

Modeling Impacts of Farming Management Alternatives on CH₄ and N₂O Emissions: A Case Study for Rice Agriculture in China

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Abstract

Since early 1980s, water management for rice agriculture in China has substantially changed. Midseason drainage gradually replaced the traditional practice, continuous flooding, during only a 20-year period. This change provided an opportunity to estimate how a management alternative could impact greenhouse gas emissions at a large region scale. To answer this question, we developed a tool by integrating a process-based model, DNDC, with a GIS database. With this tool, we simulated carbon sequestration in and methane (CH₄) and nitrous oxide (N₂O) emissions from all of the rice paddies (about 30 million ha) in China based on 1990 climate and management conditions. Two water management scenarios, continuous flooding and midseason drainage, were applied in the simulations to quantify their effects on fluxes of all of the three greenhouse gases. The modeled results indicated significant impacts of the change in water management on both CH₄ and N₂O emissions. Methane emissions were reduced over the 20-year period by about 40 percent, or by 5 Tg/yr—an amount roughly equivalent to the decrease in the rate of growth of total global CH₄ emissions. The mitigating effect of midseason drainage on CH₄ was highly uneven across the country with the highest reduction rates (200-290 kg CH₄-C/ha) for provinces Hainan, Sichuan, Hubei and Guangdong where double- or triple-cropping rice systems dominated with warm weather and high-clay soils, and the lowest reduction rates (<25 kg CH₄-C/ha) for Tianjin, Hebei, Ningxia, Liaoning and Gansu where there were only single cropping systems with relatively cool weather and low-clay soils. Shifting water management from continuous flooding to midseason drainage increased N₂O emissions from Chinese rice paddies by 0.15 Tg N per year, which offset almost half of the benefit gained by the decrease in CH₄ emissions. The midseason drainage-induced N₂O fluxes were high (>8.0 kg N/ha) in Jilin, Liaoning, Heilongjiang and Xinjinag where the paddy soils contained relatively high organic matter. In conclusion, the water management alternative (i.e., midseason drainage) has been predicted to have very different effects on mitigation when it is implemented across climatic zones, soil types, or cropping systems. The maximum CH₄ reductions and minimum N₂O increases can be obtained when the alternative management is applied in the rice areas with warm weather, high clay content, and low organic

matter content. The provinces of Sichuan, Hubei, Hunan, Guangdong, Guangxi, Anhui and Jiangsu, which possess 60% of the rice paddies in China, fall into the category.

Introduction

Agriculture represents a significant opportunity for greenhouse gas mitigation projects through soil carbon (C) sequestration and reductions of methane (CH₄) and nitrous oxide (N₂O) emissions. Food production contributes approximately 70 and 40 % of global atmospheric input of N₂O and CH₄ to the atmosphere, respectively (Cole et al. 1996). When appraising the impact of food and fiber production systems on composition of earth's atmosphere, the entire suite of greenhouse gases (i.e., CO₂, CH₄ and N₂O) needs to be considered (Li 1995; Robertson et al. 2000). Since each of the greenhouse gases has its own radiative potential (IPCC 1997), the net global warming potential (GWP) of a crop production system must be estimated accounting for all the three gas constituents.

Since early 1980s, water management for rice agriculture in China has substantially changed. Midseason drainage gradually replaced the traditional practice, continuous flooding, during only a 20-year period (Shen et al. 1998). This nationwide change provided an opportunity for us to observe how a management alternative could impact greenhouse gas emissions at large region scale. To quantify the impacts of the water management change on C sequestration in and CH₄ and N₂O emissions from all of the rice paddies (about 30 million ha) in China, we developed a tool by integrating a process-based model, DNDC, with a GIS database. DNDC, standing for DeNitrification-DeComposition, is one of the biogeochemistry models developed during the last decade. The model contains fundamental processes simulating the interactions among ecological drivers, soil environmental factors, and relevant biochemical or geochemical reactions, which collectively determine trace gas production and consumption in agricultural ecosystems. DNDC has been tested on its capacity for predicting C sequestration and trace gas emissions by numerous researchers worldwide (Saggar et al., 2003; Cai et al., 2003; Xuri et al., 2003; Brown et al., 2002; Farahbakhshazad et al., 2002; Smith et al., 2002; Zhang et al., 2002; Li 2000; Smith et al., 1997; Xiu et al., 1999; Frohling et al., 1998; Plant et al., 1998, Wang et al., 1997; Li et al., 1994, 1992). Since most of the validation results have been published, this paper only reports how we utilized this modeling tool to answer a question: In what degree the nationwide change in water management for rice agriculture in China have affected its greenhouse gas emissions into the atmosphere.

