GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 18, GB1043, doi:10.1029/2003GB002045, 2004

Modeling greenhouse gas emissions from rice-based production systems: Sensitivity and upscaling

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Received 29 January 2003; revised 12 January 2004; accepted 30 January 2004; published 25 March 2004.

[1] A biogeochemical model, Denitrification-Decomposition (DNDC), was modified to enhance its capacity of predicting greenhouse gas (GHG) emissions from paddy rice ecosystems. The major modifications focused on simulations of anaerobic biogeochemistry and rice growth as well as parameterization of paddy rice management. The new model was tested for its sensitivities to management alternatives and variations in natural conditions including weather and soil properties. The test results indicated that (1) varying management practices could substantially affect carbon dioxide (CO_2), methane (CH_4), or nitrous oxide (N_2O) emissions from rice paddies; (2) soil properties affected the impacts of management alternatives on GHG emissions; and (3) the most sensitive management practices or soil factors varied for different GHGs. For estimating GHG emissions under certain management conditions at regional scale, the spatial heterogeneity of soil properties (e.g., texture, SOC content, pH) are the major source of uncertainty. An approach, the most sensitive factor (MSF) method, was developed for DNDC to bring the uncertainty under control. According to the approach, DNDC was run twice for each grid cell with the maximum and minimum values of the most sensitive soil factors commonly observed in the grid cell. The simulated two fluxes formed a range, which was wide enough to include the "real" flux from the grid cell with a high probability. This approach was verified against a traditional statistical approach, the Monte Carlo analysis, for three selected counties or provinces in China, Thailand, and United States. Comparison between the results from the two methods indicated that 61-99% of the Monte Carlo-produced GHG fluxes were located within the MSA-produced flux ranges. The result implies that the MSF method is feasible and reliable to quantify the uncertainties produced in the upscaling processes. Equipped with the MSF method, DNDC modeled emissions of CO_2, CH_4, and N_2O from all of the rice paddies in China with two different water management practices, i.e., continuous flooding and midseason drainage, which were the dominant practices before 1980 and in 2000, respectively. The modeled results indicated that total CH_4 flux from the simulated 30 million ha of Chinese rice fields ranged from 6.4 to 12.0 Tg CH_4-C per year under the continuous flooding conditions. With the midseason drainage scenario, the national CH_4 flux from rice agriculture reduced to 1.7–7.9 Tg CH_4-C. It implied that the water management change in China reduced CH_4 fluxes by 4.2–4.7 Tg CH_4-C per year. Shifting the water management from continuous flooding to midseason drainage increased N_2O fluxes by 0.13–0.20 Tg N_2O-N/yr, although CO_2 fluxes were only slightly altered. Since N_2O possesses a radiative forcing more than 10 times higher than CH_4, the increase in N_2O offset about 65% of the benefit gained by the decrease in CH_4 emissions. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere

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0886-6236/04/2003GB002045

interactions; 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 1610 Global Change: Atmosphere (0315, 0325); 1615 Global Change: Biogeochemical processes (4805); *KEYWORDS:* climate change, methane, nitrous oxide

Citation: Li, C., A. Mosier, R. Wassmann, Z. Cai, X. Zheng, Y. Huang, H. Tsuruta, J. Boonjawat, and R. Lantin (2004), Modeling greenhouse gas emissions from rice-based production systems: Sensitivity and upscaling, *Global Biogeochem. Cycles*, *18*, GB1043, doi:10.1029/2003GB002045.

1. Introduction

[2] Rice production is arguably the most important economic activity on the planet. Almost half the people in the world eat rice at least once a day. Rice farms cover 11% of the world's arable area [*International Rice Research Institute* (*IRRI*), 2002]. Asia dominates global rice agriculture. Total rice paddy area in Asia is 1.38 million km^2, which accounts for 90% of global rice area (1.55 million km^2) and ~20% of total world cropland area for grain production [*Food and Agriculture Organization* (*FAO*), 2002]. Rice production systems in Asia are in the midst of great changes [*Wassmann et al.*, 2000]. During the last 2 decades, the management for rice production in Asia converted from "traditional" to more energy dependent systems on a broad scale. For example, rice production in China, Indonesia, Malaysia, Thailand, Philippines, and Vietnam increased from approximately 210 to 310 Tg while the cropping area remained at a fairly stable level of 62–63 million ha from 1980 to 2000 [*FAO*, 2002]. This large increase in productivity was primarily driven by improved plant varieties and enhanced use of synthetic nitrogen (N) fertilizers. In these East Asian countries, nitrogen (N) fertilizers applied for rice production increased from ~4 to ~10 Tg N from 1980 to 2000 [*FAO*, 2002; *International Fertilizer Industry Association*, 2002] while use of livestock excreta and green manure as fertilizer has decreased [*Mosier et al.*, 2001; *Denier van der Gon*, 1999]. The depletion of organic manure used in agriculture has probably led to problems in soil fertility, waste disposal, and water quality issues, the latter two problems being related to the uncontrolled disposal of livestock waste. With such a large increase in N fertilizer inputs, the biogeochemical dynamics of carbon (C) and nitrogen (N) in the rice ecosystems must have been substantially altered. In fact, soil degradation, water contamination with N, eutrophication, and increased ammonia and other N trace gas emissions have been reported from many of the rice-producing countries [*Denier van der Gon*, 1999; *Mosier and Zhu*, 2000]. *Zheng et al.* [2000b] constructed a nitrogen budget for Asia, and estimated 250–300% increases in gaseous N emissions from agriculture and total N runoff to the oceans between 1961 and 2000. According to statistics from the Ministry of Agriculture of China, the average efficiency of N fertilizer use is about 30% [*Zhu*, 1992]. Excess fertilizer can be lost to the atmosphere and surface or groundwater bodies. Changes in management have also altered greenhouse gas (GHG) emissions from rice fields by (1) depleting organic C storage in the soils [*Cai*, 1996], (2) decreasing CH_4 emissions due to the decline in organic matter return to the field [*Denier van der Gon*, 1999; *Sass*, 2002], and (3) increasing N_2O emissions due to increased fertilizer N input [*Mosier and Zhu*, 2000].

[3] Rice-based crop production is presently undergoing a new revolution. Large-scale mechanical tillage, direct seeding rather than transplanting, mid-season draining of rice fields, changing from two rice crops per year to one rice crop and one upland crop, incorporation of rice residue rather than burning, and new rice varieties are among the large changes in rice-based agriculture production management that are either being considered or are taking place today across Asia. These changes are occurring rapidly, although ongoing quantification of impacts of the changes on soil C dynamics as well as emissions of methane (CH_4) and nitrous oxide (N_2O), two important greenhouse gases, are very limited. Any management change should accommodate the needs to maintain high crop yields, to conserve diminishing natural resources, and to minimize environmental damage. A demand for predicting effects of the new changes in rice production management in Asia on global atmosphere as well as the local environmental conditions is emerging.

[4] Food production contributes approximately 70 and 40% of global input of N_2O and CH_4 to the atmosphere, respectively [*Cole et al.*, 1996], and cropped soils have the potential to sequester atmospheric carbon dioxide (CO_2) [*Cole et al.*, 1996; *Janzen et al.*, 1999; *Lal et al.*, 1998; *Follett and McConkey*, 2000]. When appraising the impact of food and fiber production systems on composition of Earth's atmosphere, the entire suite of greenhouse gases (i.e., CO_2, CH_4, and N_2O) needs to be considered [*Li*, 1995; *Robertson et al.*, 2000]. Since the three major greenhouse gases emitted from cropland are products of the biogeochemical cycles of C and N in the agroecosystems, any change in either management or climate/soil conditions will alter the biochemical or geochemical processes, which finally leads to changes in the gas fluxes. For example, incorporating crop straws into soil can increase C sequestration but elevate CH_4 fluxes [*Sass*, 2002]. Normal crop production practices generate N_2O and decrease the soil sink for atmospheric CH_4 [*Cole et al.*, 1996]. Since each of the greenhouse gases has its own radiative potential [*Intergovernmental Panel on Climate Change* (*IPCC*), 1997], the net global warming potential (GWP) of a crop production system must be estimated accounting for all the three gas constitutes. For example, a preliminary estimate indicated that the overall greenhouse effect from Thailand's agricultural sector is greater from CH_4 and N_2O than from CO_2 [*Thailand Environment Institute*, 1997]. Intensified cropping systems (i.e., two or three crops per year) with increased tillage, irrigation, and N fertilizer use have been widely applied in the Central Plain to increase rice production in Thailand. The high cropping intensity, improper use of crop residue, and overuse of N fertilizer have contributed to decreases in soil organic C and to increases in the emissions of CH_4 and N_2O from flooded rice fields. These gaseous emissions not only represent potential economic

losses but also could lead to a negative impact on the environmental quality. Therefore, maintaining both optimum crop yield and environmental safety is a great challenge.

[5] To answer the challenge, process-oriented models have been developed during approximately the last decade. Some of the models such as CASA, CENTURY, EXPERT-N, etc. [*Frolking et al.*, 1998], focus on greenhouse gas emissions from upland agricultural soils. Among the modeling efforts, the Denitrification-Decomposition (DNDC) model was developed for predicting C and N biogeochemical cycles in both upland and wetland agroecosystems [*Li et al.*, 1992, 1994; *Li*, 2000]. This paper reports how DNDC was modified for wetland soils and how the uncertainties produced in the upscaling processes can be quantified. The study was conducted as a part of an Asian Pacific Network for Global Change Research project on "Land Use/Management Change and Trace Gas Emissions in East Asia" in 1999–2002.

2. Model Modifications

[6] The Denitrification-Decomposition or DNDC model was originally developed for upland agro-ecosystems in the United States [*Li et al.*, 1992, 1994]. To enable DNDC to simulate the wetland biogeochemical processes, we made several modifications as follows.

2.1. Modeling Soil Biogeochemistry Under Anaerobic Conditions

[7] Carbon dioxide, CH_4, and N_2O, the three major greenhouse gases (GHG), are produced in soils through decomposition, nitrification/denitrification, and methanogenesis, respectively. All of the reactions are typical oxidation-reduction processes, although intermediated by the soil microbes. It means all of the reactions proceed through the exchange of electrons. Wetland soil is characterized with existence of a saturated zone. Changes in the saturated proportion of a soil profile are driven by the water table fluctuation. This feature differentiates wetland soils from upland soils by altering a series of biochemical and geochemical processes. When a soil is shifting from unsaturated to saturated conditions, the soil oxygen (O_2) will be gradually depleted, and will result in more oxidants involved in the reductive reactions. These reductive reactions usually include denitrification of nitrate (NO_3^-), reductions of manganese (Mn^{4+}), iron (Fe^{3+}), and sulfate (SO_4^{2-}), and methanogenesis. The entire reductive reactions are usually driven by the soil microbial activities, which consume dissolved organic carbon (DOC) or other C sources and pass electrons to the oxidants for obtaining energy. Since different oxidants possess different Gibbs free energies, they accept electrons only under certain redox potential (i.e., Eh) conditions. On the basis of the Nernst equation (equation (1)), soil Eh is determined by concentrations of the existing oxidants and reductants in the soil liquid phase [*Stumm and Morgan*, 1981].

