) from rice fields in the Tai-Lake region, China by coupling 1:50,000 soil database with DNDC model

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ABSTRACT

Quantifying greenhouse gas (GHG) emissions from wetland ecosystems is a relatively new issue in global climate change studies. China has approximately 22% of the world's rice paddies and 38% of the world's rice production, which are crucial to accurately estimate the global warming potential (GWP) at regional scale. This paper reports an application of a biogeochemical model (DeNitrification and DeComposition or DNDC) for quantifying GWP from rice fields in the Tai-Lake region of China. For this application, DNDC is linked to a 1:50,000 soil database, which was derived from 1107 paddy soil profiles compiled during the Second National Soil Survey of China in the 1980–1990s. The simulated results show that the 2.34 Mha of paddy soil cultivated in rice–wheat rotation in the Tai-Lake region emitted about −1.48 Tg C, 0.84 Tg N and 5.67 Tg C as CO_2, N_2O, and CH_4 respectively, with a cumulative GWP of 565 Tg CO_2 equivalent from 1982 to 2000. As for soil subgroups, the highest GWP (26,900 kg CO_2 equivalent ha^{-1} yr^{-1}) was linked to gleyed paddy soils accounting for about 4.4% of the total area of paddy soils. The lowest GWP (5370 kg CO_2 equivalent ha^{-1} yr^{-1}) was associated with submergenic paddy soils accounting for about 0.32% 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 GWP of 12,300 kg CO_2 equivalent ha^{-1} yr^{-1}. On a regional basis, the annual averaged GWP in the polder, Tai-Lake plain, and alluvial plain soil regions was distinctly higher than that in the low mountainous and Hilly soil regions. As for administrative areas, the average annual GWP of counties in Shanghai city was high. Conversely, the average annual GWP of counties in Jiangsu province was low. The high variability in soil properties throughout the Tai-Lake region is important and affects the net greenhouse gas emissions. Therefore, the use of detailed soil data sets with high-resolution digital soil maps is essential to improve the accuracy of GWP estimates with process-based models at regional and national scales.

1. Introduction

Presently, atmospheric carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) concentrations have steadily risen to 379 ppm, 1774 ppb and 319 ppm in 2005, respectively (IPCC, 2007). Agricultural activities are responsible for approximately 50% of global atmospheric inputs of CH_4 and agricultural soils are responsible for 75% of global N_2O emissions (Li et al., 2006). Thus, such soils represent a significant opportunity for greenhouse gas (GHG) mitigation through reductions of CH_4 and N_2O emissions, as well as soil carbon sequestration.

China has approximately 22% of the world's rice paddies and 38% of the world's rice production (Wang et al., 1993; Jiang et al., 2004). As such, accurate estimation of GHG emissions from the rice fields in China is vitally important to evaluating global warming potential (GWP). Recently, scientists have applied modeling to estimate GHG emissions from cropping systems (Cao et al., 1996; Sozanska et al., 2002; Huang et al., 2006). 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) and has been widely used for regional modeling studies in the USA (Tonitto et al., 2007), China (Li et al., 2006), India (Pathak et al., 2005) and Europe (Neufeldt et al., 2006). Good

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performance was noted using the DNDC model applied to seven long-term experiments selected from the Global Change and Terrestrial Ecosystems Soil Organic Matter Network (GCTE SOM-NET), representing three different land uses, a range of climatic conditions within temperate regions, and different treatments (Tang et al., 2006).

In China, scientists have also studied trace gas emissions using the DNDC model for many years. Gou et al. (1999) simulated soil N_2O emissions during a whole rice–wheat rotation in Wuxian county of the Tai-Lake region using the DNDC model. They found that the wheat growing phases of reviving, booting, flowering, and maturing were about 7–18% less than those measured. Cai et al. (2003) simulated CH_4 from rice fields in different long-term experiment stations in East Asia using the DNDC model. They found that simulated seasonal CH_4 emissions closely reflected field studies ($r^2 = 0.96$, regression slope = 1.1, $n = 23$). Li et al. (2007) simulated CO_2 and N_2O emissions in Hebei province of the Huang-Huai-Hai Plain with the DNDC model. The simulated and measured correlation coefficient of soil CO_2 and N_2O emissions was 0.79–0.90. Li et al. concluded that the DNDC model was useful in describing the characteristics of soil CO_2 and N_2O emissions.

The DNDC model has also been utilized to upscale GHG emissions from local sites to regional scales. So far, most of the DNDC modeling conducted at the regional scale used counties as the basic geographic unit. However, regional estimates of GHG fluxes cannot be derived simply from the extension of results from field-plot measurements of GHG fluxes because of the spatial variations of the drivers such as climate, soil and management (Jagadeesh Babu 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 (Cai et al., 2003; Pathak et al., 2005).

For the rice-dominated Tai-Lake region, we shifted the regional database linked to the DNDC model from county-based to a grid system which was built upon a new soil map developed in the 1980–1990s 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 1980–1990s. By linking the detailed soil database to the DNDC model, we attempted to improve the performance of the model. This goals of this study were to: 1) estimate GWP from rice paddy fields in the Tai-Lake region of China from 1982 to 2000; and 2) understand the dynamics of GWP across various paddy soil subgroups and administrative areas in the region.

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 intensive rice cultivation, is located in the middle and lower reaches of the Yangtze River paddy soil region of China. This includes the entire Shanghai city administrative area and a part of Jiangsu and Zhejiang provinces, covering about a total area of 36,500 km^2 (Fig. 1) (Xu et al., 1980). 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, with a mean temperature of 16 °C, 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 long history of rice cultivation for several centuries. 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 rice paddy fields are managed with rice and winter wheat rotation systems.