1. Methods

Quantifying trace gas emissions at regional scale is a challenge. Both CH₄ and N₂O fluxes from agro-ecosystems are highly variable in space and time, affected by ecological drivers (e.g., climate, soil, vegetation, and anthropogenic activity), soil environmental factors (e.g., temperature, moisture, pH, redox potential, and substrate concentration gradient), and biochemical or geochemical reactions (Li et al., 2000; Li 2001; Li et al., 2003). To predict trace gas emissions at large scale, we need two basic tools, i.e., process-based models and GIS databases. The process-based models are to be used to quantify trace gas fluxes driven by the local climate, soil, vegetation and management conditions at site scale. The GIS databases are

to provide the spatially differentiated information of climate, soil, vegetation and management to drive the model runs across the region. In this study, a process-based biogeochemistry model, DNDC, was adopted and linked to a GIS database to quantify the impacts of alternative water management on both CH₄ and N₂O emissions from all rice paddies in China.

1.1. The DNDC model

DNDC was originally developed for predicting C sequestration and trace gas emissions for non-flooded agricultural lands (Li et al. 1992, 1994, 1996). Detailed management measures (e.g., crop rotation, tillage, fertilization, manure amendment, irrigation, weeding, and grazing) have been parameterized and linked to the biogeochemical processes (e.g., crop growth, litter production, soil water infiltration, decomposition, nitrification, denitrification etc.) embedded in DNDC. To enable DNDC to work for paddy rice ecosystems, we modified the model by adding a series of anaerobic processes. Field measurements were conducted in a typical rice field near Nanjing in China (Huang et al. 2001). The three-year field campaign confirmed the observations early reported by other researchers (e.g., Chen et al., 1995; Zheng et al., 1997) that midseason drying or drainage could reduce CH₄ emissions meanwhile increase N₂O emissions from the treated rice paddies. The observed crop phenology, soil status, and trace gas fluxes at the site with other data were utilized to support the model modifications.

Paddy soil is characterized by frequent changes between saturated and unsaturated conditions driven by the water management. During the moisture shifting, soil redox potential (i.e., Eh) is subject to substantial changes between 600 and -300 mV. Since either CH₄ or N₂O is produced under certain Eh conditions (-300--150 mV for CH₄, and 200-500 mV for N₂O), the two gases can be produced during the soil Eh evolution although at different stages. One of the key processes controlling CH₄ and N₂O production/consumption in paddy soils is the soil Eh dynamics. To quantify soil Eh change and its impacts on N₂O or CH₄ production, we integrated two classical equations, the Nernst equation and the Michaelis-Menten equation, into DNDC. The Nernst equation is 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). The Michaelis-Menten equation is a widely applied formula describing kinetics of microbial growth with dual nutrients (Paul and Clark, 1998). The Nernst and the Michaelis-Menten equations can be merged since they share a common factor, oxidant concentration. A simple kinetic scheme was adopted in DNDC to realize the conjunction of the two classical equations. The scheme is defined to be the anaerobic volumetric fraction of a soil. Based on the concentrations of dominant oxidants and reductants in a soil, the Nernst equation calculates the soil bulk Eh. Based on 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). Based on the size proportion, DNDC allocates the substrates (e.g., DOC, NO₃⁻, NH₄⁺, etc.) into the aerobic and anaerobic microsites. We defined 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). Since the anaerobic volumetric fraction ever swells or shrinks driven by the reduction/oxidation reactions, it can be simply called as an “anaerobic balloon”. When a soil is irrigated or flooded, its oxygen content will decrease, that 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., nitrate) will become the dominant species in the soil; and a new anaerobic balloon will be born and swell driven by the depletion of nitrate (NO_3^-). 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-} consecutively, DNDC estimates soil Eh dynamics as well as rates of reductive/oxidative reactions, which produce or consume CH_4 or N_2O in the soil. With the anaerobic balloon, DNDC well linked soil water regime to trace gas emissions for rice paddy ecosystems. With the innovation, the new version of DNDC is able to predict year-around CH_4 and N_2O fluxes from the rice fields which frequently shift between flooding and draining practices. This new model has been recently tested against several CH_4 flux data sets from wetland rice sites in the U.S., Italy, China, Thailand, and Japan with satisfied results (Li et al., 2002; Cai et al., 2003).