[8] Nernst equation

$$\mathrm{Eh} = E_0 + RT/nF \times \ln([\mathrm{oxidant}]/[\mathrm{reductant}]), \qquad (1)$$

where Eh is redox potential of the oxidation-reduction system (V), E_0 is standard electromotive force (V), R is the gas constant (8.314 J/mol/k), T is absolute temperature (273 + t, °C), n is transferred electron number, F is the Faraday constant (96,485 C/mol), [oxidant] is concentration (mol/l) of dominant oxidant in the system, and [reductant] is concentration (mol/l) of dominant reductant in the system.

[9] Under anaerobic conditions, along with the consumption of certain oxidants due to the microbial activity, soil Eh gradually decreases. The consumption rates of the oxidants can be described by the Michaelis-Menten equation (equation (2)). On the basis of the dual-nutrient equation, rate of each reduction is controlled by the oxidant content and available C concentration [*Paul and Clark*, 1989],

$$F_{[\mathrm{oxidant}]} = a[\mathrm{DOC}/(b + \mathrm{DOC})] \times [\mathrm{oxidant}/(c + \mathrm{oxidant})], \qquad (2)$$

where $F_{[\mathrm{oxidant}]}$ is fraction of the oxidant reduced during a time step, DOC is available C concentration, and a, b, and c are coefficients.

[10] Since the Nernst and the Michaelis-Menten equations share a common factor (i.e., oxidant concentration), they can be merged. A simple kinetic scheme was adopted in DNDC to realize the conjunction. The kinetic scheme is defined to be the anaerobic volumetric fraction of a soil. On the basis of concentrations of the dominant oxidants and reductants in a soil, the Nernst equation calculates the soil bulk Eh. On the basis of the Eh value, the soil is divided into two parts: relatively anaerobic microsites (within the anaerobic volumetric fraction) and relatively aerobic microsites (outside of the anaerobic volumetric fraction). On the basis of the size proportion, DNDC allocates the substrates (e.g., DOC, NO_3^-, ammonium or NH_4^+) into the aerobic and anaerobic microsites in the soil. We define that the substrates allocated within the anaerobic volumetric fraction can only be involved in the reductive reactions (e.g., denitrification, methanogenesis), and the substrates allocated outside of the anaerobic volumetric fraction can only participate in the oxidations (e.g., nitrification, methanotrophy). The Michaelis-Menten equation is used to determine the rates of the reactions occurring within and outside of the anaerobic volumetric fraction. Since the anaerobic volumetric fraction swells or shrinks driven by the reduction/oxidation reactions, we simply called it an "anaerobic balloon" (Figure 1). When a soil is irrigated or flooded, its oxygen content will decrease, which will drive the anaerobic balloon to swell. As soon as the oxygen is depleted, the anaerobic balloon will reach its maximum and burst. At this moment, a new oxidant (i.e., NO_3^-) will become the dominant species in the soil, and a new anaerobic balloon will be born and swell driven by the NO_3^- depletion. By tracking the formation and deflation of a series of anaerobic balloons driven by depletions of oxygen, NO_3^-, Mn^{4+}, Fe^{3+}, and SO_4^{2-}, DNDC estimates soil Eh dynamics as well as production and consumptions of the products from the reductive/oxidative reactions, including CO_2, N_2O and CH_4 (Figure 2). With the anaerobic balloons, DNDC links soil Eh to trace gas emissions for wetland soils.

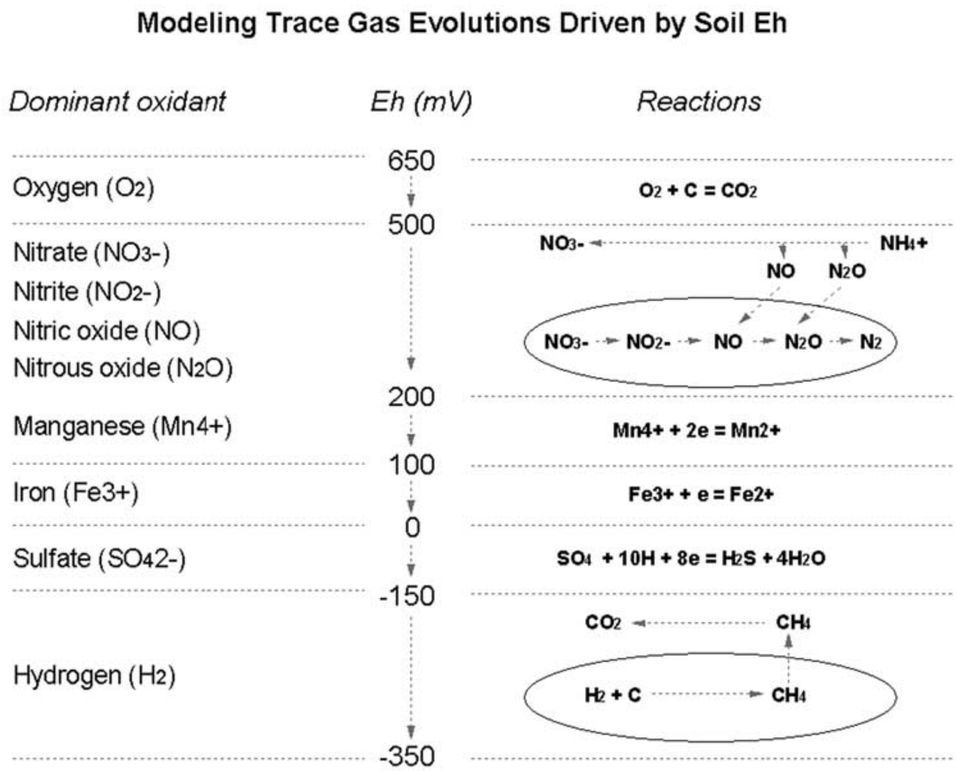


Figure 1. DNDC tracks CO_2, N_2O, and CH_4 evolutions driven by Eh and substrate concentrations in wetland soils. Soil Eh as well as concentrations of dominant oxidants are calculated based on the coupled Nernst equation and Michaelis-Menten equation embedded in DNDC.

[11] In paddy rice-involved agro-ecosystems, the frequent flooding and draining practices could cause dramatic changes in the soil Eh conditions, and hence affect production and consumption of CO_2, N_2O, and CH_4. DNDC links the water management practices to soil Eh dynamics and further to GHG emissions.

2.2. Parameterizing Paddy Rice Management

[12] Major farming management measures have been parameterized in DNDC, including tillage, fertilization, manure amendment, flooding, and crop rotation. Tillage is defined based on its timing and depth. Tilling redistributes various forms of C and N within the tilled depth, and enhances oxygen diffusion and hence accelerates decomposition of the soil organic matter in conjunction with other environmental factors (e.g., temperature, moisture, substrate concentration). Fertilization is characterized based on fertilizer type, application rate, application date, and application depth. DNDC tracks transport and transformation of seven different types of N fertilizers, namely urea, ammonium sulfate, ammonium phosphate, ammonium bicarbonate, anhydrous ammonia, ammonium nitrate, and other nitrates. Manure amendment is defined based on its type (e.g., farmyard manure, cover crop residue, straw, and fresh animal water), application rate, and application date. Different types of manure possess different C/N ratios, and will be partitioned into different soil organic pools. A flooding application is defined based on its beginning and end dates. A rice field can be flooded several times during a growing season (i.e., midseason drainage). The flooding/draining practices are precisely simulated by DNDC to track their impacts on soil water status, soil Eh dynamics, and substrate allocation between aerobic and anaerobic microsites in the soil, which finally determines the rates of nitrification, denitrification, and CH_4 production/oxidation under various water management regimes. The buffering effect of irrigation water pH on soil pH is calculated to regulate relevant processes.

2.3. Modeling Rice Development and Growth

[13] A generic crop model, MACROS, developed by *Penning de Vries et al.* [1989] in Wageningen in the Netherlands was modified and integrated with DNDC to simulate development and growth of several crops including rice. The integration enhanced the crop growth simulations by feeding the DNDC-predicted N availability to the MACROS crop model. Root respiration and exudation, two major energy sources for the soil microbes, are modeled in DNDC based on the crop growth rate and total root biomass. During the growing season, the crop roots continuously exude dissolved organic carbon (DOC) and deposit labile litter into the soil, and hence stimulate the activity of a series of soil microorganisms including nitrifiers, denitrifiers, methanogens, and methanotrophs. The development of plant-mediated transport capacity for CH_4 and other gases is quantified based on the total crop biomass. New

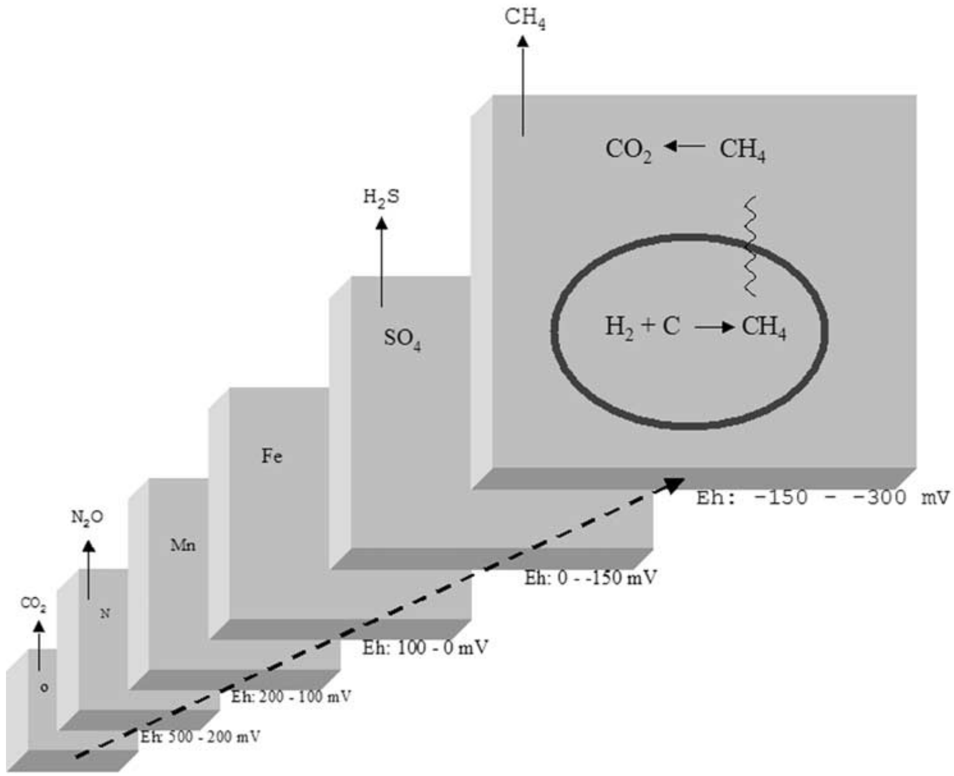


Figure 2. Driven by microbe-intermediated reductive reactions, DNDC simulates sequential births and bursts of a series of anaerobic balloons to determine the timing and magnitude of CO_2, CH_4, and N_2O production and consumption.

crop types or cultivars (e.g., deep-water rice) are allowed to be added to the model by defining their physiological and phenological parameters. DNDC allows the simulated rice to be rotated with other crops annually or interannually. This function is useful for predicting effects of crop rotation on trace gas emissions. With these mechanisms, DNDC is able to predict impacts of alternative crop rotations or new cultivars on GHG emissions from the wetland crop fields.

