9-2005

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Recommended Citation

Li, C., S. Frolking, X. Xiao, B. Moore III, S. Boles, J. Qiu, Y. Huang, W. Salas, and R. Sass (2005), Modeling impacts of farming management alternatives on CO2, CH4, and N2O emissions: A case study for water management of rice agriculture of China, Global Biogeochem. Cycles, 19, GB3010, doi:10.1029/2004GB002341.

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Modeling impacts of farming management alternatives on CO_2, CH_4, and N_2O emissions: A case study for water management of rice agriculture of China

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Received 16 July 2004; revised 10 March 2005; accepted 9 May 2005; published 17 August 2005.

[1] Since the early 1980s, water management of rice paddies in China has changed substantially, with midseason drainage gradually replacing continuous flooding. This has provided an opportunity to estimate how a management alternative impacts greenhouse gas emissions at a large regional scale. We integrated a process-based model, DNDC, with a GIS database of paddy area, soil properties, and management factors. We simulated soil carbon sequestration (or net CO_2 emission) and CH_4 and N_2O emissions from China's rice paddies (30 million ha), based on 1990 climate and management conditions, with two water management scenarios: continuous flooding and midseason drainage. The results indicated that this change in water management has reduced aggregate CH_4 emissions about 40%, or 5 Tg CH_4 yr^{-1}, roughly 5–10% of total global methane emissions from rice paddies. The mitigating effect of midseason drainage on CH_4 flux was highly uneven across the country; the highest flux reductions (>200 kg CH_4-C ha^{-1} yr^{-1}) were in Hainan, Sichuan, Hubei, and Guangdong provinces, with warmer weather and multiple-cropping rice systems. The smallest flux reductions (<25 kg CH_4-C ha^{-1} yr^{-1}) occurred in Tianjin, Hebei, Ningxia, Liaoning, and Gansu Provinces, with relatively cool weather and single cropping systems. Shifting water management from continuous flooding to midseason drainage increased N_2O emissions from Chinese rice paddies by 0.15 Tg N yr^{-1} (~50% increase). This offset a large fraction of the greenhouse gas radiative forcing benefit gained by the decrease in CH_4 emissions. Midseason drainage-induced N_2O fluxes were high (>8.0 kg N/ha) in Jilin, Liaoning, Heilongjiang, and Xinjiang provinces, where the paddy soils contained relatively high organic matter. Shifting water management from continuous flooding to midseason drainage reduced total net CO_2 emissions by 0.65 Tg CO_2-C yr^{-1}, which made a relatively small contribution to the net climate impact due to the low radiative potential of CO_2. The change in water management had very different effects on net greenhouse gas mitigation when implemented across climatic zones, soil types, or cropping systems. Maximum CH_4 reductions and minimum N_2O increases were obtained when the mid-season draining was applied to rice paddies with warm weather, high soil clay content, and low soil organic matter content, for example, Sichuan, Hubei, Hunan, Guangdong, Guangxi, Anhui, and Jiangsu provinces, which have 60% of China's rice paddies and produce 65% of China's rice harvest.

Citation: Li, C., S. Frolking, X. Xiao, B. Moore III, S. Boles, J. Qiu, Y. Huang, W. Salas, and R. Sass (2005), Modeling impacts of farming management alternatives on CO_2, CH_4, and N_2O emissions: A case study for water management of rice agriculture of China, *Global Biogeochem. Cycles*, *19*, GB3010, doi:10.1029/2004GB002341.

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0886-6236/05/2004GB002341

1. Introduction

[2] Food production contributes approximately 70% of global atmospheric input of nitrous oxide (N_2O) and 40% of global atmospheric input of methane (CH_4) [*Cole et al.*, 1996], and so represents a significant opportunity for greenhouse gas mitigation through reductions of CH_4 and N_2O emissions, as well as through soil carbon sequestration [*Oenema et al.*, 2001]. When assessing the impact of food and fiber production systems on the Earth's radiation budget, 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; *Smith et al.*, 2001; *Li et al.*, 2005]. Since each greenhouse gas has its own radiative potential [*Ramaswamy et al.*, 2001], a net global warming potential (GWP) of a crop production system can be estimated, accounting for all the three gases.

[3] Rice is a major food crop in Asia (~130 million hectares were sown in 2002 [*Food and Agriculture Organization* (*FAO*), 2004]), and the majority of rice production in Asia is from flooded paddy fields (<10% of sown area is upland rice [*Huke and Huke*, 1997]). Rice paddies contribute about 10% of total global methane emissions to the atmosphere [*Prather et al.*, 2001]. Field studies have shown that water management can have a significant influence on total methane emissions during a cropping season [*Wassmann et al.*, 2000a; *Sass et al.*, 1992] so paddy water management has become a target mitigation scenario [*Wassmann et al.*, 2000b].

[4] Water management in paddy fields can be classified as irrigated or rainfed [*Huke and Huke*, 1997]. Irrigated paddies typically have continuous management of their flooding regime, while rainfed paddy flooding can be sporadic, depending on seasonal precipitation. Water management of irrigated rice paddies can be coarsely partitioned into two categories: continuous flooding or mid-season draining. In continuous flooding, the paddy soils remain saturated and puddled from just prior to transplanting until just before harvest. Puddled paddy soils quickly become anoxic, and remain so for the duration of the growing season. Mid-season draining/drying entails active draining of the paddy or passive drying for 1 to 2 weeks, typically several times during a growing season. During this period the surface soil becomes more oxic. Field studies have shown that mid-season draining reduces total crop-season CH_4 emissions by 10–80% [*Sass et al.*, 1992; *Yagi et al.*, 1996; *Cai et al.*, 1999; *Wassmann et al.*, 2000a], giving the practice a strong potential for greenhouse gas mitigation [*Wassmann et al.*, 2000b]. Fewer field studies have measured the consequences of mid-season draining on N_2O emissions but there are strong indications that mid-season draining can cause an increase in N_2O flux [e.g., *Chen et al.*, 1995; *Zheng et al.*, 1997, 2000], probably because the oxic/anoxic transitions favor both nitrification and denitrification.

[5] Mid-season drainage was initiated in rice farming in northeastern China in the early 1980s owing to frequent shortages of irrigation water. Mid-season drainage was found to not only reduce water use but also increase crop yield. The practice was quickly adopted for rice agriculture in northern China in the 1980s, and spread through most of China's rice agriculture during the 1990s [*Shen et al.*, 1998]. Over the years, mid-season drainage has demonstrated other agronomic advantages, including reducing ineffective tillers, removing toxic substances, and maintaining healthier roots under anaerobic soil conditions. Short periods of drainage for soil aeration during vegetative growth and intermittent irrigation during reproductive growth are now common in China [*Gao et al.*, 1992] and Japan [*Yoshida*, 1981]. The intensity of drainage and the interval between the cycles of flooding-drainage-reflooding vary with soil characteristics and weather conditions.

[6] Water management for rice agriculture in China, most of which is irrigated [*Huke and Huke*, 1997], has changed substantially during the 20-year period from 1980 to 2000, with midseason drainage gradually replacing continuous flooding [*Shen et al.*, 1998]. This nationwide change provided an opportunity for us to quantify how a management alternative could impact greenhouse gas emissions at a large regional scale. In an earlier study we evaluated the impact of this changing management on methane emissions from China's rice paddies, and estimated a reduction of about 40% in total emissions from all paddy rice in China [*Li et al.*, 2002]. In this paper we extend this analysis to look at changes in both CH_4 and N_2O emissions, and to look at spatial patterns of changing greenhouse gas across China, rather than just an aggregate national total.