2.2. Description of the DNDC model

The DNDC (DeNitrification and DeComposition, version 9.1) model, under development at the University of New Hampshire since 1992, is a process-orientated simulation tool for soil carbon and nitrogen biogeochemistry cycles and 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 dynamic components of SOC and fluxes of greenhouse gases.

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 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 the rainfall, irrigation, flooding,

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

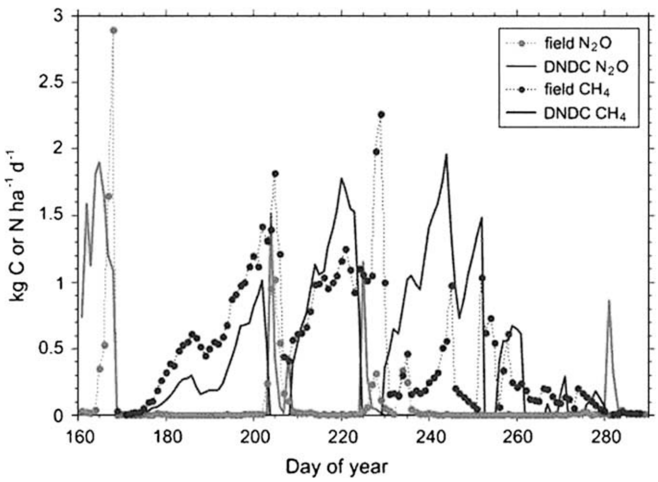


Fig. 2. Comparison between observed and DNDC-modeled CH_4 and N_2O fluxes from a paddy rice field applied with midseason drainage in Wuxian county, Tai-Lake region, China, in 1995.

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 modified by adding a series of anaerobic processes (Li et al., 2002, 2004; Cai et al., 2003; Li, 2007). Paddy soil is characterized by frequent changes between saturated and unsaturated conditions driven by water management. During these changes in soil water content, the soil Eh is subject to substantial changes between +600 and −300 mV. Dynamic soil Eh is one of the key processes controlling CH_4 and N_2O production/consumption in paddy soils. CH_4 and N_2O are produced under certain Eh conditions (−300 to −150 mV for CH_4, and 200–500 mV for N_2O), so variation in soil Eh determines the dominant greenhouse gas emitted from the paddy soil.

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; Yu and Patrick, 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 extended flooding periods or shifts between flooded and drained states through the growing and fallow seasons.

2.3. Database development

In the study, a type of polygon-based spatial soil database was used to support 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 data set covered 37 counties in the Tai-Lake region. The mapping units are based on the soil types as defined in Genetic Soil Classification of China (GSCC).

Table 1
The N_2O emission from rice field in the Tai-Lake region, China.

Author	Location	Crop	Year	Fertilizing amount (kg N ha^{-1} yr^{-1})	Observed emission (kg N ha^{-1} yr^{-1})
Zheng et al. (1997)	Wuxian WJAS[a]	Rice–wheat	1994–1995	351	9.60–13.60
Zheng et al. (2004)	Wuxi	Rice–wheat	2001–2002	300	6.47
			2001–2002	500	8.76
			2001–2002	500	12.99
			2002–2003	0	2.22
			2002–2003	300	5.16
			2002–2003	430	9.28
			2002–2003	430	6.75
Xing and Zhu (1997), Xu et al. (1997), Xing (1998), Zheng et al. (2000), Zhou et al. (2007)	Suzhou	Rice–wheat	1993–1994	0	2.53
			1993–1994	390	5.40
			1993–1994	400	6.95
			1993–1994	458	6.21
			1993–1994	490	6.30
			1994–1995	0	3.90
			1994–1995	382	11.80
			1996–1997	0	8.90
			1996–1997	384	15.27
			1996–1997	382	12.60
			1996–1997	382	15.10
Huang (2003), Zou et al. (2003, 2005), Jiang et al. (2003)	Nanjing	Rice–wheat	2000–2001	333	16.79
			2000–2001	333 + (2.25 t ha^{-1} rape manure)	17.73
			2000–2001	333 + (2.25 t ha^{-1} straw)	14.19
			2000–2001	333 + (2.25 t ha^{-1} cattle manure)	19.61
			2000–2001	333 + (2.25 t ha^{-1} swine manure)	18.05
			2000–2001	431	14.14
			2002–2003	0	4.68
			2002–2003	250	8.01
			2002–2003	500	11.33
			2002–2003	750	14.03

[a] WJAS: *W*uxian *I*nstitute for *A*griculture *S*cience.

Table 2
Comparison between observed and DNDC-modeled N_2O flux in annual rice–wheat rotation ecosystems in the Tai-Lake region, China.

Station	Year	Observed (kg N ha^{-1} yr^{-1})	Simulated (kg N ha^{-1} yr^{-1})	Relative deviation (%)
Suzhou	1994–1995	15.10	14.27	−5.5
Nanjing	2000–2001	14.14	13.90	−1.7
Wuxi	2001–2002	12.99	15.62	20.2
Nanjing	2002–2003	8.01	7.19	−10.2

The soil data set consisted of 81 soil attribute fields, including profile code, soil name (in GSCC), profile location, horizon name, profile thickness, bulk density, organic matter content, texture, pH, etc.

The crop data set included physiological data of summer rice and winter wheat. The agricultural management data set included sowing acreages, nitrogen fertilizer application rates, livestock, planting and harvest dates, and agricultural population at the county level from 1982 to 2000 (from Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences). The climate data set included daily weather data (precipitation, maximum and minimum air temperature) from 1982 to 2000, which was acquired from 13 weather stations in the 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 evaluated county.