[14] With the above described modifications, DNDC has become capable of simulating the fundamental biogeochemical processes occurring in paddy rice ecosystems across climate zones, soil types, and management regimes. In the modified DNDC, any change in the farming management will simultaneously alter several soil environmental factors including temperature, moisture, Eh, pH, and substrate concentration gradients. These altered environmental factors will simultaneously and collectively affect a series of biochemical or geochemical reactions such as elemental mechanical movement, oxidation/reduction, dissolution/crystallization, adsorption/desorption, complexation/decomplexation, assimilation/dissimilation, etc., which finally determine CO_2, CH_4, and N_2O emissions from the modeled ecosystems. For example, any management practices, if they can bring new oxidants into the soil system, will interfere or reverse the soil Eh evolution, and hence affect the balance between production and consumption of CH_4 or N_2O. Application of fertilizers containing NO_3^- or SO_4^{2-} in a flooded soil would suddenly elevate the Eh in the water/soil system, hence reducing CH_4 production and increasing CH_4 oxidation. Tillage possesses a similar function as it can bring fresh O_2 into the submerged soils. Manure or straw amendment will increase soil microbial population and DOC content, which will accelerate a wide range of microbially intermediated processes. Flooding or drainage can dramatically alter soil aeration status, causing sudden shifts between denitrification and nitrification or between CH_4 production and oxidation. DNDC has been tested against a number of field observations regarding soil organic carbon (SOC) dynamics and trace gas emissions in agroecosystems worldwide [*Cai et al.*, 2003; *Brown et al.*, 2002; *Zhang et al.*, 2002; *Li*, 2000; *Smith et al.*, 1999; *Xiu et al.*, 1999; *Frolking et al.*, 1998; *Plant et al.*, 1998; *Smith et al.*, 1997; *Wang et al.*, 1997; *Li et al.*, 1994, 1992]. Most of the validation tests indicate that DNDC is capable of producing reasonable predictions for SOC dynamics and trace gas emissions from croplands. The DNDC model is available via the internet http://www.dndc.sr.unh.edu).

3. Sensitivity Tests

[15] A great amount of field observations on C sequestration in and trace gas emissions from croplands have been accumulated worldwide, but gaps still exist for assessing the net effects of various management measures on CO_2, CH_4, and N_2O emissions from the rice ecosystems across climate zones and soil conditions. Process-oriented models such as

Table 1. Management and Natural Conditions for Baseline and Alternative Scenarios Used for Sensitivity Tests

Scenario	Conditions or Variations
Baseline	rice-winter wheat rotation (R-WW), continuous flooding (CF), 50% of above-ground crop residue incorporated in soil after harvest (LR), no straw applied (NS), conventional tillage (tilling twice to depth 20 cm) (CVT), rice optimum yield 6500 kg dry grain/ha, fertilizer 250 kg urea-N/ha per year; annual average temperature 17.2°C, annual precipitation 897 mm (in South China, annual precipitation is larger than 1000 mm), N concentration in rainfall 3 ppm, soil texture loam, SOC 2%, soil pH 6.5.
	Management Alternatives
Crop rotation	rice-winter cover crop (R-WC), and rice-fallow (RF)
Midseason drainage	1, 2, and 3 times of midseason draining (MD1, MD2, and MD3, respectively)
Tillage	conservation tillage (depth 10 cm) (CST), and no-till (NT)
Straw amendment	additional 2000 and 4000 kg straw-C/ha incorporation (LS and HS, respectively)
Percent of residue incorporated	0% and 90% of above-ground crop residue incorporation (NR and HR, respectively)
Fertilizer type	nitrate, ammonium sulfate (AS), ammonium bicarbonate (AB)
	Environmental Factor
Air temperature	decrease (DT) by 2° and 4°C and increase (IT) by 2° and 4°C
Precipitation	decrease by 20% (DP) and increase by 20% (IP)
Soil texture	loamy sand (LS), sandy loam (SL), clay loam (CL), and clay
SOC content	0.5%, 1%, and 3%
Soil pH	5.5 and 7.5

DNDC have been applied to fill the gaps. In this study, we utilized the modified DNDC to test how GHG emissions could be affected by alternative management practices as well as natural conditions for paddy rice ecosystems. The tested practices included crop rotation, water management, crop residue incorporation, tillage, and fertilization. In order to better understand the management effects in a complex climate-soil context, we conducted the sensitivity tests with

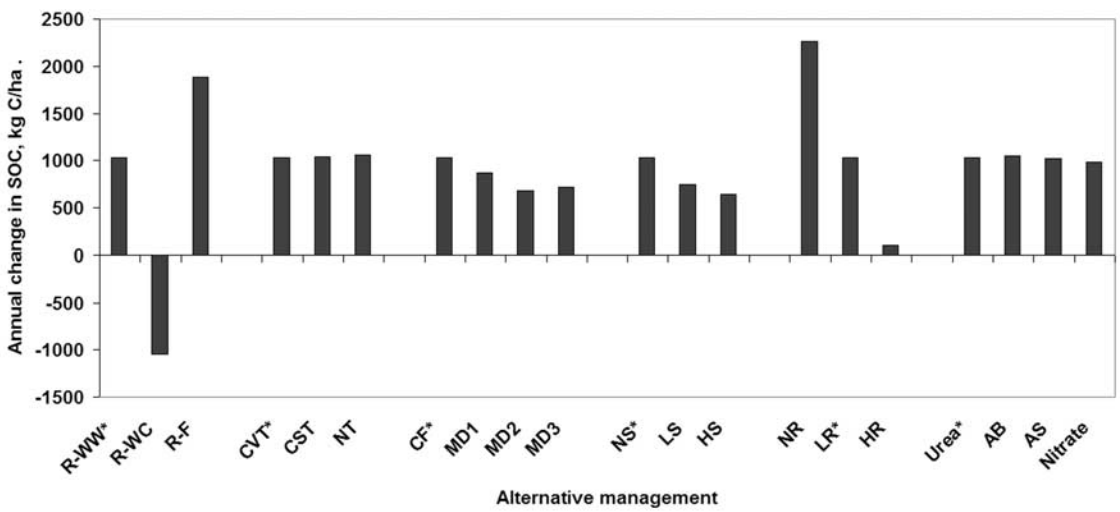


Figure 3. Sensitivity of net CO_2 flux (i.e., SOC change) to management alternatives. Change in the crop rotation from rice-winter wheat (R-WW) to rice-winter cover crop such as clover or vetch (R-WC) affected net CO_2 flux due to the crop biomass incorporation. Increase in crop residue incorporation after harvest from zero (NR) to high fraction (HR) had the same effect. The changes in tillage, water management, straw amendment, and fertilizer type had relatively moderate effects on net CO_2 fluxes. The alternative management practices, with asterisks, are of baseline scenario. (Abbreviations for this and following f igures: R-WW, rice-winter wheat rotation; R-WC, rice-winter cover crop rotation; R-F, rice-fallow rotation; CVT, conventional tillage; CST, conservation tillage; NT, no-till; CF, continuous flooding; MD1, drain once during rice growing season; MD2, drain twice during rice growing season; MD3, drain three times during rice growing season; NS, no straw incorporation; LS, low rate of straw incorporation; HS, high rate of straw incorporation; NR, no crop residue incorporation; LR, low rate of crop residue incorporation; HR, high rate of crop residue incorporation; Urea, urea fertilizer; AB, ammonium bicarbonate fertilizer; AS, ammonium sulfate fertilizer; Nitrate, nitrate fertilizer.)

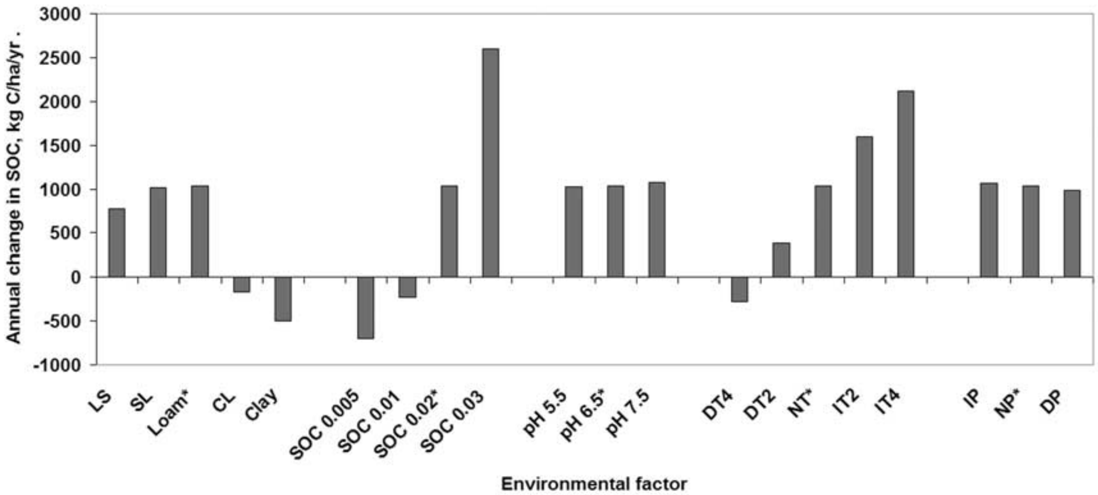


Figure 4. Sensitivity of net CO_2 flux to environmental factors. Under the tested same baseline management conditions, change in soil texture, initial SOC content, or air temperature altered the net CO_2 fluxes from the tested soil. Shifting soil texture from loamy sand (LS) to clay, or shifting initial SOC content from high (SOC 0.03) to low (SOC 0.005), converted the soil from a CO_2 source to a sink. Increase in temperature accelerated SOC loss. The alternative climate/soil conditions, with asterisks, are baseline conditions. (Abbreviations for this and following figures: LS, loamy sand; SL, silty loam; Loam, loam; CL, clay loam; Clay, clay; SOC, soil organic carbon content; pH, soil pH; DT4, temperature decrease by 4°C; DT2, temperature decrease by 2°C; NT, no temperature change; IT2, temperature increase by 2°C; IT4, temperature increase by 4°C; IP, increase in precipitation; NP, no change in precipitation; DP, decrease in precipitation.)

varied climatic or soil conditions. A baseline scenario was composed based on the typical management and natural conditions at a rice-winter wheat rotated field in southern China. Alternative scenarios were constructed by varying each of the management practices or natural factors in a range, which was commonly observed in the local farmland. The details of the baseline and alternative scenarios are listed in Table 1.

