Reduced methane emissions from large-scale changes in water management of China's rice paddies during 1980–2000

Changsheng Li,[1] Jianjun Qiu,[2] Steve Frolking,[1] Xiangming Xiao,[1] William Salas,[1] Berrien Moore III,[1] Steve Boles,[1] Yao Huang,[3] and Ronald Sass[4]

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[1] Decreased methane emissions from paddy rice may have contributed to the decline in the rate of increase of global atmospheric methane (CH_4) concentration over the last 20 years. In China, midseason paddy drainage, which reduces growing season CH_4 fluxes, was first implemented in the early 1980s, and has gradually replaced continuous flooding in much of the paddy area. We constructed a regional prediction for China's rice paddy methane emissions using the DNDC biogeochemical model. Results of continuous flooding and midseason drainage simulations for all paddy fields in China were combined with regional scenarios for the timing of the transition from continuous flooding to predominantly mid-season drainage to generate estimates of total methane flux for 1980–2000. CH_4 emissions from China's paddy fields were reduced over that period by ~5 Tg CH_4 yr^{-1}. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 1615 Global Change: Biogeochemical processes (4805); 9320 Information Related to Geographic Region: Asia. **Citation:** Li, C., J. Qiu, S. Frolking, X. Xiao, W. Salas, B. Moore III, S. Boles, Y. Huang, and R. Sass, Reduced methane emissions from largescale changes in water management of China's rice paddies during 1980–2000, *Geophys. Res. Lett.*, *29*(20), 1972, doi:10.1029/2002GL015370, 2002.

1. Introduction

[2] The rate of growth of methane concentration in the atmosphere slowed from 10–15 ppb yr^{-1} in the 1980s to 0–5 ppb yr^{-1} for most years in the 1990s, though the annual increase in methane concentration was more variable during the 1990s than the 1980s [*Dlugokencky et al.*, 2001]. Large-scale temperature and precipitation anomalies have been identified as possible causes of the interannual variability in the rate of increase of methane concentration [*Dlugokencky et al.*, 2001]. Changes in the oxidation chemistry of the atmosphere could change the CH_4 lifetime, changing the atmospheric concentration growth rate [e.g., *Karlsdottir and Isaksen*, 2000]. Decreased gas industry CH_4 emissions may have occurred in the early 1990s, particularly following the economic slowdown in the Soviet Union [e.g., *Law and Nisbet*, 1996]. *Dlugokencky et al.* [1998] noted that the decline in the growth rate could be due to atmospheric methane approaching a new steady state. In this paper we propose an additional factor, diminishing methane emissions from rice paddies.

[3] Seasonally flooded rice paddies are a significant source of methane to the atmosphere, contributing ~40 Tg CH_4 yr^{-1} [*Sass et al.*, 1999]. Over the past two decades, midseason drainage has been adopted throughout China [*Shen et al.*, 1998; *MWRUC*, 1996], commonly with 2-5 drainings during a growing season is a common management practice (Qingmu Chen, Chinese Academy of Agricultural Sciences, personal communication). While the primary motivation for this draining has been water conservation and increased yields, a significant consequence has been to reduce methane emissions. Field studies have shown that midseason draining reduces total crop-season methane emissions by 10–80% [*Sass et al.*, 1992; *Yagi et al.*, 1996; *Sigren et al.*, 1997; *Cai et al.*, 1999; *Wassmann et al.*, 2000]. We combined a process biogeochemistry model with spatial datasets of soil properties, paddy distribution, crop rotations, daily weather, and additional agricultural management factors to simulate annual methane emissions from China's rice paddies under scenarios of continuous flooding and mid-season draining.

2. Methods

[4] Lack of reliable, detailed historical water management data prohibited a fully realistic 20-year simulation. Instead, we have adopted 1990 as a representative year, and simulated two water management scenarios, continuous flooding and 3 mid-season drainings. We constructed a scenario of the transition in water management from continuous flooding to mid-season draining, 1980–2000, and estimated CH_4 emissions by averaging emissions by province for the two water management scenarios, weighted by estimated paddy area managed under each scenario.