Farming management in the study area included: 1) six N fertilizer applications: (rice: basal, tillering, and heading stage; wheat: basal, jointing, and heading stage); and two applications of organic manure (20% of the annual amount of livestock wastes and 10% of the annual amount of human wastes) were used as the basic fertilizer for rice or wheat each. Organic manure N production rates were set at 40 (cattle), 34 (horse), 2.3 (sheep), 5.1 (swine), and 5.3 (humans) kg N $head^{-1}$ yr^{-1}, respectively. 2) Residue management: 15% of the above ground crop residue was returned to the soil annually; and 3) Tillage: For the rice–wheat rotation, tillage was conducted twice before 1990 at the 20 cm tilling depth for rice and 10 cm for wheat on the planting dates; no-till was applied for wheat after 1990 (Lu and Shi, 1982; Qiu et al., 2004; Tang et al., 2006).

2.4. Calculation of GWP

For this study, the net impact was defined as the sum of the warming forces of all GHGs based on 100-yr global warming potentials (GWPs), according to the Intergovernmental Panel on Climate Change (IPCC, 2007). The warming forces of CH_4 and N_2O are 21 and 310 times higher, respectively, than CO_2 per unit of weight.

3. Results and discussion

3.1. Model validation

In China, scientists have studied rice field GHG emissions using the DNDC model for many years in the Tai-Lake region. Zheng et al. (1997) simulated N_2O and CH_4 emissions from rice fields in Wuxian county of Tai-Lake region with the DNDC model. Results showed that if the site soil characteristics, fertilization rate, fertilization type, crop and water management were well described, estimated fluxes were similar to those observed (Fig. 2).

To confirm the reliability of the DNDC model, N_2O and CH_4 emissions data, which has been published in the articles about the rice fields in the Tai-Lake region, was compiled (Tables 1 and 3) (Wang et al., 2001; Huang, 2003). Previous studies by Jiang et al. (2003), Huang (2003), Xing and Zhu (1997), Xu et al. (1997), Xing (1998), Zheng et al. (1997, 2000, 2004), Zhou et al. (2007), and Zou et al. (2003, 2005) showed that N_2O emissions in paddy soils cultivated with summer rice and winter wheat in the Tai-Lake region ranged from 5 to 20 kg N_2O–N ha^{-1} yr^{-1} (Table 1). In the present study, the DNDC-modeled N_2O emission from the majority paddy soils is also in the range of 5–20 kg N_2O–N ha^{-1} yr^{-1}, indicating that the modeled results are consistent with observations for the Tai-Lake region.

The simulated N_2O emissions using the DNDC model closely reflected field observations in Nanjing, Wuxi, and Suzhou of the Tai-Lake region (Table 2). More detailed descriptions of treatment, water regime, fertilization, and cropping systems at each site are found in work done by Zou et al. (2003, 2005) and Zheng et al. (2000, 2004). The highest and lowest deviations were found in Suzhou and Wuxi, respectively. The total discrepancies between annual simulated and observed fluxes were less than 10% of the annual field estimate of flux.

Previous field measurement of CH_4 emissions from the rice fields in the Tai-Lake region ranged from 24 to 195 kg C ha^{-1} yr^{-1} (Table 3) (Wang et al., 2001). In this study, simulated CH_4 emissions in 80% of the total paddy soil area are in the range of 24–195 kg CH_4–C ha^{-1} yr^{-1}. In most cases, the simulated CH_4 emission using the DNDC model reflected field measurement values in

Table 3
The CH_4 emission from rice field of Tai-Lake region, China.

Author	Location	Year	Treatment and fertilizing amount (kg N ha^{-1} yr^{-1})	Observed emission (kg C ha^{-1} yr^{-1})
Cai et al. (1994)	Wuxian, soil organic matter 32 g kg^{-1}	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. (1995)	Jiangsu Academy for Agriculture Science, soil organic matter 19 g kg^{-1}	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, soil organic matter 23 g kg^{-1}	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)	Wuxian, soil organic matter 35 g kg^{-1}	1994–1996	Urea 191	82.5
			Ammonium hydrogen carbonate 191	52.5

Table 4
Comparison between observed and DNDC-modeled CH_4 fluxes from rice fields in the Tai-Lake region, China.

Location	Year	Observed (kg C ha^{-1} yr^{-1})	Simulated (kg C ha^{-1} yr^{-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
Wuxian	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

Nanjing, Jiangning, Wuxian, Hangzhou, Jurong, and Suzhou of the Tai-Lake region (Table 4) (Wang et al., 2001; Cai et al., 2003). Total CH_4 emissions ranged from 14 to 180 kg C ha^{-1} yr^{-1}, while simulated emissions ranged from 15 to 198 kg C ha^{-1} yr^{-1}. Low carbon content in Nanjing (11 g kg^{-1}) and Jurong (6.0 g kg^{-1}) resulted in low CH_4 emissions (Li et al., 2004). The difference between the observed and the simulated emissions in all sites ranged from −12 to 51 kg C ha^{-1} yr^{-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 the observed yearly fluxes were less than 10% of the field estimates of flux per year, which showed that the CH_4 emissions from paddy soil in the Tai-Lake region were well simulated by the DNDC model.

3.2. Inter-annual variation in GWP

Based on simulated results, the 2.34 Mha of paddy soils in the Tai-Lake region emitted about −1.48 Tg C, 0.84 Tg N, and 5.67 Tg C as CO_2, N_2O, and CH_4, respectively, with a cumulative GWP of 565 Tg CO_2 equivalent from 1982 to 2000. Average emission rates ranged from 6340 kg CO_2 equivalent ha^{-1} yr^{-1} to 15,300 kg CO_2 equivalent ha^{-1} yr^{-1}. However, the modeled annual GWP was highly variable from year to year (Fig. 3).