[16] DNDC was run for a year with each of the designed scenarios to produce an annual change in SOC storage, an annual CH_4 flux, and an annual N_2O flux. The annual SOC change is equivalent to annual net CO_2 flux from the soil.

3.1. Net CO_2 Emission

[17] Among the tested management practices, only crop rotation and crop residue incorporation showed notable impacts on the annual net CO_2 emissions. When crop rotation shifted from the baseline (i.e., winter wheat-rice rotation) to winter cover crop-rice rotation, the soil reversed from a source to a sink of atmospheric CO_2; that is, the annual net CO_2 flux deceased from 1000 to −1000 kg C/ha. That was because most biomass of the winter cover crop (e.g., clover, vetch) was incorporated in the soil at the end of its growing season. When the rotation shifted from winter wheat-rice to fallow-rice, the SOC loss increased from 1034 to 1884 kg C/ha due to no additional crop residue incorporated in the soil during the fallow season. Increasing the percent of crop residue incorporated in the soil after harvest from 50% (i.e., baseline) to 90% almost totally eliminated the SOC loss from the soil (Figure 3). Increasing the frequency of midseason drainage slightly reduced CO_2 fluxes due to the increase in crop biomass production that led to more crop residue incorporated into the soil. Increasing straw amendment also slightly reduced SOC loss due to the direct addition of organic matter. Changes in tillage or fertilizer types didn't affect SOC dynamics very much in the paddy soil. Keeping the farming practices constant as in the baseline management scenario, their impacts on net CO_2 fluxes varied when the soil properties or climatic conditions changed. Shifting the soil texture from loamy sand to clay altered the paddy field from a source to a sink of atmospheric CO_2 (i.e., net CO_2 flux decreased from 780 to −500 kg C/ha/yr). A decrease in the initial SOC content from 3% to 0.5% also converted the soil from a source to a sink of atmospheric CO_2 (i.e., the net CO_2 flux reduced from 2500 to −800 kg C/ha/yr). Increasing air temperature by 4°C elevated net CO_2 flux from −280 to 2100 kg C/ha/yr (Figure 4).

3.2. CH_4 Emission

[18] All of the tested management practices except fertilizer type showed notable impacts on annual CH_4 emissions. Changing crop rotation from winter wheat-rice to winter cover crop-rice dramatically elevated CH_4 fluxes because a large amount of fresh residue from the winter cover crop was incorporated in the soil just before the soil was flooded for rice transplanting. Early incorporation of the crop residue substantially reduced its stimulating effect. This modeled result is consistent with field observations [*Cai*

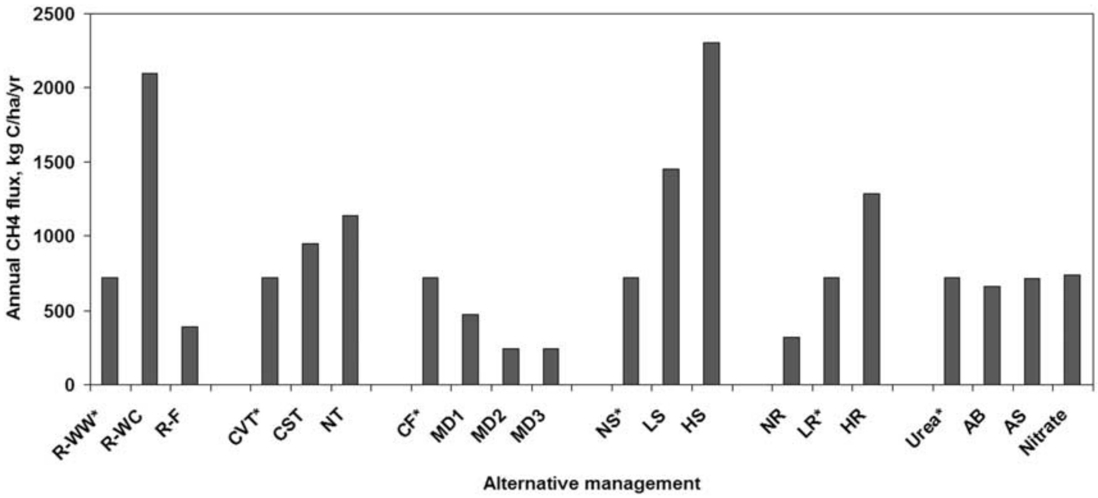


Figure 5. Sensitivity of CH_4 fluxes to alternative management practices. Increases in SOC content through changing crop rotation (R-WW → R-WC), straw amendment (NS → HS), or crop residue incorporation (NR → HR) increased CH_4 fluxes due to the increase in soil available C content. Application of midseason drainage (CF → MD3) decreased CH_4 emissions due to elevating soil Eh. The alternative management practices, with asterisks, are of baseline scenario.

et al., 2001]. In contrast, fallowing the soil during the winter-spring season reduced CH_4 emissions. Increases in straw addition or percent of crop residue incorporation increased CH_4 emissions due to the increase in soil organic matter (SOM) content. Increasing frequency of midseason drainage decreased CH_4 fluxes due to elevating the soil Eh values (Figure 5). Methane emission was also sensitive to soil texture. Heavier textured soils emitted less CH_4 than lighter soils under the same management conditions due to the clay adsorption which limits DOC availability to the soil microbes. Increasing the initial SOC content or air temperature moderately increased CH_4 fluxes (Figure 6). CH_4 emissions slightly decreased when soil pH shifted from 7.5 to 5.5 although substantial decreases in CH_4 emission could occur when the soil pH further decreased to 4.0 or lower.

3.3. N_2O Emission

[19] Among all tested management practices, water management showed substantial impact on N_2O fluxes from the paddy soil. Increasing frequency of midseason drainage increased N_2O fluxes due to the elevated soil redox potential during the draining time periods. In the simulation,

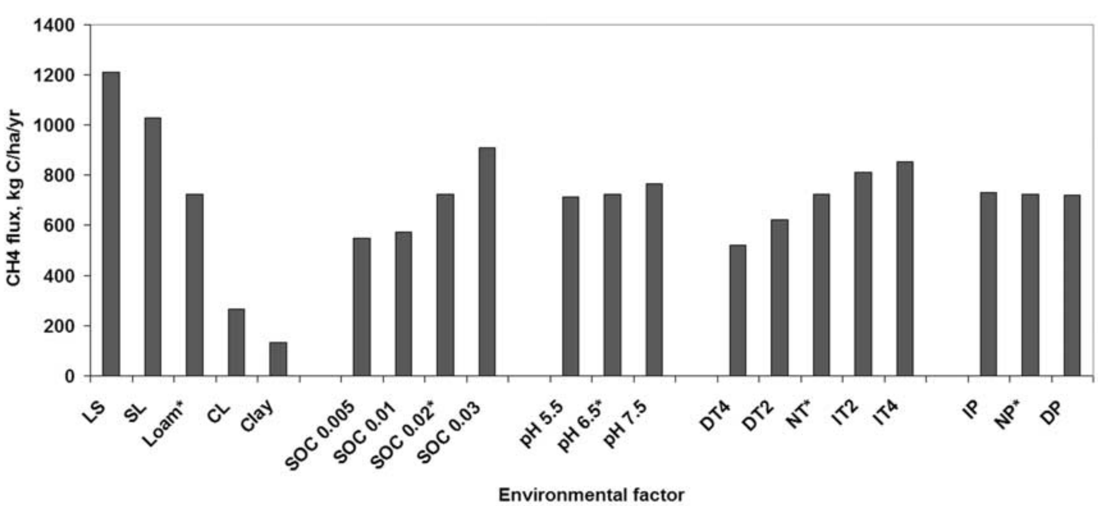


Figure 6. Sensitivity of CH_4 flux to environmental factors. Shifting soil texture from light soil (LS) to heavy soil (clay) reduced CH_4 fluxes. Increase in SOC content or temperature increased CH_4 fluxes. The alternative climate/soil conditions, with asterisks, are baseline conditions.

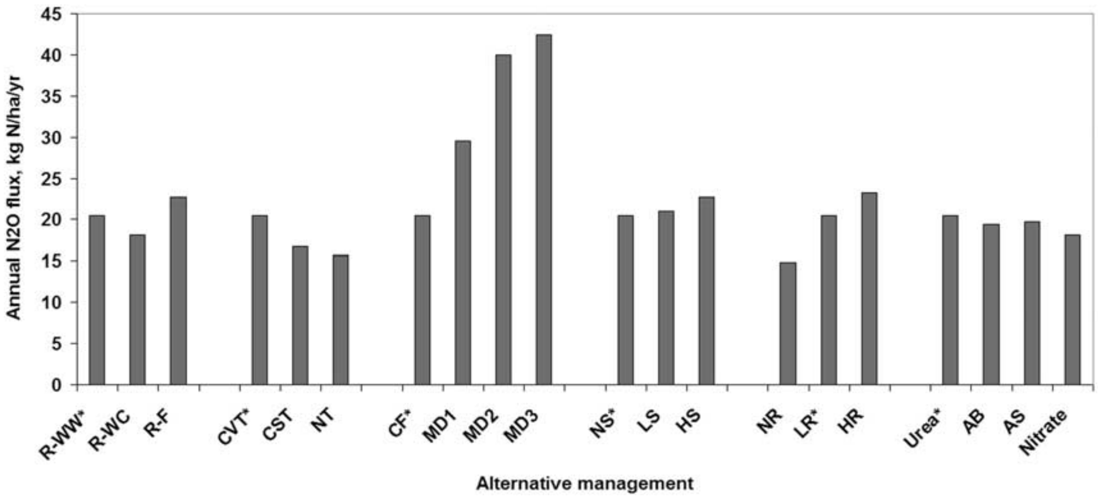


Figure 7. Sensitivity of soil N_2O flux to alternative management practices. Midseason drainage (MD1, MD2, and MD3) had the most significant impacts on N_2O fluxes, while other practices had moderate effects. The alternative management practices, with asterisks, are of baseline scenario.

when midseason drainage started, the soil moisture suddenly decreased from saturation to about the field capacity, atmospheric oxygen diffused into the soil profile, and the soil Eh suddenly increased. The ammonium reserved in the soil profile during the flooded time period was immediately oxidized into nitrate by the nitrifiers due to the elevated Eh. Since the soil was still quite wet, part of the nitrate was allocated to the anaerobic microsites to undergo denitrification. Thus DNDC models activations of nitrification and denitrification, which are major sources of N_2O, driven by the draining procedure. Other management measures also affected N_2O fluxes, although less notably in comparison with the water management (Figure 7). Nitrous oxide emission was sensitive to initial SOC content or temperature. Increase in SOC content or temperature increased N_2O fluxes (Figure 8). Change in precipitation did not affect GHG fluxes very much due to the season-long submerged conditions in the paddy soils.