2.1. Biogeochemical Model

[5] To predict soil Eh dynamics under both aerated and submerged conditions, a simple kinetic scheme was developed for DNDC [*Li et al.*, 1992] to capture the soil redox dynamics [*Li et al.*, 2000]. Combining the Nernst and Michaelis-Menten equations, DNDC simulates interactions among substrates, soil Eh, and the activity of microbial reducers. With a dynamic anaerobic fractional volume, DNDC predicted a series of oxidation-reduction processes in both wetland and upland soils [*Li*, 2000; *Li*

[1]Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH, USA.
[2]Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Science, Beijing, China.
[3]College of Resource and Environmental Sciences, Nanjing Agricultural University, Nanjing, China.
[4]Department of Ecology and Evolutionary Biology, Rice University, Houston, TX, USA.

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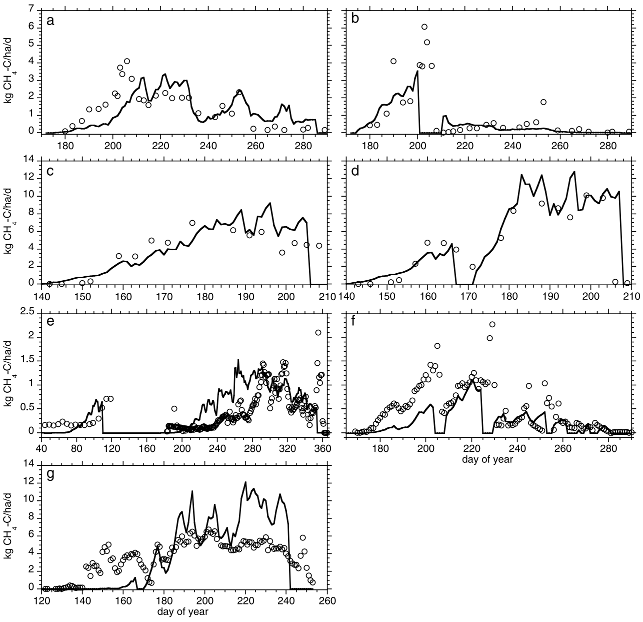

Figure 1. Measured (O) and simulated (lines) CH_4 fluxes. Single rice with (a) continuous flooding midseason drainage and (b) midseason drainage at Jianning, Jiangsu Province, China [*Huang et al.*, 2001]; single rice with (c) continuous flooding and (d) midseason drainage at Beaumont, Texas, USA [*Sigren et al.*, 1997; R. Sass, unpublished data]; (e) double rice with continuous flooding at Prachin Buri, Thailand [*Charoensilp et al.*, 2000]; (f) single rice with midseason drainage at Wuxian, Jiangsu Province, China [*Zheng et al.*, 1999]; and (g) single rice with continuous flooding at Ver, Italy [*Butterbach-Bahl*, 1997].

et al., 2000]. A detailed rice growth sub-model was also developed for DNDC [*Zhang et al.*, 2002]. The model was tested against methane flux data sets from wetland rice sites in the U.S., Italy, China, Thailand, the Philippines, and Japan, and was generally consistent with observations, with reduced emissions for mid-season drainage (Figures 1b, 1d, and 1f) compared to continuous flooding (Figures 1a, 1c, 1e, and 1g).

2.2. Spatial Datasets

[6] County-scale paddy area for single rice and 10 different multi-crop paddy rice rotations were from *Frolking et al.* [2002]. Manure production was based on animal and human populations using standard manure production rates [*IPCC*, 1997], and field application rates of 50% for animal manure and 10% for human manure. 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]. General data on tillage, planting and harvest dates, crop residue management, and crop varieties were taken from *CRTSA* [1995], *Huang et al.* [1997a], *Cui et al.* [1994], *Liu and Mu* [1993], and *Beijing Agricultural University* [1992], and *Shen* [1998].

[7] Daily weather 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. Earlier simulations with only 175 stations yielded very similar results.

[8] 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. In the early 1980s, midseason drying 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]. In 2000, 80% of paddies had mid-season drying (Qingmu Chen, personal communication). We chose approximate values for the percent of paddies with mid-season drainage for six regions in China for 1980, 1985, 1990, 1995, and 2000 (Table 1). This is a very rough estimate, with an aim of characterizing the magnitude of change.