From 1982 to 1992, the application rates of synthetic fertilizers as well as livestock manure continuously increased, producing a general trend of increasing GWP (Figs. 3 and 4). The increase in livestock number provided more manure, which in turn enhanced substrates for methanogenesis (Zheng et al., 1999). 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 elevation induced by fertilizers such as ammonium sulfate is also plausible (Lindau et al., 1990; Dunfield et al., 1995). Moreover, increased chemical fertilizer use could elevate N_2O emissions due to enhanced nitrification and denitrification (Huang and Lv, 2004; Xiong et al., 2007). However, the rate of the modeled GWP decreased from 1993 to 2000 (Fig. 3). Agricultural statistics show that the amount of synthetic fertilizers used in the region has decreased since 1993 (Fig. 4). Also, most of the region has adopted no-tillage practices for wheat planting since 1991, leading to a decrease in the CO_2 emissions (Li et al., 2004; Liang et al., 2007).

Fig. 3 also shows yearly variation of GWPs of different GHG from 1982 to 2000 in the Tai-Lake region. Overall, N_2O contributed to 73% of the total GWPs, with a cumulative GWP of 411 Tg CO_2 equivalent. CH_4 was the second most influential gas in the GWPs (28%), with a cumulative GWP of 158 Tg CO_2 equivalent. CO_2 was the lowest influential gas in the GWPs, with a cumulative GWP of −5.4 Tg CO_2 equivalent, accounting for −1.0% of total GWPs. These proportions differ from the results of Li et al. (2003), who found that GWP contributions of CO_2, N_2O and CH_4 in Chinese croplands were 29%, 50%, and 21% in 1990, respectively. In this study, the contribution of CO_2 to global warming is lower than that of the national average while the contribution rates of N_2O and CH_4 to global warming were higher than the national average. The main reason was that no-till was applied for wheat after 1990 in the Tai-Lake region, leading to decreased CO_2 emissions. N_2O and CH_4 have a high input of fertilizer rate applying to the two crops a year, leading to the increase of N_2O and CH_4 emissions (Li et al., 2003).

3.3. Impacts of paddy soil subgroups on GWP emissions

The hydromorphic subgroup is the most prominent paddy soil type in the Tai-Lake region, accounting for 53% of the total paddy soil area (Fig. 5a). This group contains a high organic carbon content and total nitrogen making it favorable for GHG production by providing more substrates (soluble C, ammonium, and nitrate) (Li et al., 1992b, 2004). The modeled average fluxes of CO_2, N_2O and CH_4 were as high as −49 kg CO_2–C ha^{-1} yr^{-1}, 19 kg N_2O–N ha^{-1} yr^{-1}, and 106 kg CH_4–C ha^{-1} yr^{-1}, respectively, with a cumulative GWP of 12,300 kg CO_2 equivalent ha^{-1} yr^{-1} (Fig. 5b).

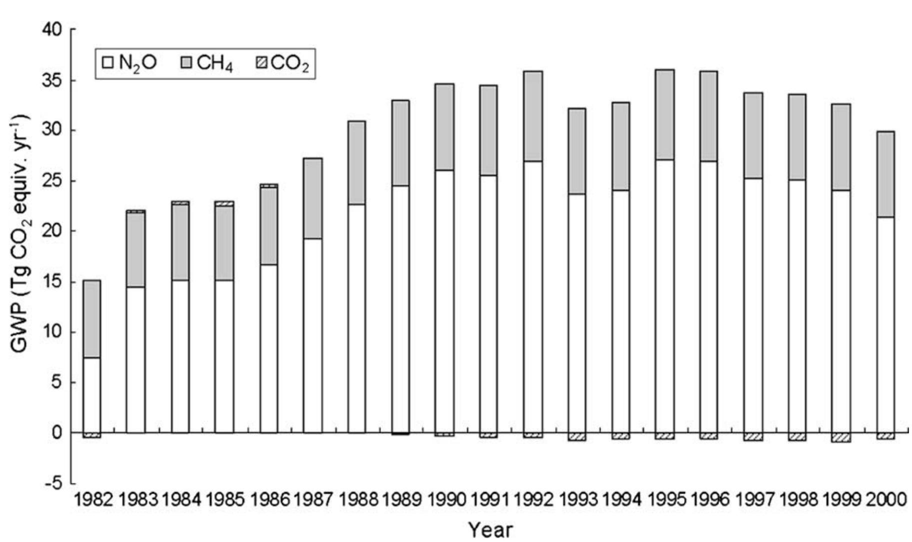


Fig. 3. Contribution of GWPs of different GHG from 1982 to 2000 in the Tai-Lake region, China.

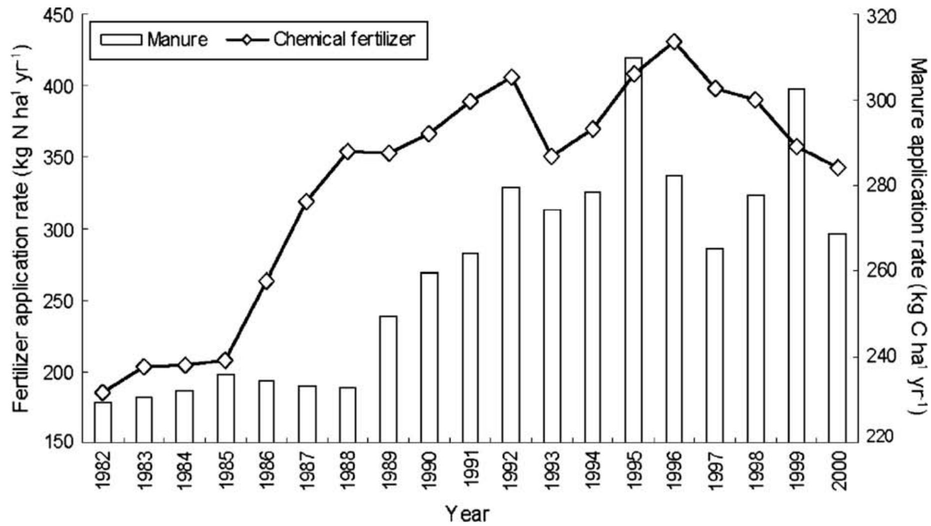


Fig. 4. Distribution of chemical fertilizer and manure application rate from 1982 to 2000 in the Tai-Lake region, China.