3.4. Net Effect

[20] Since each of the management alternatives simultaneously affected CO_2, CH_4, and N_2O fluxes, a net effect of each scenario on global warming need to be assessed. In the study, the net impact was defined to be the sum of the warming forces of all the three greenhouse gases based on the concept of Global Warming Potential (GWP). According to *IPCC* [1997], with the 100-year time horizon, the warming forces of CH_4 and N_2O are 21 and 310 times higher than that of CO_2 per unit of weight.

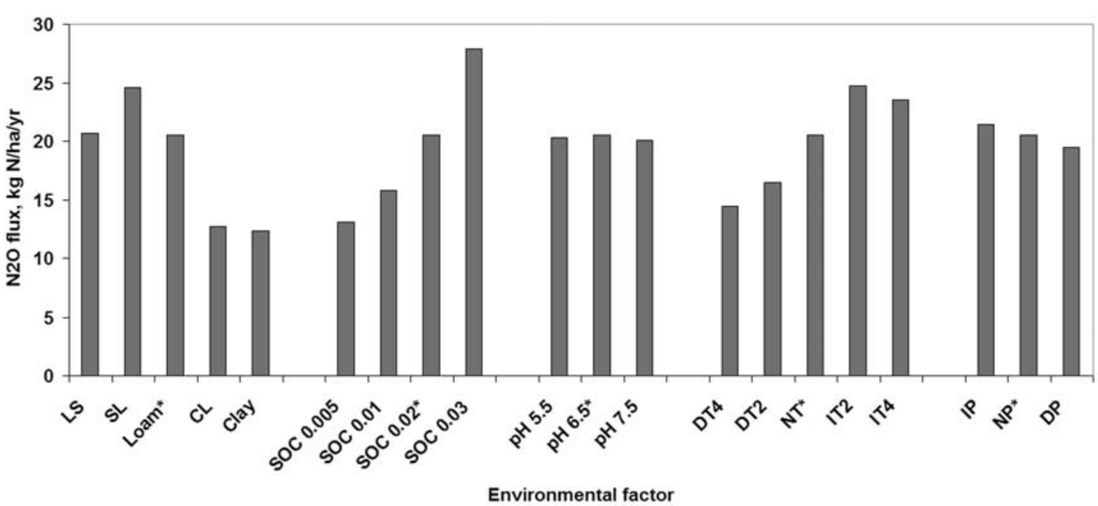


Figure 8. Sensitivity of N_2O flux to environmental factors. Under the same management conditions, increasing SOC content or temperature increased N_2O fluxes. Heavier soils emitted less N_2O than lighter soils. The alternative climate/soil conditions, with asterisks, are baseline conditions.

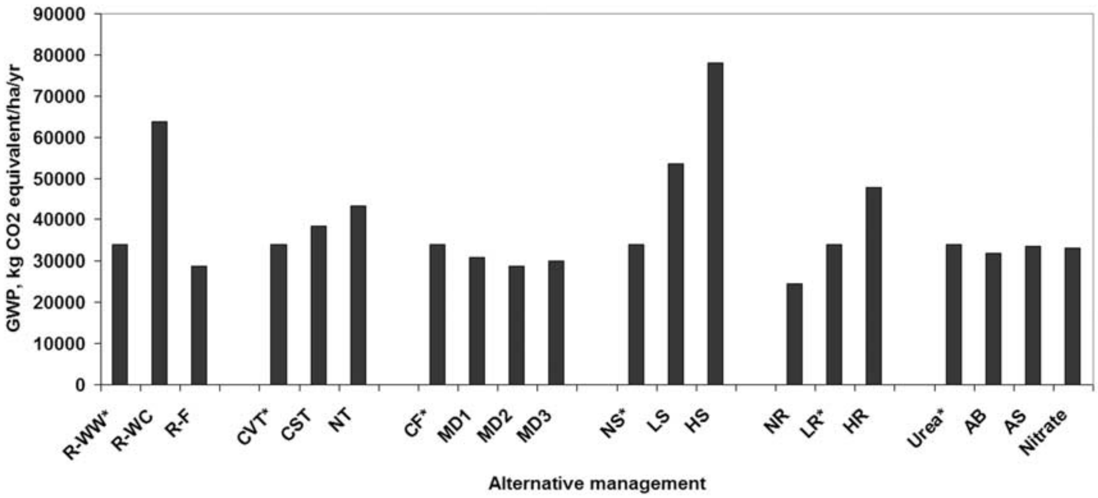


Figure 9. Sensitivity of GWP (i.e., the net effect of CO_2, N_2O, and CH_4 emissions) to alternative management practices. All of the tested management alternatives had positive GWP values. The results implied that the tested rice paddy was always a GWP source although its strength varied when change in the practices occurred. The alternative management practices, with asterisks, are of baseline scenario.

The GWP value for each scenario is calculated as follows:

$$GWP_i = CO_{2i}/12 \times 44 + N_2O_i/28 \times 44 \times 310 + CH_{4i}/12 \times 16 \times 21,$$

where GWP_i (kg CO_2 equivalent/ha/yr) is the Global Warming Potential induced by scenario i; CO_{2i}, N_2O_i, and CH_{4i} are CO_2 flux (kg C/ha/yr), N_2O flux (kg N/ha/yr), and CH_4 flux (kg C/ha/yr), respectively, induced by scenario i.

[21] The calculated GWP values for all the tested scenarios are shown in Figure 9. The calculated results indicated that CH_4 dominated the rice paddy GWP (60–90% of total GWP) for most of the tested scenarios, although the weight of N_2O substantially increased when the midseason drainage was applied. The effects of the management alternatives on the SOC dynamics accounted for only a small portion (<15%) of the net GWP values. The sensitivity tests indicated that reducing fresh organic matter incorporation through fallowing or less residue amendment could effectively mitigate the net effect of this rice paddy on global warming. In addition, the sensitivity test results showed that all of the alternatives had positive GWP values. The results imply that the tested paddy rice field was basically a source of atmospheric GHG although some management alternatives may be less effective than others. Under the same management conditions, heavier soils, low SOC soils, and lower temperature produced lower

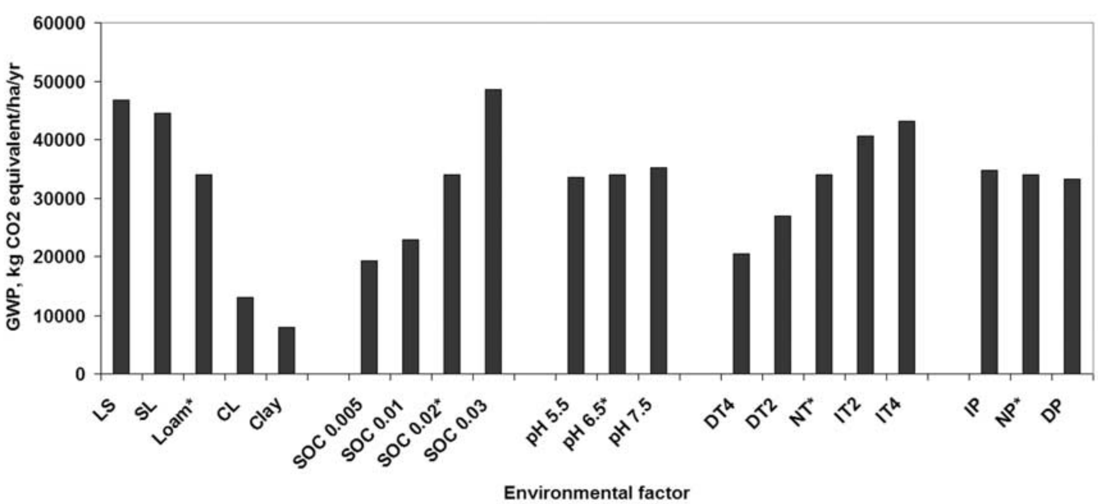


Figure 10. Sensitivity of GWP to environmental factors. Under the same baseline management conditions, heavier or poor soils produced lower GWP values because these soils produced less CH_4, which usually dominated GWP of paddy rice ecosystems. Lower temperature also reduced GWP values. The alternative climate/soil conditions, with asterisks, are baseline conditions.

Table 2. Comparison Between Most Sensitive Factor (MSF) and Monte Carlo Methods on Uncertainties Derived From Soil Heterogeneity for Three Counties in China, Thailand, and the United States

County	Climate	Soil Properties	Monte Carlo-Produced Ranges[a]	MSF-Produced Ranges[a]	Percent of Monte Carlo-Produced Fluxes Within MSF-Produced Flux Range
Chuxiong, Yunnan, China	temperature: 16.57°C; precipitation: 118.57 cm	SOC: 0.007–0.02 kg C/ha; clay: 0.2–0.6; pH: 4.0–6.0; bulk density: 1.08–1.32	dSOC: 58–2503; CH4: 17–154; N2O: 0.4–17	dSOC: 270–2448; CH4: 18–139; N2O: 4–10	SOC: 97%; CH4: 98%; N2O: 61%
Ang-Thong, Thailand	temperature: 27.86°C; precipitation: 130.25 cm	SOC: 0.0079–0.0147 kg C/ha; clay: 0.11–0.31; pH: 4.9–6.9; bulk density: 1.29–1.5	dSOC: −1206–383; CH4: 256–990; N2O: 15–46	dSOC: −1006–317; CH4: 280–870; N2O: 19–36	SOC: 96%; CH4: 94%; N2O: 88%
Colusa, California, USA	temperature: 16.92°C; precipitation: 62.85 cm	SOC: 0.004–0.0146 kg C/ha; clay: 0.24–0.36; pH: 5.4–7.4; bulk density: 1.3–1.5	dSOC: 483–2750; CH4: 154–507; N2O: 4–25	dSOC: 617–2722; CH4: 159–431; N2O: 9–20	SOC: 99%; CH4: 70%; N2O: 63%

[a]Here dSOC is increase in soil organic carbon content (equivalent to negative CO_2 emission) in kg C/ha/yr, CH4 is methane emission in kg C/ha/yr, and N2O is nitrous oxide emission in kg N/ha/yr.