3. Results and Discussion

[9] Sensitivity tests conducted for typical rice fields in China indicated that CH_4 fluxes were most sensitive to soil

Table 1. Paddy Areas (10^3 km^2), Fraction Drained, and Methane Flux (Tg CH_4 yr^{-1}) by Region in China

	Crop area[b]		Fraction drained					Methane flux[c] (Tg CH_4 yr^{-1})				
Region[a]	R-1	R-2	1980	1985	1990	1995	2000	1980	1985	1990	1995	2000
North	10	0.8	0.04	0.3	0.6	0.8	0.8	0.46	0.42	0.37	0.35	0.35
Northeast	26	0	0.05	0.3	0.6	0.8	0.8	0.68	0.62	0.57	0.54	0.54
Central	41	98	0	0	0.3	0.6	0.8	6.54	6.54	5.68	4.82	4.25
South	6	40	0	0	0.2	0.4	0.8	1.99	1.99	1.72	1.45	0.98
Southwest	40	24	0	0	0.3	0.6	0.8	2.41	2.41	2.00	1.59	1.32
Northwest	6	0.1	0	0.3	0.6	0.8	0.8	0.21	0.19	0.16	0.14	0.14
TOTAL	130	163	0.01	0.05	0.33	0.6	0.8	12.3	12.2	10.5	8.9	7.6

[a] *North*: Beijing, Tianjin, Hebei, Shanxi, Shandong, and Henan Provinces; *Northeast*: Liaoning, Jilin, and Heilongjiang Provinces; *Central*: Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, and Hunan Provinces; *South*: Fujian, Guangdong, Guangxi, and Hainan Provinces; *Southwest*: Sichuan, Guizhou, and Yunnan Provinces; *Northwest*: Inner Mongolia, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang Provinces.

[b] R-1: single rice and rice plus non-rice rotation; R-2: double rice and double rice plus non-rice rotation [*Frolking et al.*, 2002]. Areas in 10^3 km^2.

[c] Regional methane flux as mean of high and low emission estimates. Typical provincial flux ranges were ±10–35% of the mean for the continuous flooded scenarios and ±35–75% of the mean for the mid-season drained scenarios. Full range reported for national total in Table 2.

Table 2. Rice Paddy Statistics for China

Year	Area[a] (10^6 km^2)	Yield[a] (10^3 kg ha^{-1})	Production[a] (10^9 kg yr^{-1})	CH_4 flux (Tg CH_4 yr^{-1})
1980	0.34	4.1	143	8.6–16.0
1985	0.33	5.2	171	8.4–16.0
1990	0.34	5.7	192	6.6–14.4
1995	0.31	6.0	187	4.9–12.9
2000	0.30	6.3	190	3.5–11.6

[a] *FAOSTAT* [2002].

texture values. Varying soil texture from coarsest to finest texture value reported in the county-scale database produced a range of CH_4 fluxes broad enough to cover >80% of the CH_4 variations caused by varying any or all other input parameters between minimum and maximum values. DNDC was run twice for each of the 11 rice crop rotation that occurred in each county, with the county's maximum and minimum soil texture values. Final CH_4 fluxes are then expressed as ranges that likely bound the true CH_4 flux. While this cannot be fully evaluated because of very limited field data, for five sites we compared our annual county-level emission range (not site-specific simulations in Figure 1) to reported emissions. For the China sites, the three scenarios of observed annual emissions were within the simulated range, while for the Texas site, the continuous flooding annual emission was below the simulated range and the mid-season drainage annual emission was above the simulated range.