In the Tai-Lake region, the total GWPs from the subgroup was 286 Tg CO_2 equivalent accounting for 50% of the total GWPs.

The degleyed and percogenic subgroups cover 18% and 16% of the total paddy soil area in the region, respectively (Fig. 5a). The modeled GWP from the degleyed and percogenic subgroups were 133 and 60 Tg CO_2 equivalent, and accounted for 24% and 11% of the total GWPs, respectively. The average annual GWP from the degleyed subgroup was higher than the percogenic subgroup as the former has higher soil organic carbon (33 vs. 20 g kg^{-1}) (Li et al., 2004). In the Tai-Lake region, submergenic soils supported 0.0073 Mha of rice fields with a low GWP rate of 5370 kg CO_2 equivalent ha^{-1} yr^{-1} due to the low organic carbon content in these soils (Fig. 5a and b). The areas dominated by gleyed and bleached soils are equivalent to 4.4 and 8.8% of the regional paddy soil area, respectively, with an average annual GWP of 27,000 and 8280 kg CO_2 equivalent ha^{-1} yr^{-1}.

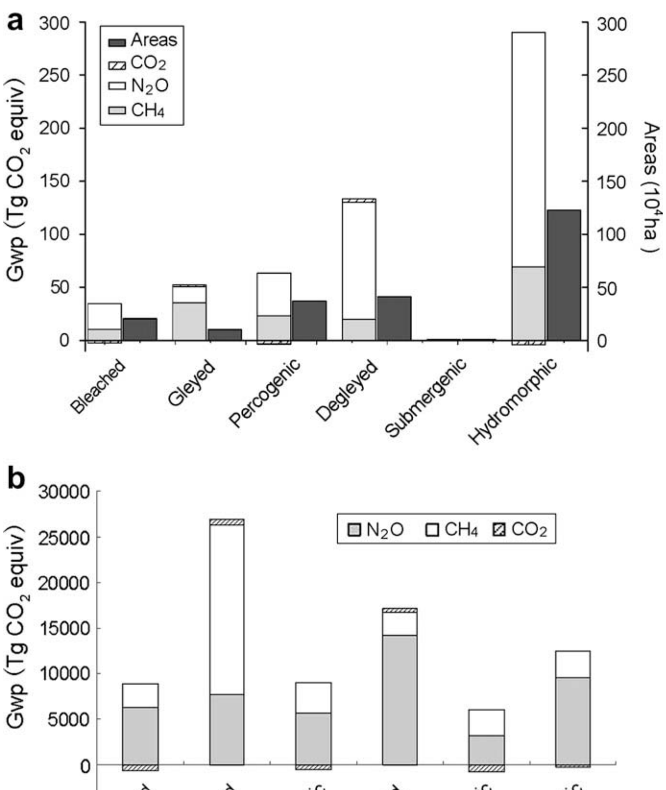


Fig. 5. (a) Comparison between areas and total GWPs in various paddy soil subgroups of the Tai-Lake region, China. (b) Comparison of the average annual GWP in various paddy soil subgroups of the Tai-Lake region, China.

3.4. Spatial distribution of GWP in different sub-regions

The Tai-Lake region can be divided into four sub-regions based on landscape characteristics: rolling hills and low mountains, plains around the lake, alluvial 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 the paddy fields of 0.39 Mha. Soils in this sub-region are less fertile with relatively low fertilizer application rates (300 kg N ha^{-1}) and low soil organic carbon content (13 g kg^{-1}). The modeled average fluxes of CO_2, N_2O