2. Methods

[7] Both CH_4 and N_2O fluxes from agro-ecosystems are highly variable in space and time, affected by ecological drivers (e.g., climate, vegetation, and anthropogenic activity), soil environmental factors (e.g., temperature, moisture, pH, redox potential, and substrate concentration gradients), and biochemical or geochemical reactions [*Li*, 2000, 2001; *Li et al.*, 2004]. Process-based models are used to quantify trace gas fluxes driven by the local climate, soil, vegetation, and management conditions at the site scale. GIS databases provide spatially differentiated information of climate, soil, vegetation, and management to drive the model runs across the region. To quantify the impacts of the water management change on C sequestration and CH_4 and N_2O emissions from ~30 million hectares of rice paddies in China, we integrated a process-based model, DNDC, with a GIS database of paddy area, soil properties, paddy management (fertilizer use, water management, crop residue management, planting and harvest dates), and daily weather data.

2.1. DNDC Model

[8] DNDC was originally developed for predicting carbon sequestration and trace gas emissions for non-flooded agricultural lands, simulating the fundamental processes controlling the interactions among ecological drivers, soil environmental factors, and relevant biochemical or geochemical reactions, which collectively determine the rates of trace gas production and consumption in agricultural ecosystems [*Li et al.*, 1992, 1994, 1996]. Details of management (e.g., crop rotation, tillage, fertilization, manure amendment, irrigation, weeding, and grazing) have been parameterized and linked to the various biogeochemical processes (e.g., crop growth, litter production, soil water infiltration, decomposition, nitrification, denitrification) embedded in DNDC. To enable DNDC to simulate C and N biogeochemical cycling in paddy rice ecosystems, we modified the model by adding a series of anaerobic processes. The paddy-rice version of DNDC has been described and tested in recent manuscripts [*Li et al.*, 2002; *Cai et al.*, 2003; *Li et al.*, 2004], and is summarized briefly here.

Table 1. DNDC Oxidation-Reduction Scheme

Dominant Oxidant	Eh Range, mV	Dominant Reactions Simulated
O_2	650–500	aerobic decomposition, CH_4 oxidation, nitrification
NO_3^-, NO_2^-, NO, N_2O	500–200	denitrification sequence
Mn^{4+}	200–100	manganese reduction
Fe^{3+}	100–0	iron reduction
SO_4^{2-}	0––150	sulfate reduction
H_2	−150––350	methanogenesis

[9] Paddy soil is characterized by the frequent changes between saturated and unsaturated conditions driven by water management. During these changes in soil water content, the soil redox potential (i.e., Eh) is subject to substantial changes between +600 and −300 mV. One of the key processes controlling CH_4 and N_2O production/consumption in paddy soils is soil Eh dynamics; CH_4 or N_2O are produced or consumed under certain Eh conditions (−300 to −150 mV for CH_4, and 200 to 500 mV for N_2O), so the two gases are produced during different stages of the varying soil redox potential.

[10] To quantify Eh dynamics and its impacts on N_2O and CH_4 production, DNDC combines the Nernst equation, a basic thermodynamic formula defining soil Eh based on concentrations of the existing oxidants and reductants in the soil liquid phase [*Stumm and Morgan*, 1981], with the Michaelis-Menten equation, a widely applied formula describing kinetics of microbial growth with dual nutrients [*Paul and Clark*, 1989]. The Nernst and the Michaelis-Menten equations can be linked in model calculations since the two equations share a common factor, oxidant concentration. A simple kinetic scheme was adopted in DNDC to define the effective anaerobic volumetric fraction of a soil, based on the Eh value as calculated with the Nernst equation, using the concentration of the dominant active oxidant (in order of descending Eh: O_2, NO_3^-, Mn^{4+}, Fe^{3+}, SO_4^{2-}, CO_2). Each oxidant is assigned an Eh range (Table 1). When a soil layer's Eh value is in a particular oxidant's range, the layer is divided into a high Eh zone (Eh = range upper value) and a low Eh zone (Eh = range lower value), as a linear function of where within the range the Eh value is. DNDC allocates substrates (e.g., DOC, NO_3^-, NH_4^+, CH_4) to reductive reactions (e.g., denitrification, methanogenesis) and oxidative reactions (e.g., nitrification, methanotrophy) based on relative fractional volumes of the oxidizing and reducing zones, and the potential oxidation and reduction reactions are determined by Eh (and pH) [*Stumm and Morgan*, 1981]. When a soil is flooded, oxygen diffusion into the soil is severely restricted, and ongoing decomposition lowers the oxygen concentration, reducing the soil Eh and causing the low Eh volume fraction to increase. As the oxygen is depleted, the low Eh volume fraction reaches its maximum. At this moment, a new oxidant (i.e., NO_3^-) will become the dominant species in the soil, and a new, lower Eh volume fraction will begin to swell, driven by NO_3^- depletion. 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, DNDC 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 links the soil water regime to trace gas emissions for rice paddy ecosystems, and DNDC predicts daily CH_4 and N_2O fluxes from rice fields through the growing and fallow seasons, as they remain flooded or shift between flooded and drained.

[11] This new DNDC model has been tested against several methane flux data sets from wetland rice sites in the United States, Italy, China, Thailand, and Japan [*Li et al.*, 2002; *Cai et al.*, 2003]. For sites in East Asia, simulated seasonal CH_4 emissions from paddy soils were in good agreement with field studies (r^2 = 0.96, regression slope = 1.1, n = 23, range in fluxes 9 to 725 kg CH_4-C ha^{-1} $season^{-1}$) [*Cai et al.*, 2003]. There were fewer sites with N_2O flux data. If the site soil characteristics and crop and water management were well described, simulated fluxes were similar to observation (Figure 1) [*Zheng et al.*, 1997]. However, for the three cases where the management details were not so well known, there were discrepancies between model and field, though there was overlap in the range in fluxes, 0.6 to 2.0 kg N_2O-N ha^{-1} $season^{-1}$ for the field and 0.4 to 5.7 kg N_2O-N ha^{-1} $season^{-1}$ for the model [*Cai et al.*, 2003]. The results from the tests indicate that DNDC is capable of estimating the seasonal magnitudes of CH_4 and N_2O fluxes from paddy sites, although discrepancies exist for about 20% of the tested cases.

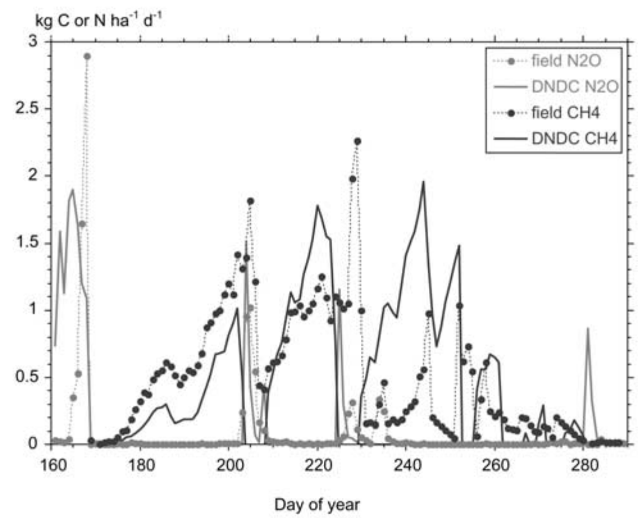

Figure 1. Comparison between observed and DNDC-modeled CH_4 and N_2O fluxes from a paddy rice field applied with mid-season drainage in Wu County, Jiangsu Province, China, in 1995. DNDC captured the episodes of CH_4 emission depressions and N_2O emission increases during the soil drying time periods by tracking the soil oxygen diffusion, CH_4 oxidation, labile organic matter decomposition, and stimulated nitrification and denitrification fueled by the increased ammonium and nitrate production due to the conversions of soil anaerobic to aerobic conditions driven by the mid-season drainage. (Field data were adopted from *Zheng et al.* [1997]). See color version of this figure at back of this issue.