1.2. GIS database

The entire rice planted areas in China was selected as the modeled target. The domain contained 30 million ha of rice paddies, which were rotated in 10 different cropping systems including double rice, triple rice, rice-winter wheat, rice-rapeseed, rice-vegetable etc. The acreage of each cropping system in each county was quantified based on a county statistical database on crop sown areas with a Landsat TM derived land-cover map for all of mainland China (Frolking et al. 2002). Daily weather for 1990 from 610 weather stations across China was 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, 1993-1997). General data on tillage, planting and harvest dates, crop residue management, and crop varieties were taken from 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 (IPCC, 1997), and field application rates of 20% for animal manure and 10% for human manure.

Detailed data on water management at the county scale were not available, so we developed a simple scenario of the evolution of paddy water management in China from 1980-2000, based on a recent Chinese publication and discussion with a member of the Chinese Academy of Agricultural Sciences. In the early 1980s, midseason drainage was first successfully tested as a water conservation measure in northern China (Shen et al., 1998). Due to water savings and increased yield, the new management regime was widely adopted in northern China in the 1980s. In the 1990s, the technique was introduced to the major rice-producing areas along the Yangtze River. In the late 1990s, midseason drainage became popular in the southern provinces (Shen et al., 1998). The current (year 2000) fraction of rice paddies with alternative water management is ~80% (Qingmu Chen, personal communication). This is a very rough

estimate, with an aim of characterizing the magnitude of change. To quantify the impacts of alternative water management practices, we designed two scenarios: continuous flooding (CF) and midseason drainage (MD) for 100% of the rice paddies in China in 1990. By calculating area-weighted averages for each province every five years from 1980 through 2000, we generated historical changes in CH₄ emissions from the Chinese rice paddies during the 20 years.

1.3. Uncertainty

Meteorological data, soil properties, and agricultural management data were obtained from ground-based statistical sources. County was chosen as the basic, spatial unit for our GIS database construction since most of the statistical data was county-based. Since each county is regarded to be uniform during the model simulation runs, uncertainty must be estimated due to the inherent heterogeneities of many input parameters within the county scale. Sensitivity tests were conducted to prioritize the environmental factors regarding their effects on CH₄ or N₂O emissions. Among the tested factors including soil properties, temperature and precipitation, the most sensitive factors for CH₄ and N₂O emissions were soil texture and soil organic carbon (SOC) content, respectively. Varying soil texture from its coarsest to its finest texture value reported in the county-scale database produced a range of CH₄ fluxes that was broad enough to cover more than 80% of the CH₄ variations caused by varying any or all other input parameters between minimum and maximum values. By running DNDC twice with the coarsest and finest soil textures for a county, we produced two CH₄ emission values. The couple of fluxes formed a range, which was wide enough to cover any variations in CH₄ flux caused by varying other environmental factors. With the “most sensitive factor method”, we run DNDC for each cropping system in each county twice with the lightest and heaviest soil textures, respectively, to produce a range of CH₄ emission. We then summed the emissions from all of the rice-involved cropping systems in the county to get a total CH₄ emission for the county. We summed CH₄ emissions from all of the counties to get total CH₄ emissions for the country. The final results were expressed as ranges, and the true CH₄ flux should have a high probability of falling within the reported range. The same is true to N₂O simulations but with a different most sensitive factor, SOC. This methodology is comparable to the Monte Carlo method or other uncertainty analyzers although most of the latter methods are time consuming and hence difficult to be applied at large region scales.

2. Results

The modeled results demonstrated that change in water management from CF to MD significantly affected both CH₄ and N₂O emissions from the rice paddies in China. The total CH₄ emissions with CF and MD were 6.4—12.0 and 1.7—7.8 Tg C per year, respectively (Table 1). It means that CH₄ emissions were reduced over the 20-year period by about 40 percent, or by 5 Tg/yr—an amount roughly equivalent to the decrease in the rate of growth of total global CH₄ emissions (Li et al., 2003). The CH₄ mitigating effect of MD was highly uneven across the country, with the highest reduction rates (200-290 kg CH₄-C/ha) for provinces Hainan, Sichuan, Hubei and Guangdong where double- or triple-cropping systems dominated with warm weather and high-clay soils, and the lowest reduction rates (<25 kg CH₄-

C/ha) for Tianjin, Hebei, Ningxia, Liaoning and Gansu where there were only single cropping systems with relatively cool weather and low-clay soils (Table 1).