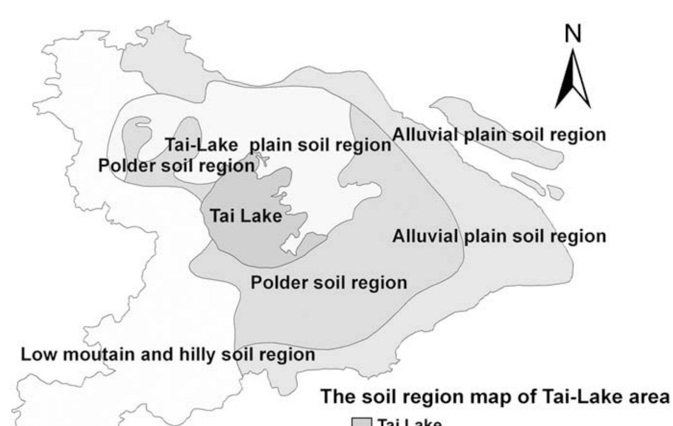
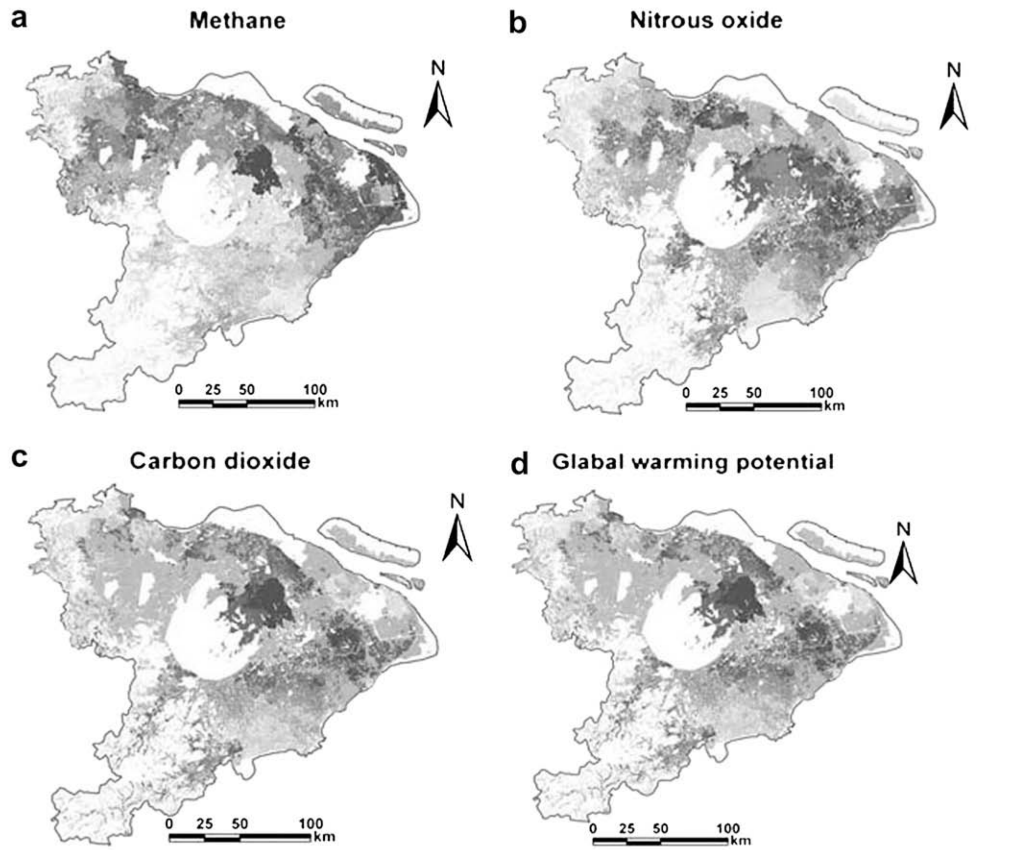


Fig. 6. The paddy soil region map of the Tai-Lake region, China.



Legend	(a) CH_4 (CH_4-C ha^{-1} yr^{-1})	(b) N_2O (kg N_2O-N ha^{-1} yr^{-1})	(c) CO_2 (kgCO_2-C ha^{-1} yr^{-1})	(d) GWP (kg CO_2 equiv.ha^{-1} yr^{-1})
	<50	<10	<-250	<5000
	50-100	10-20	-250-0	5000-10000
	100-150	20-25	0	10000-15000
	150-200	25-30	0-250	15000-20000
	>200	>30	>250	>20000

Fig. 7. Annual fluxes of CH_4, N_2O, CO_2 and GWP of the Tai-Lake region, China.

and CH_4 were −87 kg CO_2–C ha^{-1} yr^{-1}, 12 kg N_2O–N ha^{-1} yr^{-1} and 68 kg CH_4–C ha^{-1} yr^{-1}, respectively, with a cumulative GWP of 7430 kg CO_2 equivalent ha^{-1} yr^{-1} (Fig. 7).

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 carbon content (16 g kg^{-1}) and large amounts of fertilizers applied (302 kg N ha^{-1}). Moreover, gleyed soils cover an extensive area in this sub-region. So, the modeled average fluxes of CO_2, N_2O and CH_4 were −6.7 kg CO_2–C ha^{-1} yr^{-1}, 19 kg N_2O–N ha^{-1} yr^{-1} and 173 kg CH_4–C ha^{-1} yr^{-1}, respectively, with a cumulative GWP of 14,100 kg CO_2 equivalent ha^{-1} yr^{-1} (Fig. 7).

The alluvial plains along the river sub-region contain about 0.64 Mha of rice fields. The soil organic carbon is 23 g kg^{-1}, and the soil pH is 7.3. A reaction range of 7.0–8.0 is favorable for nitrification and denitrification, but also in the range (6.8–7.2) favorable for methane production (Pacey and DeGier, 1986; Yu et al., 2006). Moreover, fertilizer application (370 kg N ha^{-1}) was also high in this sub-region. The modeled average fluxes of CO_2, N_2O, and CH_4 were −104 kg CO_2–C ha^{-1} yr^{-1}, 18 kg N_2O–N ha^{-1} yr^{-1}, and 132 kg CH_4–C ha^{-1} yr^{-1}, respectively, with a cumulative GWP of 11,600 kg CO_2 equivalent ha^{-1} yr^{-1} (Fig. 7).

The polder sub-region is low in elevation, having 0.69 Mha of rice fields with high soil organic carbon (31 g kg^{-1}). The modeled average fluxes of CO_2, N_2O, and CH_4 amounted to 39 kg CO_2–C ha^{-1} yr^{-1}, 24 kg N_2O–N ha^{-1} yr^{-1}, and 118 kg CH_4–C ha^{-1} yr^{-1}, respectively, with a cumulative GWP of 15,100 kg CO_2 equivalent ha^{-1} yr^{-1} (Fig. 7).