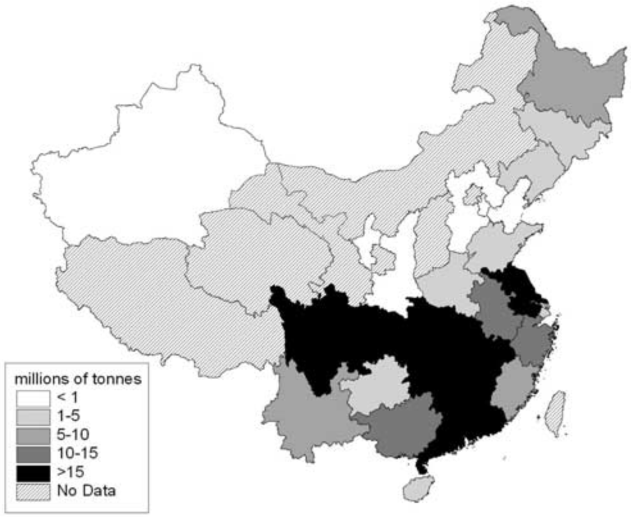

Figure 2. Mean annual provincial rough rice production for 1991–2000 (IRRI 2004) in millions of tonnes per year. No provincial data were reported for Tibet (Xizang), Qinghai, Xinjiang, Gansu, Shanxi, Inner Mongolia, and Beijing; 1991–2000 total mean annual rough rice production for these seven provinces was 740,000 t yr^{-1}. Taiwan was excluded from our entire analysis because of a lack of crop rotation data.

2.2. GIS Database

[12] The model domain contained 30 million ha of rice paddies in China [*Frolking et al.*, 2002]. There were 11 different crop rotations, including single-rice, double-rice, rice-winter wheat, rice-rapeseed, rice-rice-vegetable, etc. The area occupied by each rotation in each county was quantified by combining a county-scale statistical database of crop-sown areas with a Landsat TM-derived land-cover map for all of mainland China [*Frolking et al.*, 2002]. The majority of rice production occurs in southern China, and particularly along the Yangtze River (Figure 2 [*International Rice Research Institute* (*IRRI*), 2004]). Daily weather data (maximum and minimum air temperatures, precipitation) for 1990 from 610 weather stations across China were acquired from the National Center for Atmospheric Research (http://dss.ucar.edu/index.html). Station data were assigned to each county on a nearest neighbor basis. Maximum and minimum values of soil texture, pH, bulk density, and organic carbon content were derived for each county from digitization of national soil maps [*Institute of Soil Science*, 1986] and other information [*National Soil Survey Office of China*, 1997]. Model simulations could then be conducted for each county by choosing soil parameter values spanning the observed range. Soil Mn, Fe, and sulfate contents were set to average values for Chinese paddy soils: Mn = 30 mg kg^{-1} soil, Fe = 80 mg kg^{-1} soil, and sulfate = 220 mg kg^{-1} soil [*Li*, 1992]. General data on fertilizer use, tillage, planting and harvest dates, crop residue management, and crop varieties were taken from *Central Radio and Television School of Agriculture* (*CRTSA*) [1995], *Huang et al.* [1997], *Cui et al.* [1994], *Liu and Mu* [1993], and *Beijing Agricultural University* [1992]. *Shen* [1998] reported that based on national statistics, an average of 30% of total crop residue (leaves + stems + roots) was returned to the soil, which we adopted for all fields. Manure production was based on animal and human populations from the county database assembled by the Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, using standard manure production rates [*Intergovernmental Panel on Climate Change* (*IPCC*), 1997], and field application rates of 20% for animal manure and 10% for human manure.

[13] Changing water management of China's rice paddies is not well documented. *Li et al.* [2002] constructed a simple scenario of the evolution of paddy water management in China from 2000, as paddies went from near 100% continuous flooding in 1980 [*Shen et al.*, 1998] to ~80% midseason drainage by 2000 (Qingmu Chen, Chinese Academy of Agricultural Sciences, personal communication, 2002). In this study we wish to quantify the potential impacts of alternative water management practices, so we designed two water management scenarios: continuous flooding (CF) and midseason drainage (MSD) for 100% of the rice paddies in China.

2.3. Uncertainty

[14] The county was chosen as the basic spatial unit for GIS database construction since most of the statistical cropland data was county-based. Meteorological data, soil properties, 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. With ~2500 counties, most with rice crops and many with several crop rotations, a set of annual simulations with a single parameter set required about 10,000 model runs, so Monte Carlo analysis (randomly adjusting all parameters thousands of times to get a statistical distribution of outputs) was computationally prohibitive.

[15] Instead, sensitivity tests were conducted to prioritize the environmental factors regarding their effects on CH_4 or N_2O emissions [*Li et al.*, 2004]. Among the tested factors, including soil properties, temperature, and precipitation, the most sensitive factors for CH_4 and N_2O emissions were soil texture and soil organic carbon (SOC) content, respectively. Varying soil texture and SOC over the ranges reported in the county-scale database produced a range of CH_4 and N_2O emissions. The range in fluxes generated by this "most sensitive factor" method was compared to the distribution of fluxes generated by a Monte Carlo simulation for three paddy sites (Yunnan Province, China; Suphan Buri Province, Thailand; and California, United States); 70–98% of annual CH_4 fluxes and 61–88% of annual N_2O fluxes generated in 5000 Monte Carlo simulations for each site fell within the range generated by varying the most sensitive factor [*Li et al.*, 2004].

[16] Applying the "most sensitive factor" method, we ran DNDC for each rice rotation in each county twice, once

Table 2. Provincial Paddy Area and Simulated CO_2, CH_4, and N_2O Maximum and Minimum Fluxes for Continuous Flooding (CF) and Mid-Season Draining (MSD) Water Management[a]