GWP values (Figure 10). The results indicated that effective mitigation policies should be spatially differentiated.

[22] The results from the sensitivity tests are basically consistent with observations. For example, the sensitivity tests indicate that (1) midseason drainage and organic matter incorporation are two major management measures affecting CH_4 emissions from the paddy soils, although the impacts vary with the quality and quantity of the incorporated organic matter; (2) increase in temperature elevates CH_4 fluxes; and (3) CH_4 flux is sensitive to soil texture. The conclusions are in agreement with numerous observations [e.g., *Smith et al.*, 1982; *Lindau et al.*, 1990; *Sass et al.*, 1990, 1991; *Kimura et al.*, 1992; *Yagi et al.*, 1990; *Watanabe et al.*, 1995; *Nouchi et al.*, 1994; *Cai et al.*, 1995; *Denier van der Gon et al.*, 1996; *Xing and Zhu*, 1997; *Chen et al.*, 1995]. The modeled results also indicated midseason drainage substantially increased N_2O fluxes from the paddy soil. Several researchers have measured N_2O fluxes from rice paddies and reported high fluxes of N_2O from the drained soils during the rice growing season [e.g., *Zheng et al.*, 1997, 2000a; *Abao et al.*, 2000; *Bronson et al.*, 1997; *Cai et al.*, 1999]. Modeled net CO_2 emissions are sensitive to (1) quantity and quality of the incorporated organic matter added in the soils, (2) initial SOC content and soil texture, and (3) temperature. These trends have been observed by *Fox and Bandel* [1986], *Molina et al.* [1983], *Erickson* [1982], and *Jenkinson* [1990]. However, the sensitivity tests reported in the paper are only for a specific site, which may not be representative of all the climate/soil/management regimes across the world's rice fields. However, the general trends presented from the tests could be applicable to other locations.

4. Upscaling With Quantified Uncertainty

[23] The above-described sensitivity tests demonstrated that natural factors, especially some soil properties, affect the impacts of management on soil GHG gas emissions. This conclusion is in agreement with observations in many soils where measured CH_4 or N_2O fluxes differed, although under the similar management conditions [*Sass*, 2002; *Husin et al.*, 1995; *Huang et al.*, 1997; *Xiu et al.*, 1999]. The effect of soil heterogeneity on GHG emissions is a major source of uncertainties when applying process-based models such as DNDC to regional scale. In a regional modeling study, we usually need to divide the region into many grid cells, and assume all of the attributes in each grid cell are uniform. Only on the basis of the presetting, we can run the model grid cell by grid cell across the entire region to obtain regional results. This approach has been widely utilized to build various geographic information system (GIS) databases to support modeling calculations at regional scale, although quantification of the uncertainty still remains as a challenge. Soil properties (e.g., texture, SOC content, pH) are highly variable in space. It is not uncommon to find several different soil types with various SOC contents or pH values within a county or farm. When applying DNDC for a country such as China, a county is only a grid cell in which the soil properties are inherently heterogeneous. Averaging the variations of the soil properties may not resolve the complexity as the correlation between GHG and any of the soil properties is nonlinear. How can we correctly use the soil survey data as input to run the model to predict GHG emissions for the county? To answer this question, we developed the most sensitive factor (MSF) method for the regional applications of DNDC [*Li et al.*, 1996, 2001, 2002]. On the basis of this method, we constructed the soil databases with the range values which were commonly reported in the soil survey records for each county. This means that in the databases, each soil factor (e.g., texture, SOC content, pH, and balk density) has two values (i.e., maximum and minimum) for each grid cell. We have found that there are general trends regarding the relations between GHG emissions and the soil factors through sensitivity tests at site scale. For example, the modeled CH_4 emissions from paddy soils usually increase along with increase in SOC content and pH as well as decrease in soil clay fraction. Therefore, when modeling CH_4 emissions for a county, DNDC will automatically select the minimum SOC content, minimum pH, and maximum clay fraction to form a scenario, which is assumed to produce a low value of CH_4 flux for the county, and then select the maximum SOC content, maximum pH, and minimum clay fraction to form another scenario, which is assumed to produce a high value of CH_4 flux for the county. Thus DNDC will run twice with the two scenarios for each county to produce two CH_4 fluxes. The two fluxes

will form a range, which is assumed to be wide enough to cover the "real" flux with a high probability.

[24] To verify the MSF method, we also built a Monte Carlo routine in DNDC to quantify the uncertainties derived by the soil heterogeneity during regional simulations. When DNDC runs in the Monte Carlo mode, the range of each soil factor in a grid cell will be divided into eight intervals. DNDC will randomly select an interval from each of the four soil properties (e.g., soil texture, SOC content, pH, and bulk density) to form a scenario to conduct a simulation. The processes will repeat 5000 times to produce 5000 fluxes for the simulated greenhouse gas based on the randomly combined soil properties. Frequencies of the modeled 5000 fluxes will be calculated and compared with the flux ranges produced by the MSF method.

[25] In this study, we selected three areas to test the MSF method as well the Monte Carlo approach. The tested grid cells are Chuxiong County in Yunnan Province, China, Ang-Thong Province, Thailand, and Colusa County in California, United States, with similar areas of about $0.5^\circ \times 0.5^\circ$. All of the three areas are typical rice-farming areas, although with different climate/soil conditions (Table 2). The management practices in each grid cell are relatively uniform. The variations in soil texture, SOC content, pH, and balk density are shown in Table 2. For Chuxiong County in China, the annual fluxes simulated with the MSF method ranged from 270 to 2448 kg C/ha, 18 to 139 kg C/ha, and 4 to 10 kg N/ha for CO_2, CH_4, and N_2O, respectively, and the fluxes simulated with the Monte Carlo method ranged from 58 to 2503 kg C/ha, 17 to 154 kg C/ha, and 0.4 to 17 kg N/ha for CO_2, CH_4, and N_2O, respectively. The Monte Carlo results provided information on the frequency distribution of the modeled fluxes for each gas in each region (Figures 11, 12, and 13). By comparing the results from Monte Carlo and MSF, we found that the flux ranges produced by the MSF method accounted for 97, 98, and 61% of the fluxes produced by the Monte Carlo method for CO_2, CH_4, and N_2O, respectively (Figures 11a, 11b, and 11c). The same comparisons were conducted for other two grid cells in Thailand and the United States, and it was found that the MSF-produced flux ranges accounted for 88–96% and 63–99% of the Monte Carlo-produced fluxes for the Thailand and United States grid cells, respectively (see details in Table 2 and Figures 12 and 13). The Monte Carlo method provides frequency distribution information but requires longer computing time (about 3 hours for 5000 simulations). The MSF method provides reasonable ranges without frequency information but requires much less computing time (10 s for two simulations). We adopted the MSF method due to its feasibility and effectiveness for a case study for China, which contains 11 rice-involved cropping systems in more than one thousand counties.

5. A Case Study: Modeling GHG Emissions From Rice Paddies in China

[26] Equipped with the MSF methodology, DNDC was applied for a large region, China, to estimate CO_2, CH_4 and N_2O emissions from all of rice paddies in the country. Through a multiyear collaboration between the United States and Chinese scientists, a GIS database was established for the entire rice area in China. The database includes meteorological data (e.g., daily air temperature, precipitation, and atmospheric N deposition), soil properties (e.g., texture, bulk density, pH, and total organic matter content), rice field area, and management parameters (e.g., crop rotation, water management, fertilization, manure amendment, tillage, irrigation, flooding). Most of the data were obtained from ground-based statistical sources [*Li et al.*, 2002]. The crop area has been modified based on remote sensing analysis [*Frolking et al.*, 2002]. Since many of the statistical data were county-based, county was chosen as the basic geographic unit of the database to maintain the maximum accuracy of the original data sets. Eleven dominant rice cropping systems, such as single rice, double rice, triple rice, rice/winter wheat, rice/vegetables, rice/oats, rice/soybeans, rice/rice/legume hay, rice/rice/rapeseeds, rice/rice/vegetables, and rice/rice/wheat rotations, have been included in the database.

[27] Water management in rice paddies experienced a gradual but substantial change during the past 2 decades in China. Before 1980, most rice fields were managed with continuous flooding during the entire rice growing seasons. Since early 1980s, mid-season drainage was applied in northern China for water saving and yield elevation. The alternative management practice was adopted in most rice areas in China by the end of 1990s [*Shen et al.*, 1998]. Two scenarios of water management were designed in this study to quantify the impacts of the water management change on global GHG budget. DNDC calculated annual SOC change (equivalent to net CO_2 emission), CH_4 flux, and N_2O flux from each rice-involved cropping system with continuous flooding and midseason drainage scenarios, respectively, in each county for entire China. The 1990 meteorological data from more than 600 climatic stations across China were utilized in the upscaling study.