3.5. Spatial distribution of GWP in different administrative areas

Paddy soils of Tai-Lake region cover about 1.33 Mha in Jiangsu province, 0.54 Mha in Zhejiang province, and 0.46 Mha in Shanghai city with GWP in these three provinces of 53%, 22%, and 25% of total GWPs, respectively (Table 5). Overall, the average annual GWP values of counties in Shanghai city were all high due to high N fertilizer application (390 kg N ha^{-1}) and low clay content (26%). By contrast, the average annual GWP values of counties in Jiangsu province were low due to the low N fertilizer application rate (300 kg N ha^{-1}) and low soil organic carbon content (14 g kg^{-1}) (Fig. 8).

The spatial differentiation of the average annual GWP was also shown at the county scale in the Tai-Lake region (Fig. 8). The average annual GWP in Qingpu, Wuxian, and Songjiang counties was higher than 20,000 kg CO_2 equivalent ha^{-1}, due to the high soil organic carbon content (24 g kg^{-1}, 20 g kg^{-1}, and 23 g kg^{-1}, respectively). Dantu and Jurong counties had the lowest GWP, 2670 and 2590 kg CO_2 equivalent ha^{-1}, respectively. The soil organic

Table 5
Distribution of GHG (CO_2, N_2O and CH_4) and GWP of administrative areas in the Tai-Lake, China from 1982 to 2000.

Province	County	Area	Distribution of GHG and GWP				Contribution rate of GWP		
		10^4 ha	CO_2	CH_4	N_2O	GWP	CO_2	CH_4	N_2O
			Tg C	Tg C	Tg N	Tg CO_2 equiv.	%	%	%
Jiangsu	Zhangjiagang	2.54	−0.001	0.087	0.006	5.45	−0.1	44.7	53.7
	Changshu	7.55	0.092	0.221	0.027	20.0	1.7	30.9	65.7
	Taicnang	6.14	−0.050	0.180	0.019	14.3	−1.3	35.3	64.9
	Kunshan	7.57	−0.055	0.115	0.041	23.1	−0.9	13.9	86.5
	Wuxian	14.78	0.483	0.819	0.071	60.7	2.9	37.8	57.0
	Wujiang	9.79	−0.099	0.087	0.038	20.6	−1.8	11.8	89.8
	Wuxi	9.77	−0.091	0.224	0.022	16.8	−2.0	37.3	63.8
	Jiangyin	8.69	−0.004	0.189	0.046	27.9	−0.1	19.0	80.3
	Wujin	14.85	−0.256	0.653	0.057	45.6	−2.1	40.1	60.9
	Jintan	7.10	−0.197	0.256	0.028	20.2	−3.6	35.5	67.6
	Liyang	10.84	−0.365	0.215	0.020	14.3	−9.4	42.1	68.2
	Yixing	10.34	−0.289	0.187	0.030	18.7	−5.7	28.0	78.1
	Dantu	5.07	−0.357	0.053	0.005	2.3	−56.6	64.2	105.4
	Jurong	8.03	−0.363	0.083	0.006	3.6	−36.5	63.8	80.3
	Danyang	9.58	−0.085	0.172	0.024	16.3	−1.9	29.5	71.7
	Total	133	−1.64	3.54	0.438	300	−2.0	33.0	69.0
Zhejiang	Jiaxing	6.57	0.155	0.092	0.031	18.5	3.1	13.9	81.5
	Jiashan	4.13	0.081	0.037	0.022	12.2	2.4	8.5	87.9
	Pinghu	4.81	−0.116	0.072	0.020	11.3	−3.8	17.8	86.1
	Haiyan	2.74	−0.021	0.027	0.014	7.52	−1.0	10.1	90.7
	Haining	3.92	−0.113	0.045	0.006	3.71	−11.2	34.0	78.9
	Tongxiang	4.42	−0.107	0.077	0.008	5.64	−7.0	38.2	69.1
	Huzhou	6.02	0.353	0.092	0.035	21.4	6.0	12.0	79.7
	Changxing	5.62	−0.045	0.063	0.027	14.8	−1.1	11.9	88.9
	Anji	4.18	0.052	0.008	0.006	3.4	5.6	6.6	85.9
	Deqing	3.11	−0.010	0.041	0.016	8.95	−0.4	12.8	87.1
	Yuhang	5.27	0.092	0.109	0.022	14.3	2.4	21.3	74.8
	Linan	3.06	0.128	0.004	0.005	3.15	14.9	3.6	77.2
	Total	53.9	0.449	0.668	0.212	125	2.0	15.0	83.0
Shanghai	Minhang	3.49	−0.041	0.128	0.016	11.3	−1.3	31.6	68.8
	Jiading	4.29	−0.194	0.124	0.017	11.0	−6.5	31.6	75.4
	Chuangsha	3.71	−0.133	0.149	0.011	9.07	−5.4	46.0	59.1
	Nanhui	4.11	−0.119	0.113	0.020	12.5	−3.5	25.3	78.0
	Qingpu	5.68	0.056	0.237	0.035	24.2	0.8	27.4	70.4
	Songjiang	5.90	0.322	0.167	0.046	28.8	4.1	16.2	77.8
	Jinshan	5.63	−0.083	0.185	0.024	16.7	−1.8	31.0	70.0
	Fengxian	5.87	−0.010	0.201	0.025	18.0	−0.2	31.3	67.7
	Baoshan	3.13	−0.119	0.067	0.006	4.32	−10.1	43.5	67.7
	Chongming	3.73	−0.138	0.092	0.005	4.46	−11.3	57.7	54.6
	Total	45.5	−0.459	1.464	0.204	140	−1.0	30.0	71.0