Province[b]	Production,[c] Gg C yr^{-1}	CO_2, Gg C yr^{-1}				CH_4, Gg C yr^{-1}				N_2O, Gg N yr^{-1}			
		CF_{min}	CF_{max}	MSD_{min}	MSD_{max}	CF_{min}	CF_{max}	MSD_{min}	MSD_{max}	CF_{min}	CF_{max}	MSD_{min}	MSD_{max}
Sichuan[d]	11,000	1500	240	1600	−380	1800	1300	1300	200	49	34	72	47
Hunan	12,000	370	−1700	280	−2000	1100	550	580	110	38	32	54	41
Jiangsu	9000	1800	1400	1900	1300	1200	770	1000	480	25	18	36	25
Jiangxi	7600	74	−1000	−3	−1200	1100	560	710	72	33	22	54	31
Anhui	6300	600	−710	780	−920	1100	460	870	77	29	14	38	19
Hubei	8300	510	−1200	490	−1300	1100	410	650	46	24	13	33	16
Guangdong	7600	310	−700	57	−870	860	470	400	150	26	22	40	29
Guangxi	6200	1800	15	1700	−13	670	260	260	13	38	26	56	33
Yunnan	2600	180	−290	130	−320	160	81	18	3	12	12	17	14
Guizhou	2200	450	−560	530	−550	200	96	74	9	14	10	21	13
Fujian	3600	−1	−180	−39	−250	260	170	140	29	14	10	21	13
Henan	1600	340	88	300	26	340	140	230	27	6	3	9	4
Liaoning	1800	490	390	660	450	1800	140	230	61	10	8	19	17
Jilin	1700	650	370	680	500	150	100	120	30	12	8	22	24
Shaanxi	450	130	180	120	160	110	64	77	7	4	3	7	4
Shanghai	800	160	140	160	120	150	95	120	56	2	2	3	2
Inner Mongolia	n.a.[e]	120	160	120	180	34	21	27	5	3	2	4	3
Shandong	520	−47	20	−44	27	61	50	50	34	1	1	2	2
Hebei	450	−22	22	−5	37	28	26	34	27	1	1	1	1
Zhejiang	6100	340	−390	340	−480	730	390	550	140	23	17	34	23
Heilongjiang	3200	1800	1400	1800	1600	270	180	230	78	36	26	44	44
Tianjin	190	−14	11	7	27	17	16	32	26	0.7	0.6	1	1
Ningxia	270	−47	−38	−29	−36	2	3	10	2	0.7	0.5	1	1
Gansu	n.a.[e]	7	11	7	12	2	2	2	0.6	0.1	0.1	0.2	0.2
Hainan	790	610	210	610	200	200	100	73	19	8	4	12	5
Beijing	n.a.[e]	−1	7	3	7	5	4	6	2	0.1	0.1	0.2	0.1
Shanxi	n.a.[e]	4	7	6	8	3	3	3	2	0.1	0.1	0.2	0.2
Xinjiang	n.a.[e]	51	56	57	63	51	27	42	7	2	1		2
China	**94,000**	**12,000**	**−2000**	**12,000**	**−3500**	**12,000**	**6400**	**7800**	**1700**	**410**	**290**	**610**	**420**

[a]CO_2 flux equals negative of change in soil organic carbon storage. Sign convention for all fluxes is positive flux equals net emission from soil. All areas and all flux values greater than 10 Gg were rounded to two significant figures.
[b]Provinces are sorted by paddy area (see Table 3). Tibet and Qinghai Provinces are excluded due to small paddy areas.
[c]Mean annual rough rice production is given for 1991–2000 [*IRRI*, 2004]; carbon fraction of dry weight is assumed to be 50%.
[d]This includes Chongqing Province, which was established from land in Sichuan Province in 1997.
[e]Production data (see note 2 above) are not reported individually for some provinces; total production for all non-reported provinces = 370 Gg C yr^{-1}; China total equals sum of all reported and non-reported provinces.

with low SOC, low pH, and high clay content, and once with high SOC, high pH, and low clay content, to produce a range in CH_4 and N_2O emissions wide enough to represent likely variations in actual fluxes caused by the heterogeneous nature of soil properties.

2.4. Emissions Calculations

[17] Of 11 possible paddy rotations mapped across China [*Frolking et al.*, 2002], a single county typically had 2–4 paddy rotations. For each paddy crop rotation in each county, we simulated annual change in SOC (ΔSOC), and annual CH_4 and N_2O emissions for the range of soil conditions (as discussed in section 2.3). We consider ΔSOC as the negative of the site's net annual CO_2 flux. Methane flux is another pathway for carbon out of wetland soil, but the substrates for methane production are primarily plant-derived C (e.g., root exudation, deposition, and respiration CO_2) [*Watanabe et al.*, 1999; *Lu et al.*, 2002; *King et al.*, 2002], which are not included in the simulation's SOC budget, so methane flux would only be a small fraction of simulated ΔSOC. We then summed the low and high emissions from all of the rice cropping systems in the county, based on each rotation's fraction of total cropland area, to get a range in total CO_2, CH_4, and N_2O emissions for the county. We calculated a change in flux due to changing water management from continuous flooding to mid-season draining as the different between the mean MSD flux and the mean CF flux, where the mean flux is the average of the high and low fluxes.

[18] The climate impact of these flux changes can be compared by converting them to a common basis of CO_2-equivalent fluxes using the global warming potential (GWP) methodology [*Ramaswamy et al.*, 2001]. GWP values for CH_4 and N_2O depend on the time horizon chosen. Methane, with a much shorter atmospheric adjustment time than N_2O or CO_2, has very different 20-year, 100-year, and 500-year GWP values [*Ramaswamy et al.*, 2001]. A CO_2-equivalent flux for a 1-kg CH_4 or N_2O flux is the mass of CO_2 emissions that would generate the same integrated radiative forcing, over the chosen time horizon, as a 1-kg emission CH_4 or N_2O. (Note that GWP calculations are done with molecular masses, not C or N masses.) For example, let ΔCO_2, ΔCH_4, and ΔN_2O be the differences between the mean carbon dioxide, methane, and nitrous oxide fluxes (MSD minus CF) in kg C or N ha^{-1} yr^{-1}. Then the 20-year

time horizon CO_2-equivalent flux, in kg CO_2 ha^{-1} yr^{-1}, is calculated as

$$\begin{aligned}(CO_{2-eq.})_{20} &= \Delta[CO_2 \text{ flux}] + \Delta[\text{methane's } CO_2 - \text{equivalent}] \\ &\quad + \Delta[\text{nitrous oxide's } CO_2 - \text{equivalent}] \\ &= \Delta CO_2 \cdot \frac{44}{12} + \Delta CH_4 \cdot \frac{16}{12} \cdot GWP_{20}^{CH_4} + \Delta N_2O \cdot \frac{44}{28} \\ &\quad \cdot GWP_{20}^{N_2O}, \end{aligned} \tag{1}$$

where the numerical fractions in the second line are the ratios of molecular weights (CO_2, CH_4, and N_2O) to elemental weights (C and N); $GWP_{20}^{CH_4}$ equals 62 kg $CO_{2\text{-eq}}$ kg^{-1} CH_4 and $GWP_{20}^{N_2O}$ equals 275 kg $CO_{2\text{-eq}}$ kg^{-1} N_2O; $GWP_{100}^{CH_4}$ equals 23 kg $CO_{2\text{-eq}}$ kg^{-1} CH_4 and $GWP_{100}^{N_2O}$ equals 296 kg $CO_{2\text{-eq}}$ kg^{-1} N_2O; $GWP_{500}^{CH_4}$ equals 7 kg $CO_{2\text{-eq}}$ kg^{-1} CH_4, and $GWP_{500}^{N_2O}$ equals 156 kg $CO_{2\text{-eq}}$ kg^{-1} N_2O [*Ramaswamy et al.*, 2001].

3. Results

[19] The ranges in total CO_2 emissions with CF and MSD managements were +12,000 to −2000 and +12,000 to −3500 Gg CO_2-C yr^{-1}, respectively (Table 2). A positive CO_2 emission corresponds to a net loss of soil organic carbon, so overall mean behavior was probably an SOC loss in both scenarios though zero net flux fell within both predicted ranges. The CO_2 flux range went more negative (i.e., CO_2 uptake) for the MSD scenario, implying a small shift toward lower CO_2 emissions. The shift on CO_2 emission between the two water management scenarios was caused by changes in soil decomposition rates and crop residue incorporation rates. The latter was affected by soil N availability and total crop biomass production, which were both affected by water management. Taking the mean values, changing water management from continuous flooding to midseason draining caused a net uptake (i.e., reduced loss rate) of CO_2 of 640 Gg CO_2-C yr^{-1}. For perspective, in 2000, fossil fuel carbon emissions from China were about 700,000 Gg C yr^{-1} [*Marland and Boden*, 2004]. Changing water management to MSD led overall to net losses of CO_2 in northern China, and net uptake of CO_2 in southern China (Figure 3a), but changes were generally not large (Table 2).