[28] The modeled results indicated that total CH_4 flux from the simulated 30 million ha of rice fields in China ranged from 6.4 to 12.0 Tg C per year under continuous flooding conditions (Figure 14). With the midseason drainage scenario, the national CH_4 flux from rice agriculture reduced to 1.7–7.9 Tg C per year. It implied the water management change in China reduced CH_4 fluxes by 4.7–4.1 Tg C/yr. This value is nearly 20% of the current imbalance in the global CH_4 budget of about 22 Tg CH_4/yr [*Prather and Ehhalt*, 2001]. The growth of global CH_4 concentration in the atmosphere slowed from 10–15 ppb/yr in the 1980s to 0–5 ppb/yr for most years in the 1990s [e.g., *Dlugokencky et al.*, 1994, 2001]. Large-scale temperature and precipitation anomalies have been identified as possible causes of the interannual variability in the rate of increase of CH_4 concentration [e.g., *Hogan and Harriss*, 1994; *Dlugokencky et al.*, 2001]. These factors cannot explain the decadal trend to lower rates of growth of CH_4 concentration (1990s versus 1980s). On the basis of the DNDC-predicted results, CH_4 emissions from paddy fields in China declined over this period and could have contributed to the slowing of the global growth rate of atmospheric CH_4 observed in the 1990s [*Li et al.*, 2002]. The total area of rice paddies in Asia is about 4 times of that in China alone, and 80% of the rice area

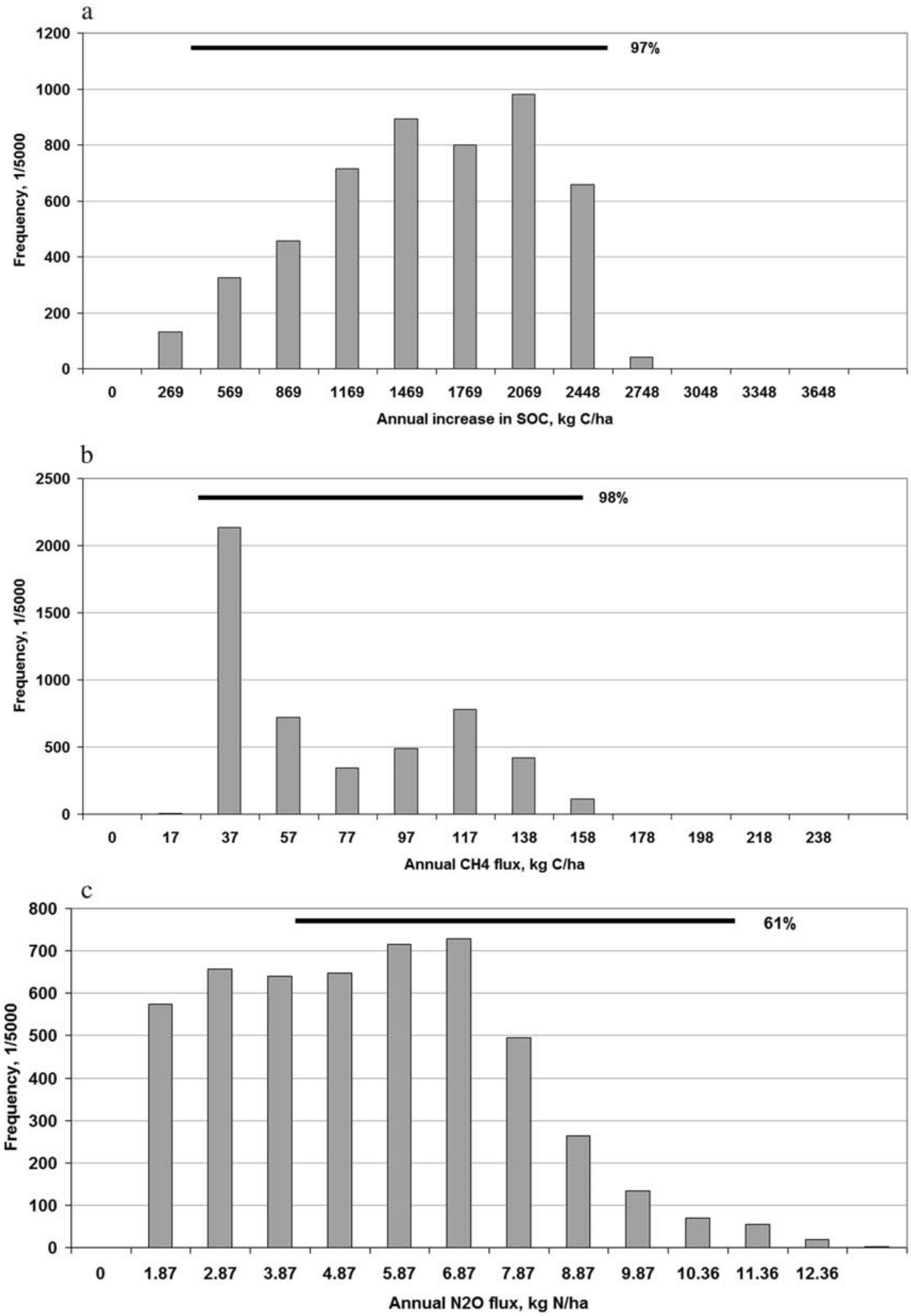


Figure 11. DNDC-modeled annual net (a) CO_2, (b) CH_4, and (c) N_2O flux frequencies with Monte Carlo approach (vertical bars) and flux ranges with most sensitive factor (MSF) method (horizontal line) for the rice paddies in Chuxiong County in Yunnan Province, China. Here 97% of CO_2 fluxes, 98% of CH_4 fluxes, and 61% of N_2O fluxes produced by the Monte Carlo method are located within the MSF-produced flux ranges.

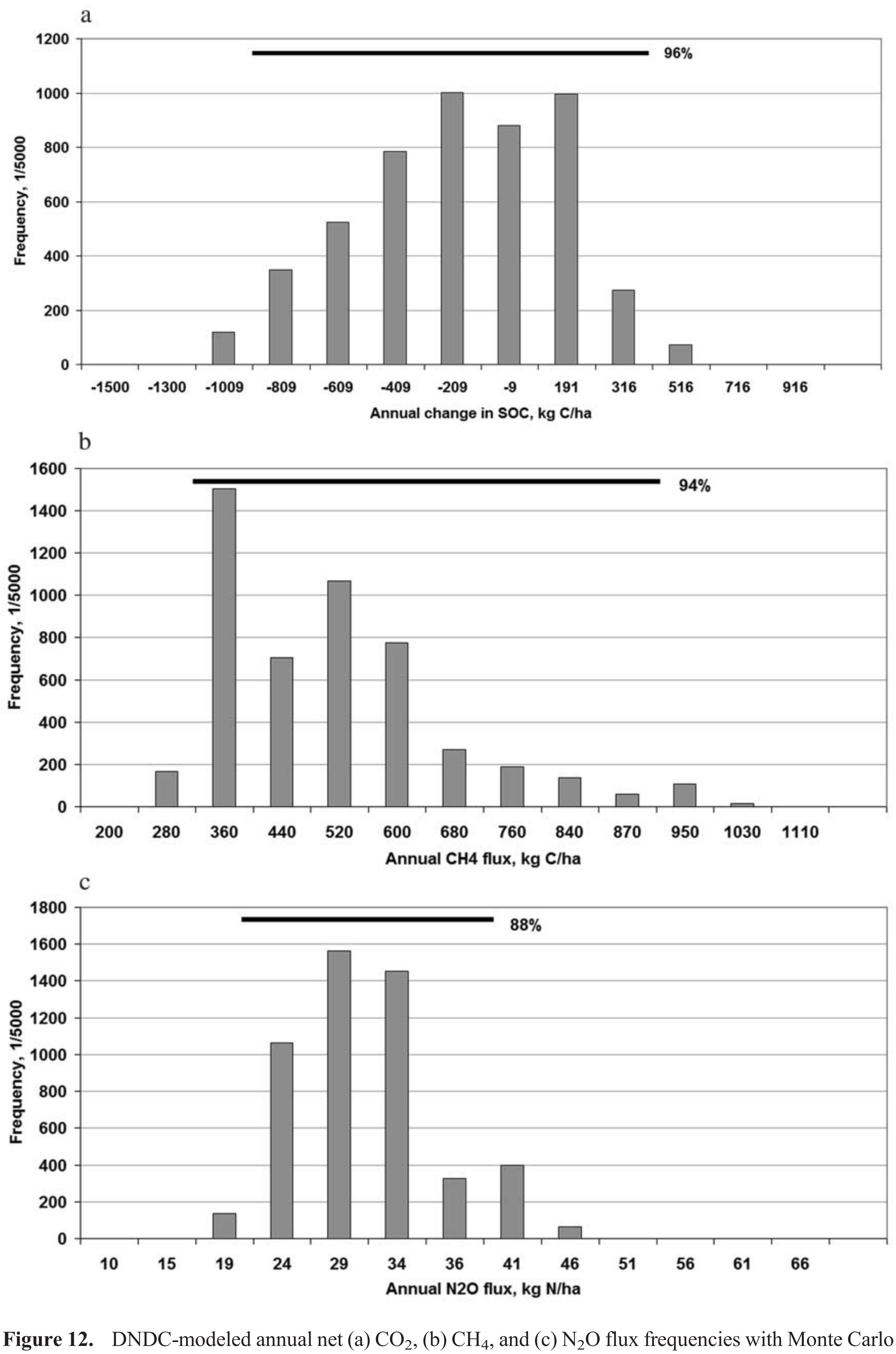
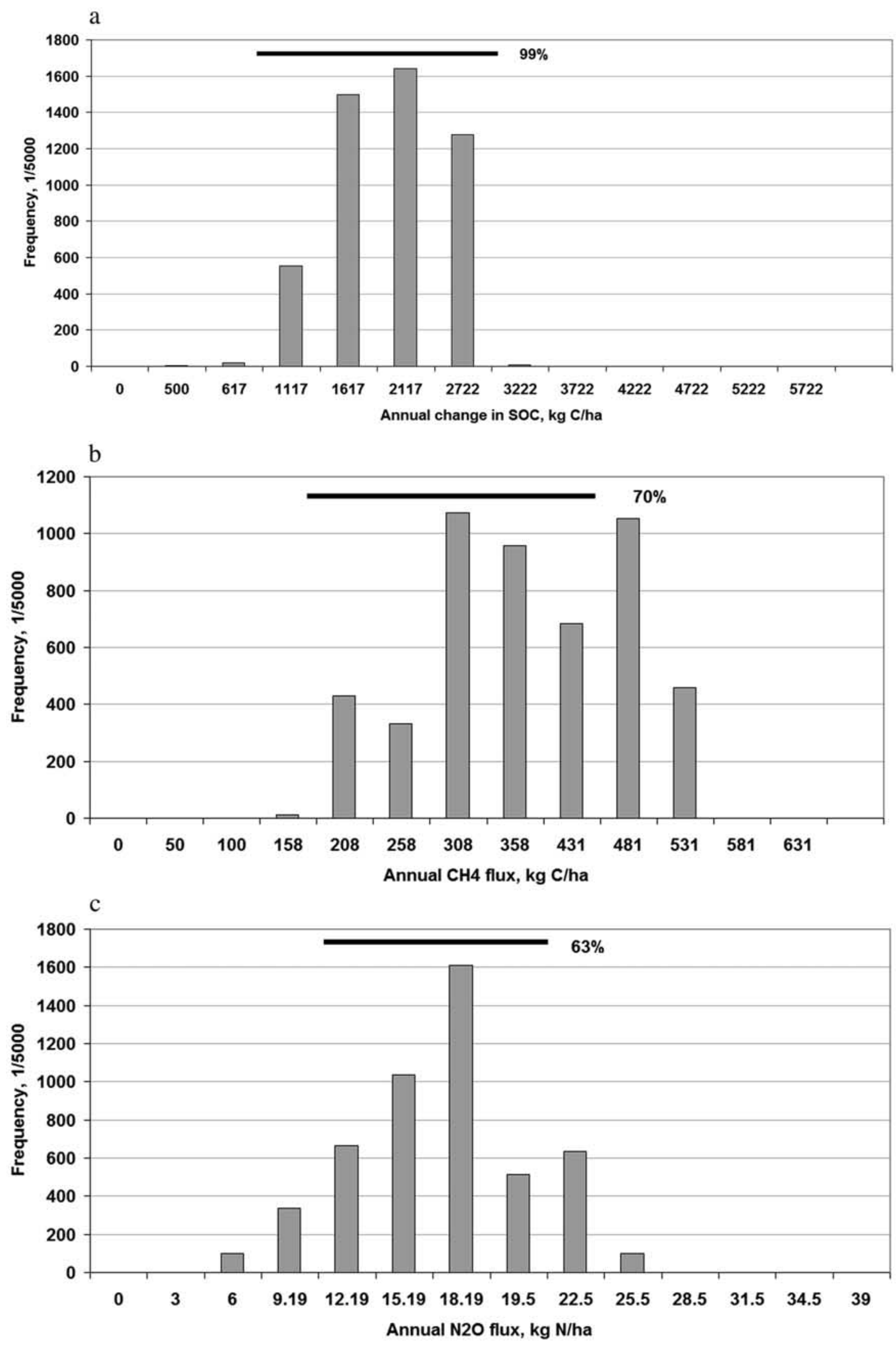