Shifting water management from CF to MD increased N₂O emissions from all of the rice paddies in China although the MD-induced N₂O flux rates varied from province to province. The total N₂O emissions from the Chinese rice paddies under CF and MD scenarios were 0.29—0.41 and 0.42—0.61 Tg N per year, respectively (Table 2). It implies that MD increased the rice paddy N₂O flux ranged from 0.13-0.20 Tg N per year. Converting the gas fluxes into global warming potential (GWP, not reported in the paper), we found the MD-induced N₂O emission offset almost half of the benefit gained by the decrease in CH₄ emissions. The MD-induced N₂O fluxes were high (>8.0 kg N/ha) in Jilin, Liaoning, Heilongjiang and Xinjinag where the paddy soils contained relatively high SOC, and low (<3.0 kg N/ha) in Beijing, Tianjin, Hebei, Henan, Yunan, Gansu, and Ningxia where SOC contents were relatively low (Table 2).

In summary, by shifting water management from continuous flooding to midseason drainage, CH₄ emissions reduced by 4.5 Tg C and N₂O emissions increased by 0.16 Tg N in China. The effects of the management change on CH₄ or N₂O fluxes were different across the country. The best mitigation effects were achieved in the areas with worm weather, high clay content, and low SOC content. The provinces of Sichuan, Hubei, Hunan, Guangdong, Guangxi, Anhui and Jiansu, which possess 60% of the rice paddies in China, fall into the category.

Conclusion

Mitigating effects of the water management alternative reported in the paper highly varied across climatic zones, soil types, or farming systems. This conclusion may be applicable to other mitigating practices such as conservation tillage, organic fertilizer etc. Applying process-based models integrated with GIS databases could provide a solution to quantify the spatially differentiated effects of management alternatives on mitigation. We hope the methodologies and results reported in the paper will fuel more discussions in this direction.

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Table 1. Modeled impacts of alternative water management practices on CH₄ emissions from rice paddies for China (based on 1990 climate and cropping conditions)

Province	Paddy rice area, ha	CH ₄ fluxes, Tg C/yr		Drainage-induced change in CH ₄ emission	
		Continuous flooding	Midseason drainage	Total, Tg C/yr	Rate, kg C/ha
Beijing	22581	0.004—0.005	0.002—0.006	0.000	-13.3
Tianjin	103407	0.016—0.017	0.015—0.016	-0.001	-6.8
Hebei	151431	0.026—0.028	0.026—0.027	-0.001	-5.6
Shanxi	16137	0.003—0.003	0.002—0.003	-0.001	-49.6
Inner Mongolia	192002	0.021—0.034	0.005—0.027	-0.011	-57.6
Liaoning	688734	0.138—0.180	0.061—0.228	-0.015	-21.3
Jilin	652121	0.101—0.151	0.030—0.124	-0.049	-75.4
Heilongjiang	1399143	0.182—0.268	0.078—0.227	-0.072	-51.6
Shanghai	237261	0.095—0.150	0.056—0.125	-0.032	-135.5
Jiangsu	2530072	0.771—1.211	0.480—1.039	-0.232	-91.6
Zhejiang	1517040	0.389—0.730	0.138—0.550	-0.215	-142.0
Anhui	2043957	0.456—1.129	0.077—0.865	-0.321	-157.2
Fujian	966463	0.170—0.262	0.029—0.144	-0.130	-134.5
Jiangxi	2510899	0.556—1.092	0.072—0.711	-0.432	-172.1
Shandong	178376	0.050—0.061	0.034—0.050	-0.013	-72.6
Henan	708449	0.143—0.340	0.027—0.229	-0.113	-160.0
Hubei	1922875	0.405—1.138	0.046—0.653	-0.422	-219.6
Hunan	3207661	0.550—1.144	0.113—0.583	-0.499	-155.6
Guangdong	1898437	0.468—0.859	0.152—0.399	-0.388	-204.4
Guangxi	1721824	0.256—0.667	0.013—0.256	-0.327	-190.2
Sichuan	3708485	1.264—1.827	0.195—1.265	-0.815	-219.8
Guizhou	1197740	0.096—0.197	0.009—0.074	-0.105	-87.6
Yunnan	1521290	0.081—0.156	0.003—0.018	-0.108	-70.8
Tibet	376	0.000—0.000	0.000—0.000	0.000	0.0
Shaanxi	279020	0.064—0.115	0.007—0.077	-0.047	-169.2
Gansu	37616	0.002—0.002	0.001—0.002	-0.001	-23.9
Qinghai	352	0.000—0.000	0.000—0.000	0.000	0.0
Ningxia	92951	0.003—0.002	0.002—0.001	-0.001	-10.8
Xinjiang	114873	0.027—0.051	0.007—0.042	-0.014	-123.6
Hainan	376099	0.104—0.204	0.019—0.073	-0.108	-287.0
China	29997654	6.44—12.02	1.71—7.85	-4.454	-148.5