[20] The ranges in total CH_4 emissions with CF and MSD managements were 6400–12,000 and 1700–7800 Gg CH_4-C yr^{-1}, respectively (Table 2). Taking the mean values, changing water management from continuous flooding to midseason draining caused a reduction in aggregate methane emissions from rice paddies of about 40%, or 6000 Gg CH_4 yr^{-1}. This is 5–10% of total global rice paddy methane emissions [*Prather et al.*, 2001]. The mitigating effect of MSD on CH_4 flux was highly uneven across the country.

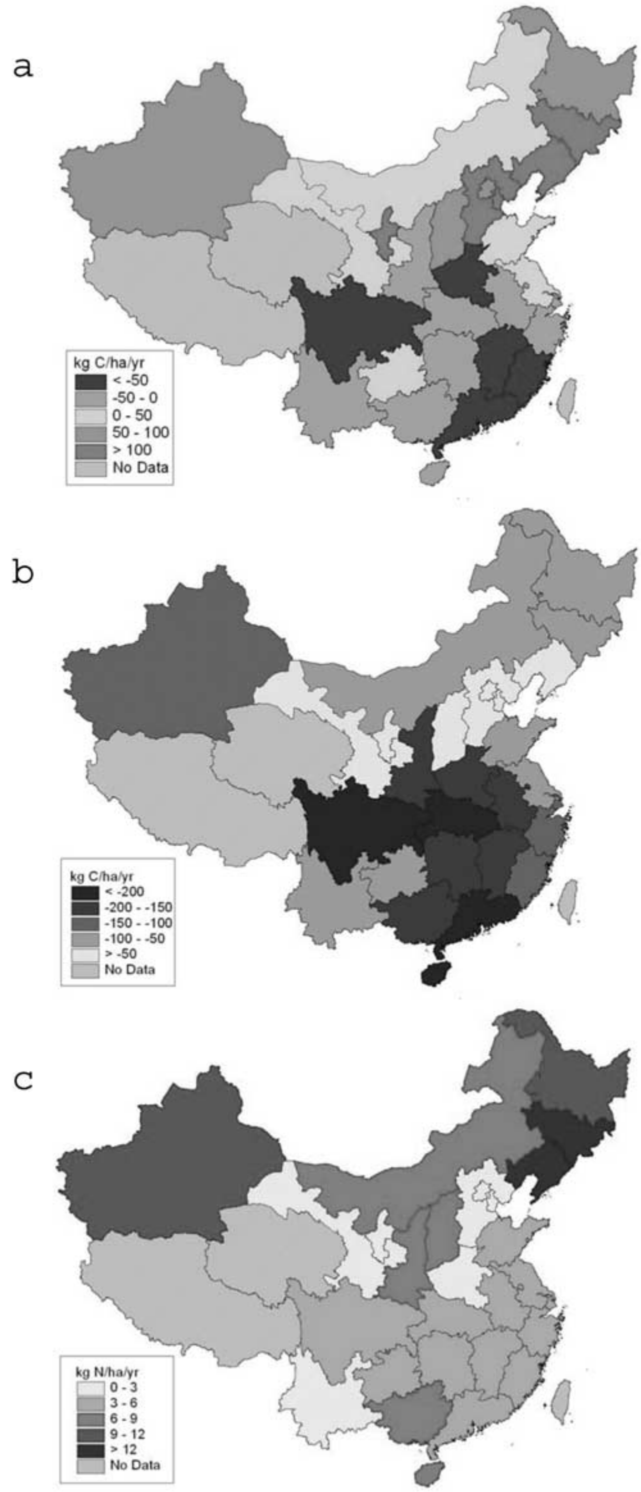

Figure 3. Change, due to conversion from continuous flooding to mid-season draining, in annual paddy flux rates of (a) CO_2, (b) CH_4, and (c) N_2O. Each provincial value is the difference between the mean for all counties of high and low values for mid-season draining and the mean for all counties of high and low values for continuous flooding. Sign convention: a positive flux difference (red shades) represents an increase in flux to the atmosphere, and a negative flux difference (blue shades) represents a decrease in flux to the atmosphere. For all provinces, the water management conversion reduced mean CH_4 flux and increased mean N_2O flux. Tibet (Xizang) and Qinghai Provinces have very small paddy areas, and are reported here as no data; Taiwan was excluded from the analysis because of a lack of crop rotation data. See color version of this figure at back of this issue.

Table 3. Provincial Rice Production and CO_2-Equivalent Fluxes for Greenhouse Gas Impact of Changing Management From Continuous Flooding to Mid-Season Drainage (MSD Mean Flux Minus CF Mean Flux), Using 20-, 100-, and 500-Year Time Horizons[a]

		20-Year CO_2 Equivalent, kg CO_2 ha^{-1} yr^{-1}				100-Year CO_2 Equivalent, kg CO_2 ha^{-1} yr^{-1}				500-Year CO_2 Equivalent, kg CO_2 ha^{-1} yr^{-1}			
Province[b]	Paddy Area,[c] ha	**Total**	CO_2	CH_4	N_2O	**Total**	CO_2	CH_4	N_2O	**Total**	CO_2	CH_4	N_2O
Sichuan[d]	3,700,000	**−16,000**	270	−18,000	2100	**−4200**	270	−6700	2200	**−610**	270	−2100	1200
Hunan	3,200,000	**−11,000**	180	−13,000	1700	**−2800**	180	−4800	1800	**−330**	180	−1500	940
Jiangsu	2,500,000	**−6000**	−5	−7600	1600	**−1100**	−5	−2800	1700	**+22**	−5	−850	880
Jiangxi	2,500,000	**−11,000**	210	−14,000	2600	**−2300**	210	−5300	2800	**+70**	210	−1600	1500
Anhui	2,000,000	**−12,000**	19	−13,000	1400	**−3300**	19	−4800	1500	**−630**	19	−1500	820
Hubei	1,900,000	**−17,000**	110	−18,000	1400	**−5200**	110	−6700	1500	**−1200**	110	−2100	770
Guangdong	1,900,000	**−14,000**	410	−17,000	2400	**−3300**	410	−6300	2500	**−150**	410	−1900	1300
Guangxi	1,700,000	**−12,000**	83	−16,000	3100	**−2400**	83	−5800	3400	**+95**	83	−1800	1800
Yunnan	1,500,000	**−4600**	94	−5900	1200	**−840**	94	−2200	1200	**+85**	94	−660	650
Zhejiang	1,200,000	**−9100**	100	−12,000	2500	**−1500**	100	−4400	2700	**+220**	100	−1300	1400
Heilongjiang	1,000,000	**−460**	−360	−4300	4200	**+2500**	−360	−1600	4500	**+1500**	−360	−480	2400
Guizhou	710,000	**−5500**	−130	−7200	1800	**−830**	−130	−2700	2000	**+98**	−130	−820	1000
Fujian	690,000	**−8700**	210	−11,000	2200	**−1600**	210	−4100	2400	**+200**	210	−1300	1200
Henan	650,000	**−12,000**	270	−13,000	1200	**−3300**	270	−4900	1300	**−530**	270	−1500	690
Liaoning	280,000	**+3300**	−630	−1800	5600	**+4800**	−630	−650	6100	**+2400**	−630	−200	3200
Jilin	240,000	**+1800**	−470	−6200	8400	**+6300**	−470	−2300	9100	**+3600**	−470	−700	4800
Hainan	190,000	**−20,000**	55	−24,000	3200	**−5300**	55	−8800	3500	**−800**	55	−2700	1800
Shaanxi	180,000	**−11,000**	140	−14,000	3300	**−1500**	140	−5200	3500	**+400**	140	−1600	1800
Shanghai	150,000	**−9600**	110	−11,000	1500	**−2500**	110	−4200	1600	**−330**	110	−1300	830
Inner Mongolia	150,000	**−1900**	−170	−4800	3000	**+1300**	−170	−1800	3300	**+1000**	−170	−540	1700
Shandong	140,000	**−3700**	−110	−6000	2400	**+270**	−110	−2200	2600	**+590**	−110	−680	1400
Hebei	100,000	**+2700**	−390	1800	1300	**+1700**	−390	680	1400	**+540**	−390	210	730
Xinjiang	93,000	**−6300**	−200	−10,000	4100	**+460**	−200	−3800	4500	**+990**	−200	−1200	2300
Tianjin	38,000	**+10,000**	−660	9800	840	**+3900**	−660	3600	900	**+920**	−660	1100	470
Ningxia	38,000	**+3800**	−390	3000	1200	**+2000**	−390	1100	1300	**+610**	−390	340	660
Gansu	23,000	**−870**	−44	−2000	1100	**+460**	−44	−730	1200	**+380**	−44	−220	650
Beijing	16,000	**−460**	−320	−1100	960	**+310**	−320	−410	1000	**+100**	−320	−120	540
Shanxi	11,000	**−1700**	−280	−4100	2700	**+1100**	−280	−1500	2900	**+770**	−280	−460	1500
China[e]	**30,000,000**	−9900	**79**	**−12,000**	**2300**	−2000	**79**	**−4600**	**2500**	+6	**79**	**−1400**	**1300**