Figure 12. DNDC-modeled annual net (a) CO_2, (b) CH_4, and (c) N_2O flux frequencies with Monte Carlo approach (vertical bars) and flux ranges with most sensitive factor (MSF) method (horizontal line) for the rice paddies in Ang-Thong Province, Thailand. Here 96% of CO_2 fluxes, 94% of CH_4 fluxes, and 88% of N_2O fluxes produced by the Monte Carlo method are located within the MSF-produced flux ranges.


a
99%
Frequency, 1/5000
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1600
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1200
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400
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3722
4222
4722
5222
5722
Annual change in SOC, kg C/ha
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70%
1200
1000
800
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200
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50
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158
208
258
308
358
431
481
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581
631
Annual CH4 flux, kg C/ha
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39
Annual N2O flux, kg N/ha

Figure 13.

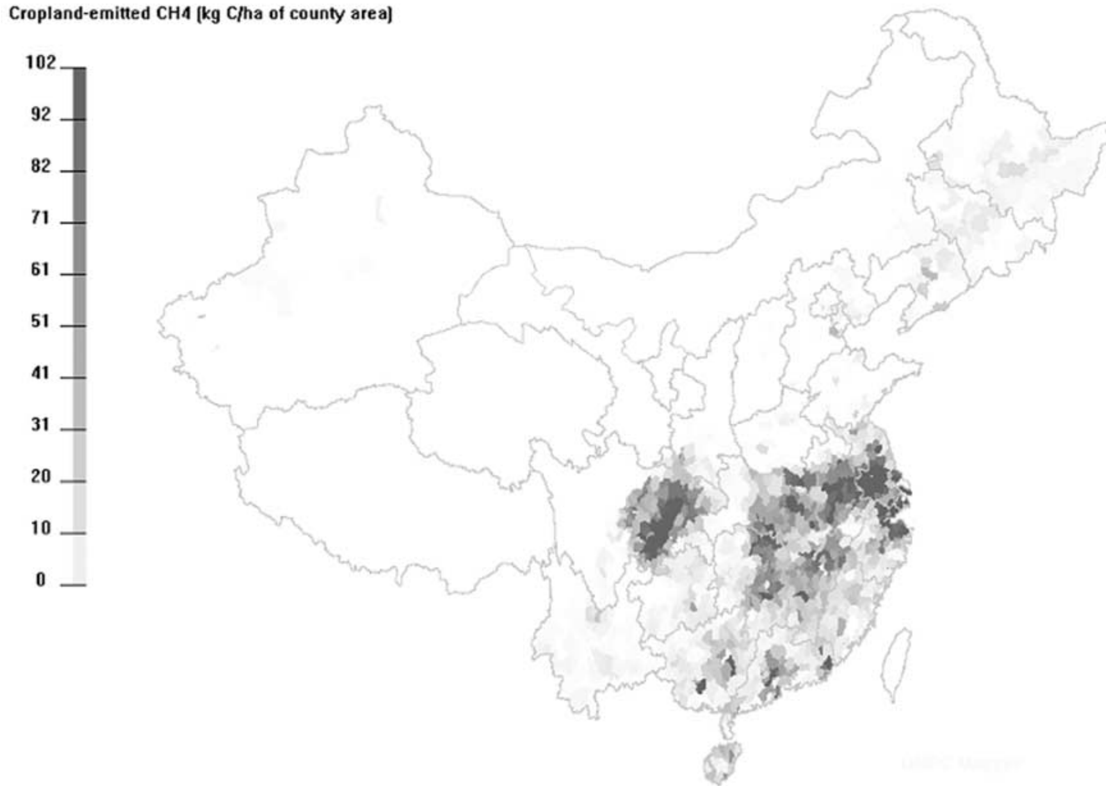

Figure 14. DNDC-modeled CH_4 emissions from rice agriculture at county scale in China. Chinese rice fields emitted 6.4–12.0 Tg CH_4-C per year with the continuous flooding scenario under 1990 climate and land-use conditions (data for Taiwan were missing).

in Asia is irrigated or rainfed [*IRRI*, 2002]. A midseason drainage water management approach has been applied in many other Asian countries such as India [*Jain et al.*, 2000; *Adhya et al.*, 2000], Philippines [*Corton et al.*, 2000], Japan [*Yagi et al.*, 1996], Korea [*Neue*, 1993], and Indonesia [*Kimura*, 1994; *Husin et al.*, 1995]. The DNDC-modeled total CH_4 flux for China is comparable with the estimates by *Wang and Aiguo* [1993] (12.6 Tg CH_4-C) and *Huang et al.* [1997] (5.4–10.2 Tg CH_4) based on field observations. Extending the modeling study from China to Asia and even the world could improve our understandings of atmospheric impacts of agriculture.

[29] During the regional simulations for China, annual SOC change (i.e., net CO_2 flux) and N_2O flux were also calculated for each of the rice-involved cropping systems with the two different water management scenarios for all of the Chinese rice paddies. Shifting the water management from continuous flooding to midseason drainage increased N_2O fluxes by 0.13–0.20 Tg N/yr, although CO_2 fluxes were only slightly altered (Table 3). The upscaling study for China revealed the complexity of GHG mitigation. When CH_4 emissions were reduced in China due to the alternative water management, N_2O emissions increased. Since N_2O possesses higher GWP, the increased N_2O offset about 65% of the benefit gained by decreasing CH_4 fluxes. The conflict between the CH_4 and N_2O mitigation measures again demonstrates the challenge of mitigating GHG emissions through managing biogeochemical cycles in terrestrial ecosystems.

6. Discussion

[30] World human population is expected to exceed nine billion by 2050 [*United Nations Population Division*, 2001]. To meet food security needs, rice production will definitely increase through various management developments globally. These alternative management measures will alter the dynamics of C, N, and water in the rice

Figure 13. DNDC-modeled annual net (a) CO_2, (b) CH_4, and (c) N_2O flux frequencies with Monte Carlo approach (vertical bars) and flux ranges with most sensitive factor (MSF) method (horizontal line) for the rice paddies in Colusa County in California, United States. Here 99% of CO_2 fluxes, 70% of CH_4 fluxes, and 63% of N_2O fluxes produced by the Monte Carlo method are located within the MSF-produced flux ranges.

Table 3. DNDC-Predicted CH_4, N_2O, and Net CO_2 Fluxes From Paddy Rice Agriculture Under Alternative Water Management Conditions in China

Greenhouse Gas	Range of Modeled Fluxes: Continuous Flooding	Range of Modeled Fluxes: Midseason Drainage
CH_4, Tg C/yr	6.44–12.02	1.71–7.85
N_2O, Tg N/yr	0.29–0.41	0.42–0.61
CO_2, Tg C/yr	12.08–2.05	12.23–3.49
GWP, Tg CO_2 equivalent/yr	314–581	240–562

ecosystems. Predicting impacts of the management alternatives on C and N biogeochemical cycles is becoming crucial not only for sustainable crop yield but also environmental safety. This paper reports an attempt to utilize a biogeochemical model to quantify effects of cropping management on atmospheric chemistry at site and regional scales. Since the model simultaneously tracks crop yield, soil fertility, nitrogen leaching, and trace gas emissions, the modeled results can be used for comprehensive assessments on impacts of management alternatives on production and mitigation for agroecosystems. Continuously developing this kind of tool will be a central effort for advancing rice production in Asia or other parts of the world.

[31] Results from both the site and regional simulations in the study revealed the complexity of mitigating GHG emissions from rice agroecosystems. For example, some management alternatives (e.g., changing crop rotation system, increasing crop residue incorporation) could sequester a substantial amount of C into the soil, but usually elevated CH_4 and/or N_2O emissions. The link between soil C sequestration and other GHG fluxes comes from a basic concept, biogeochemical coupling. Through a series of biochemical or geochemical reactions, such as photosynthesis, assimilation, nitrification, denitrification, and so on, C and N are tightly linked to each other not only in the plant tissues but also in the soil microbes. Any variation in SOM quantity or quality in an ecosystem will certainly alter both C and N dynamics. Increase in CH_4 or N_2O fluxes due to elevated SOM content has been widely observed by many researchers in various ecosystems. DNDC just synthesized the individual observations into a generic mathematical framework. We assume that the increase in N_2O or CH_4 emissions due to soil C sequestration modeled in the study is applicable to many other terrestrial ecosystems. Nowadays, many research projects focus on C sequestration in terrestrial ecosystems for mitigating global climate change. If done without adequate consideration of the net effects on the whole suite of GHGs, the research conclusions may not be able to stand firmly alone.

[32] Through the modeling predictions in this study, more opportunities have been explored to mitigate GHG emissions from paddy rice agriculture. For example, the modeled results demonstrated substantial differences in the impact of a same management practice on GHG fluxes between different soil textures. In the sensitivity tests, the rice field with clay soil had a GWP value 20% less than that produced by the rice field with loamy sand soil. It means that with the same cost, applying a management alternative at a heavy soil could be more efficient regarding mitigating GHG fluxes. The results imply that the future policies for regulating agricultural management need to account for the local climate-soil conditions in a more precise way. Biogeochemical modeling is emerging in precision agriculture as well as global change studies. We hope this paper will fuel more interest in this research area.

[33] **Acknowledgments.** The authors thank the Asian-Pacific Global Change Network for its financial support to this study (Land Use/Management Change and Trace Gas Emissions in East Asia—APN 2001-16). Changsheng Li's study was supported by NASA's Terrestrial Ecology Program (TE/02-0000-0018).

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