Table 2. Modeled impacts of alternative water management practices on N₂O emissions from rice paddies for China (based on 1990 climate and cropping conditions)

Province	N ₂ O fluxes from rice fields, Tg N/yr		Drainage-induced change in N ₂ O emission		Ratio N ₂ O/CH ₄ change, kg N/kg C
	Continuous flooding	Midseason drainage	Average, g N/yr	Rate, kg N/ha	
Beijing	0.0001—0.0001	0.0001—0.0002	0.000	2.2	0.167
Tianjin	0.0006—0.0007	0.0008—0.0009	0.000	1.9	0.286
Hebei	0.0008—0.0009	0.0013—0.0013	0.000	3.0	0.529
Shanxi	0.0001—0.0001	0.0002—0.0002	0.000	6.2	0.125
Inner Mongolia	0.0018—0.0027	0.0032—0.004	0.001	7.0	0.122
Liaoning	0.008—0.0104	0.0171—0.0193	0.009	13.1	0.612
Jilin	0.0083—0.0118	0.0238—0.0218	0.013	19.6	0.259
Heilongjiang	0.0257—0.0356	0.0442—0.0441	0.014	9.6	0.187
Shanghai	0.0018—0.0021	0.0024—0.0031	0.001	3.4	0.025
Jiangsu	0.0183—0.0245	0.0247—0.0363	0.009	3.6	0.039
Zhejiang	0.0167—0.0232	0.0233—0.0344	0.009	5.9	0.041
Anhui	0.0144—0.0291	0.0187—0.0384	0.007	3.3	0.021
Fujian	0.0104—0.0143	0.0132—0.0213	0.005	5.1	0.038
Jiangxi	0.0218—0.0331	0.0314—0.0536	0.015	6.0	0.035
Shandong	0.0011—0.0012	0.0022—0.0021	0.001	5.6	0.077
Henan	0.0029—0.0056	0.0039—0.0086	0.002	2.8	0.018
Hubei	0.0125—0.0238	0.0157—0.0327	0.006	3.1	0.014
Hunan	0.0321—0.0376	0.0408—0.0536	0.012	3.9	0.025
Guangdong	0.0216—0.0264	0.0292—0.0396	0.010	5.5	0.027
Guangxi	0.0261—0.0382	0.033—0.0564	0.013	7.3	0.038
Sichuan	0.0343—0.0492	0.0469—0.0723	0.018	4.8	0.022
Guizhou	0.0096—0.014	0.0126—0.0212	0.005	4.3	0.049
Yunnan	0.0117—0.0117	0.0144—0.0171	0.004	2.7	0.038
Tibet	0—0	0—0	0.000	0.0	-
Shaanxi	0.0025—0.004	0.004—0.0067	0.002	7.5	0.044
Gansu	0.0001—0.0001	0.0002—0.0002	0.000	2.7	0.111
Qinghai	0—0	0—0	0.000	0.0	-
Ningxia	0.0005—0.0007	0.0007—0.001	0.000	2.7	0.250
Xinjiang	0.001—0.0018	0.0018—0.0032	0.001	9.6	0.077
Hainan	0.0039—0.0081	0.0052—0.0124	0.003	7.4	0.026
China	0.2889—0.411	0.415—0.6062	0.161	5.4	0.036