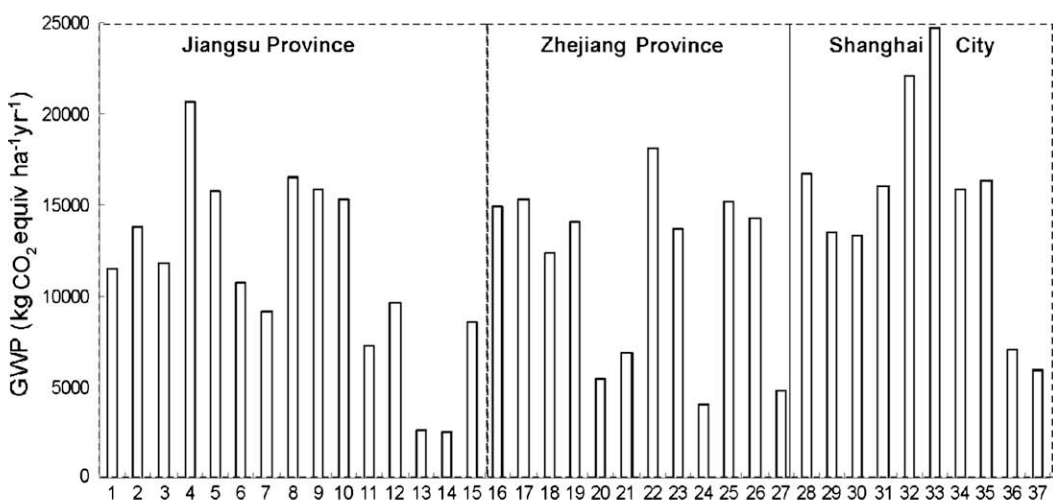


Fig. 8. Comparison of the average annual GWP in different counties of the Tai-Lake region, China. (1. Zhangjiagang; 2. Changshu; 3. Taicang; 4. Kunshan; 5. Wuxian; 6. Wujiang; 7. Wuxi; 8. Jiangyin; 9. Wujin; 10. Jintan; 11. Liyang; 12. Yixing; 13. Dantu; 14. Jurong; 15. Danyang; 16. Jiaxing; 17. Jiashan; 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 content of Dantu county is only 7.0 g kg^{-1}. Low carbon content often results in low GHG emissions (Li et al., 2004). Jurong county has a relatively low pH value (5.6), which can result in a decrease in nitrification and denitrification, and activity of methane-producing bacteria (Li et al., 2004).

3.6. Emissions uncertainty of GHG

Many studies have shown that natural factors, especially some soil properties, affect the impacts of management on soil GHG emissions (Cai et al., 2003; Li et al., 2004; Pathak et al., 2005). This conclusion supports observations in many soils where measured GHG fluxes differed, even under similar management conditions (Li et al., 2004). The effect of soil heterogeneity on GHG emissions is a major source of uncertainty when applying process-based models of the DNDC at regional scales. In this study, we used a high-resolution soil map derived from over 1000 soil profiles and yielding polygons of less than one square kilometer to cover the study region. However, uncertainties have always been an important problem, given that the county was chosen as the basic spatial unit for our GIS database construction since most of the statistical cropland data was county-based. Meteorological data and agricultural management data were obtained from ground-based sources. Since each county is regarded to be uniform during a single model simulation, uncertainty estimates related to the inherent heterogeneities of many input parameters within the county must be generated during the scaling-up process. Therefore, in order to reduce uncertainties, more detailed meteorological and agricultural management data is required with a high spatial resolution.

4. Conclusion

Quantifying GHG emissions from wetland ecosystems is a relatively new issue in global climate change studies. Paddy rice in China accounts for 22% of the world's rice fields and is crucial to accurately estimate GWP. Models such as the DNDC should be very useful to accelerate the application of available knowledge at regional levels for optimizing agronomic management and quantifying change in GHG emissions. By linking to a detailed soil database, the DNDC model estimated −1.48 Tg C, 0.84 Tg N, and 5.67 Tg C of CO_2, N_2O, and CH_4, respectively, with a cumulative GWP of 565 Tg CO_2 equivalent were emitted from the 2.34 Mha of paddy rice fields of rice–wheat rotation in the Tai-Lake region from 1982 to 2000. Furthermore, GWP tended to increase initially, then decrease temporally. The trend is mainly attributed to the increase or decrease of N fertilizer and livestock manure application.

The DNDC model concluded that N_2O dominated the rice paddy GWPs, CH_4 was the second most influential gas in the GWPs, and CO_2 was the least influential gas in the GWPs of the Tai-Lake region. Contribution rates of CO_2, N_2O, and CH_4 in the Tai-Lake region on global warming were −1.0%, 73%, and 28%, respectively. These proportions are different from the results of Li et al. (2003), who found contribution rates CO_2, N_2O, and CH_4 in Chinese croplands on global warming were 29%, 50%, and 21% in 1990, respectively. The main reason was that no-till was applied for wheat after 1990 in the Tai-Lake region, leading to decreased CO_2 emissions. Also, N_2O and CH_4 emissions are strongly tied to fertilizer application rates.

The average annual GWP in the Tai-Lake region is highly differentiated based on paddy soil subgroups, sub-regions, and county levels due to heterogeneity in soil properties. Therefore, uncertainty in soil properties introduces large uncertainty into GWP estimates. As such, the government should adjust the proper policy to mitigate GHG emissions according to different soil types in the Tai-Lake region. Moreover, various crop management practices, climate conditions, and fertilizer application play a major role in the GHG emission. What is the Tai-Lake region or China agriculture's real contribution to GWP has the potential to offer an accurate estimation using simulation models. This will not only improve estimates of GHG emissions and related impact assessments, but also provide a baseline from which future GHG emissions trajectories may be developed to identify and evaluate mitigation strategies.

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