[a]The CO_2-equivalent flux was calculated as in equation (1) in the text. A positive CO_2-eq. flux means a net emission to the atmosphere, and a negative flux means a net uptake from the atmosphere. All production values and all flux values greater than 10 kg CO_2-eq. ha^{-1} yr^{-1} were rounded to two significant figures.

[b]Tibet and Qinghai Provinces (not included) have little paddy rice, and generate <1 Gg CO_2-C yr^{-1}, <0.1 Gg CH_4-C yr^{-1}, and <0.1 Gg N_2O-N yr^{-1}.

[c]This comprises paddy land area, and does not double-count double rice crops; from *Frolking et al.* [2002].

[d]This includes Chongqing Province, which was established from land in Sichuan Province in 1997.

[e]China totals equal sum of all reported and nonreported provinces.

The highest reduction in CH_4 flux rates (>200 kg CH_4-C ha^{-1} yr^{-1}) occurred in Hainan, Sichuan, Hubei, and Guangdong provinces (Figure 3b), which are dominated by double-cropping rice systems with warm weather and high-clay soils; the lowest reduction in CH_4 flux rates (<25 kg CH_4-C ha^{-1} yr^{-1}) occurred in Tianjin, Hebei, Ningxia, Liaoning, and Gansu provinces (Figure 3b), which are dominated by single cropping systems with relatively cool weather and low-clay soils.

[21] Shifting water management from CF to MSD increased N_2O emissions from almost all rice paddies in China, although the MSD-induced N_2O flux rates varied from province to province (Table 2). The total N_2O emissions from the Chinese rice paddies under CF and MSD conditions were 290–410 and 420–610 Gg N_2O-N yr^{-1}, respectively (Table 2). Taking mean values, changing water management to MSD increased the rice paddy N_2O flux for China from 160 Gg N_2O-N yr^{-1}, equivalent to 2–3% of global total anthropogenic N_2O emissions [*Prather et al.*, 2001]. The MSD-induced increase in N_2O fluxes were high (>8.0 kg N_2O-N ha^{-1} yr^{-1}) in Jilin, Liaoning, Heilongjiang, and Xinjiang where the paddy soils contained relatively high organic matter content, and low (<3.0 kg N_2O-N ha^{-1} yr^{-1}) in Beijing, Tianjin, Hebei, Henan, Yunnan, Gansu, and Ningxia (Figure 3c) where the soil organic matter (SOM) contents were relatively low.

[22] The aggregate radiative forcing of changes in CO_2, CH_4, and N_2O emissions due to changing water management was quantified as a CO_2-equivalent flux (Table 3, Figure 4). With a 20-year time horizon, the nationally aggregated average flux was a net uptake of 9900 kg CO_2-eq ha^{-1} yr^{-1} (equivalent to 81 Gg C yr^{-1} uptake for all rice paddies). As the time horizon for the GWP analysis lengthened, the relative importance of reduced methane fluxes diminished, and the average flux dropped to a net uptake of 2000 kg CO_2-eq ha^{-1} yr^{-1} for a 100-year horizon (~16 Gg C yr^{-1} uptake for all rice paddies), and approximately zero net emission for a 500-year time horizon (Table 3).

4. Discussion and Conclusions

[23] China's total rice paddy methane emissions with continuous flooding (6400–12,000 Gg CH_4-C yr^{-1}) were about 10–20% of recent estimates of global methane emissions from rice paddies [*Prather et al.*, 2001]; China's paddy area is about 20% of the global total paddy area [*Maclean et al.*, 2002]. Total rice paddy nitrous oxide

emissions for mid-season draining management (420–610 Gg N_2O-N yr^{-1}) were about 10% of global N_2O emissions from cropland [*Prather et al.*, 2001]; China's paddy area is about 2.2% of total global cropland area [*FAO*, 2004]. Multiple cropping (including paddy and upland crop rotations) and heavy fertilizer use (up to 240 kg N ha^{-1} yr^{-1}) probably account for proportionally high N_2O emissions. Total paddy CO_2 emissions ranged from −3500 to +12,000 Gg C yr^{-1}, with most losses occurring in northern provinces, which have been more recently cultivated and have higher SOC values. Net CO_2 emissions in eastern China (Fujian, Jiangxi, Anhui, Jiangsu, and Zhejiang provinces) were near zero. *Cai* [1996] quantified the effects of land use on SOC in these eastern provinces, based on mean SOC values reported in the Second Soil Survey of China. He found that mean paddy field SOC was about half that of natural vegetation soils, and mean upland crop field SOC was about half that of paddy fields. He estimated total SOC loss for the cropland soils (0–0.62 m) in the region at 850,000 Gg C, based on the assumption that soils supporting natural vegetation at the time of the Second Soil Survey were representative of all pre-agricultural soils. Losses of SOC typically occur during the first few decades of cultivation [e.g., *Smith et al.*, 1997; *Li et al.*, 1994], and most paddies in eastern China are old enough that their SOC may have stabilized at low levels.