[10] The predicted 1990 CH_4 emission ranges from all paddy rice fields in China were 2.3–10.5 Tg CH_4 yr^{-1} for midseason drainage scenario and 8.6–16.0 Tg CH_4 yr^{-1} for continuous flooding. Changing continuous flooding to mid-season drainage reduced both the high and low estimates by a similar amount, so we conclude that the change in national emissions due to changing water management is not very sensitive to soil texture variability. Water management scenario area-weighted averages were estimated for each province every five years from 1980 through 2000 (Table 1). From 1980 to 2000 China's annual rice paddy methane flux dropped from 8.6–16.0 Tg CH_4 yr^{-1} to 3.5–11.6 Tg CH_4 yr^{-1} (Table 2). China produces ~33% of the world's rice on ~20% of the world's paddy land [*FAOSTAT*, 2002]. Multiplying the DNDC estimate of methane emissions for China's paddies, continuously flooded, by 3 (production) to 5 (area) gives a global rice paddy methane flux estimate of 25–80 Tg CH_4 yr^{-1}, compared with recent global estimates of ~40 Tg CH_4 yr^{-1} [e.g., *Sass et al.*, 1999; *Neue and Sass*, 1998].

[11] To quantify the atmospheric impact, we constructed a simple, one-box, first order model of atmospheric methane burden, with a constant global source of 595.7 Tg CH_4/yr, a methane lifetime of 8.4 years, and 1ppbv per 2.78 Tg CH_4 [*Prather and Ehhalt*, 2001], which had a steady state concentration of 1800 ppbv. If, over 20 years, emissions drop by 4.7 Tg/yr (Table 1), the atmospheric concentration drops to 1792 ppbv. If the source continues at this lower rate (591 Tg CH_4/yr) the atmosphere reaches a new steady state of 1786 ppbv, after 20 more years. We conclude that reduced emissions from China's rice paddies probably played an important but perhaps not dominant role in the reduced growth rate in the 1990s, and will affect the atmosphere for another few decades.

[12] Several additional factors could have influenced methane emissions from China's rice paddies from 1980 to 2000. First, weather patterns vary from one year to the next, but are not likely to have caused a two-decade-long trend in paddy methane emissions, particularly because paddies have managed water regimes. Second, nitrogen fertilizer use doubled [*FAOSTAT*, 2002]. Impacts of nitrogen fertilizer use on methane emissions from rice paddies are indirect and fertilizer-type dependent, and thus highly variable. Increased fertilizer use could lead to an increase in emissions due to an increase in rice plant productivity and biomass, or to a decrease due to soil Eh elevation induced by fertilizers such as ammonium sulfate [*Dunfield et al.*, 1995; *Lindau et al.*, 1990; *Denier van der Gon and Neue*, 1994; *Wassmann et al.*, 1994; *Yao and Chen* 1994]. Third, the direct effects of rice cultivar type on methane emissions are complex, due to differences in aerenchyma development, biomass allocation to roots and grain, and total plant height and biomass [*Kludze et al.*, 1993; *Huang et al.*, 1997b; *Ding et al.*, 1999], and no clear consensus has emerged from field measurements to date. New cultivars introduced in China between 1980 and 2000 generally have had lower stature and more allocation to grain [*Zhou et al.*, 2001]. Finally, paddy area was fairly constant during the 1980s but declined by ~10% during the 1990s (Table 2), likely with a similar decline in methane emissions.

4. Conclusions

[13] Demand for rice in Asia is projected to increase by 70% over the next 30 years [*IRRI*, 2002]. At the same time, population increase and intensification of economic development will lead to significant land use conversion [e.g., *Seto et al.*, 2000]. Paddy rice cropland distributions and management intensity (fertilizer use, cultivars, water management, multi-cropping) will have to change. As water resources become scarcer [*Vörösmarty et al.*, 2000], rising water costs will force all agriculture to improve its water-use efficiency. As this occurs, midseason draining of rice paddies, which requires less water than continual flooding, is likely to increase throughout many parts of Asia. Continuing changes in the rice paddy contribution to the global methane budget are likely over the coming decades.

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S. Boles, S. Frolking, C. Li, B. Moore III, W. Salas, and X. Xiao, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824, USA. (steve.frolking@unh.edu)

Y. Huang, College of Resource and Environmental Sciences, Nanjing Agricultural University, Nanjing, China.

J. Qiu, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Science, Beijing, China.

R. Sass, Department of Ecology and Evolutionary Biology, Rice University, Houston, TX 77005, USA.