[24] Shifting water management from continuous flooding to midseason drainage reduced total net CO_2 emissions by 0 to −1500 Gg CO_2-C yr^{-1}, reduced total CH_4 emissions from paddy rice fields in China by 4200 to 4700 Gg CH_4-C yr^{-1}, and increased total N_2O emissions from paddy rice fields in China by 130 to 200 Gg N_2O-N yr^{-1}. The response to changing water management was not spatially uniform, which has significant implications for the design of greenhouse gas mitigation strategies. Although the change in CO_2 flux was small from an aggregate greenhouse gas perspective (Table 3), enhanced CO_2 losses were greater in northern China (Figure 3a), where SOC content was generally higher. The reduction in CH_4 emission per unit area was also generally higher in northern China (Figure 3b), as was the increase in N_2O emissions (Figure 3c). Evaluated as CO_2-equivalent fluxes using 100-year GWP values, shifting water management from continuous flooding to midseason drainage made northern China a net source, and southern China a net sink (Figure 4b). For a 20-year time horizon, most provinces are effectively net sinks (Figure 4a), while for a 500-year time horizon most provinces are effectively net sources, except along the Yangtze River and in the south (Figure 4c).

[25] Implementing alternative water management in areas with warm weather, high clay content, and low organic matter content caused the largest reduction in radiative forcing, particularly for the short time horizons where the impact of changes in methane emissions is more pro-

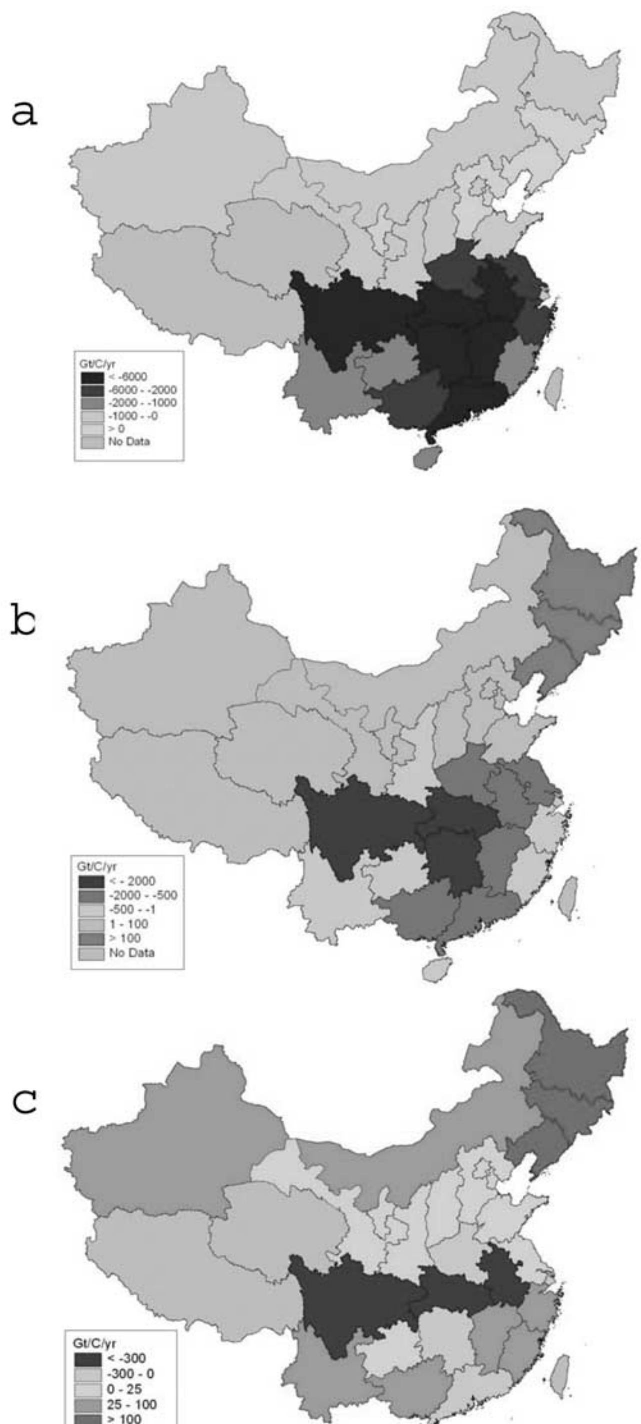

Figure 4. Net provincial CO_2-equivalent emissions for conversion from continuous flooding to mid-season draining, calculated using (a) 20-year, (b) 100-year, and (c) 500-year global warming potential conversion factors for CH_4 and N_2O (see equation (1)) [*Ramaswamy et al.*, 2001]. Sign convention is a positive flux difference (red shades) represents an increase in flux to the atmosphere, and a negative flux difference (blue shades) represents a decrease in flux to the atmosphere. Tibet (Xizang) and Qinghai Provinces have very small paddy areas, and are reported here as no data; Taiwan was excluded from the analysis because of a lack of crop rotation data. See color version of this figure at back of this issue.

nounced (Figure 4, Table 3). Sichuan, Hubei, Hunan, Guangdong, Guangxi, Anhui, and Jiangsu provinces, which possess almost 60% of China's rice paddies and produce just over 60% of the rice, fall into this category. In northeastern China, Heilongjiang, Jilin, and Liaoning provinces produce ~10% of the annual rice harvest on ~10% of the paddy area. Switching to mid-season draining in this region led to net increase in greenhouse gas emissions on all timescales except the 20-year time horizon for Heilongjiang Province, which had a nearly neutral 20-year GWP (Figure 4, Table 3).

[26] Although mid-season drainage is now widespread in China and Japan, alternative water management regimes are not common for many of the rice producing countries in South and Southeast Asia, where they are still being evaluated by agronomists [*Barker and Molle*, 2004]. Although adopting changes in water management probably will be driven primarily by grain yield and water use, as was the case for China, quantifying impacts of alternative management practices on greenhouse gas emissions may play a role in decision making. These changes could include both switching from continuous flooding to mid-season draining and switching from rainfed to irrigated rice. The effects of management alternatives for mitigation are likely to vary when they are applied across climatic zones, soil types, or farming systems. Process-based models integrated with GIS databases can play an important role in linking management changes to biogeochemical cycles based on spatially differentiated information, and either target mitigation efforts to the most beneficial regions or evaluate spatial variability of greenhouse gas impacts of management changes.

[27] **Acknowledgment.** The research has been supported by NASA's Terrestrial Ecology Program (NAG5-12838 and NAG5-7631) and the NASA EOS-IDS program (NAG5-10135).

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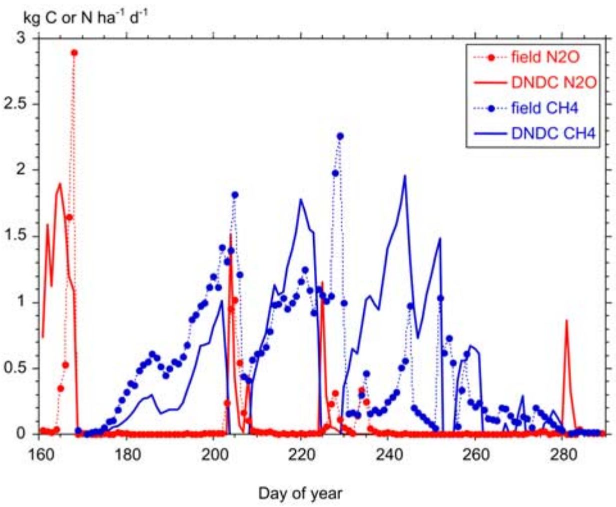

Figure 1. Comparison between observed and DNDC-modeled CH_4 and N_2O fluxes from a paddy rice field applied with mid-season drainage in Wu County, Jiangsu Province, China, in 1995. DNDC captured the episodes of CH_4 emission depressions and N_2O emission increases during the soil drying time periods by tracking the soil oxygen diffusion, CH_4 oxidation, labile organic matter decomposition, and stimulated nitrification and denitrification fueled by the increased ammonium and nitrate production due to the conversions of soil anaerobic to aerobic conditions driven by the mid-season drainage. (Field data were adopted from *Zheng et al.* [1997]).

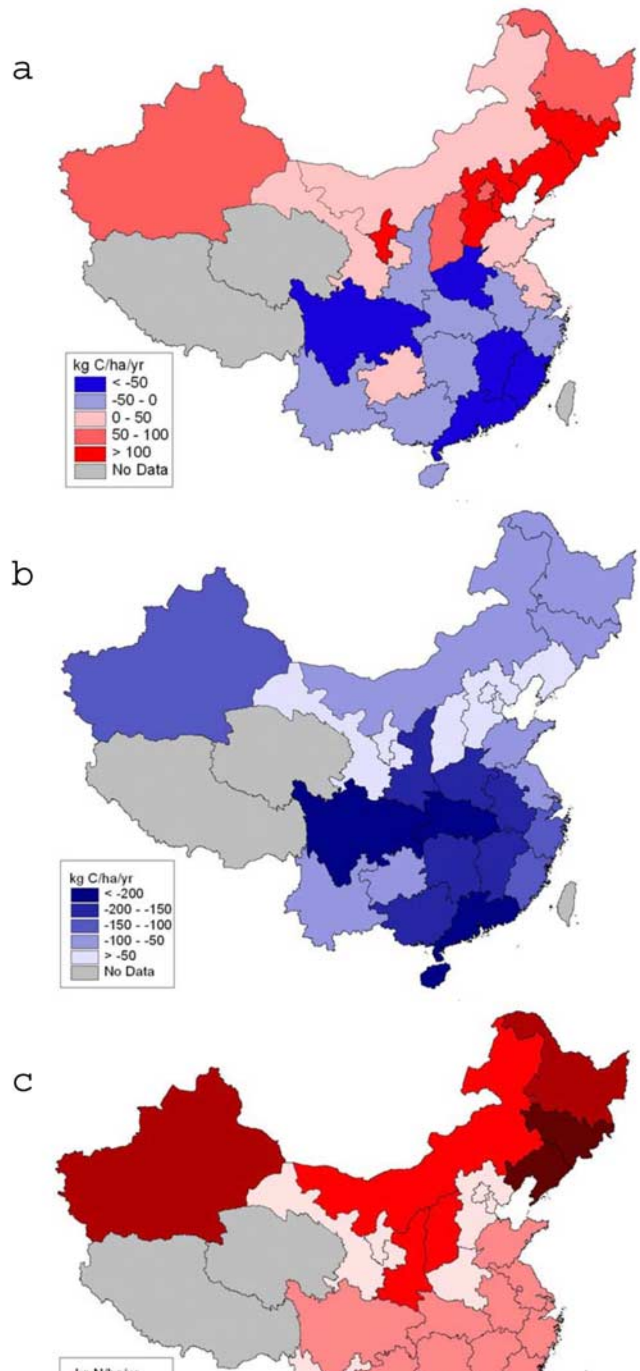

Figure 3. Change, due to conversion from continuous flooding to mid-season draining, in annual paddy flux rates of (a) CO_2, (b) CH_4, and (c) N_2O. Each provincial value is the difference between the mean for all counties of high and low values for mid-season draining and the mean for all counties of high and low values for continuous flooding. Sign convention: a positive flux difference (red shades) represents an increase in flux to the atmosphere, and a negative flux difference (blue shades) represents a decrease in flux to the atmosphere. For all provinces, the water management conversion reduced mean CH_4 flux and increase mean N_2O flux. Tibet (Xizang) and Qinghai Provinces have very small paddy areas, and are reported here as no data; Taiwan was excluded from the analysis because of a lack of crop rotation data.

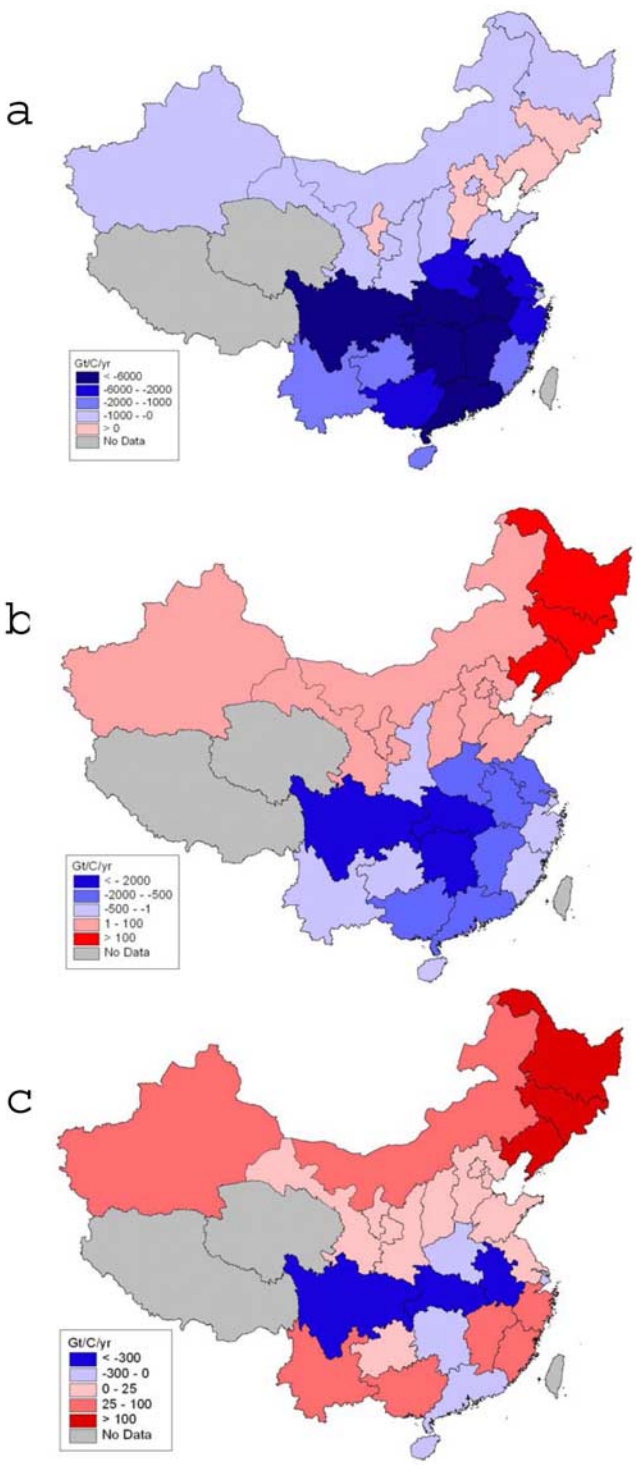

Figure 4. Net provincial CO_2-equivalent emissions for conversion from continuous flooding to mid-season draining, calculated using (a) 20-year, (b) 100-year, and (c) 500-year global warming potential conversion factors for CH_4 and N_2O (see equation (1)) [*Ramaswamy et al.*, 2001]. Sign convention is a positive flux difference (red shades) represents an increase in flux to the atmosphere, and a negative flux difference (blue shades) represents a decrease in flux to the atmosphere. Tibet (Xizang) and Qinghai Provinces have very small paddy areas, and are reported here as no data; Taiwan was excluded from the analysis because of a lack of crop rotation data.