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Modeling methane emissions from rice agriculture in China during 1961–2007

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We assessed decadal changes in CH_4 fluxes from rice fields in China during 1961–2007 using an empirical model that was modified to include the effects of changing patterns of fertilizer use and water management. We reviewed studies of the effects of organic amendments and found that an application rate of 6 tons/ha increased emissions by $115 \pm 42\%$ based on experimental manipulations from 10 studies. We also reviewed studies of mid-season drainage in rice fields and found that drainage reduced CH_4 emissions by $35 \pm 12\%$ based on experiments reported from nine studies. Our simulations showed that the CH_4 flux was about 8 Tg/year in 1961, gradually increased to a maximum of approximately 17 Tg/year in 1982, and then gradually declined to 7.5 Tg/year in 2007. The reduction in the total rice emissions after 1982 was caused primarily by changing agricultural practices, including mid-season drainage, increases in inorganic fertilizer use, improved crop yields, and decreases in the area used for rice production.

Keywords: methane; rice paddies; water management; fertilizer; agriculture

1. Introduction

Methane (CH_4) is the major anthropogenic greenhouse gas after CO_2 (Forster et al. 2007). Rice paddy emissions of CH_4 have been assessed in numerous studies, and they remain one of the largest uncertainties among the anthropogenic component of the global methane budget (e.g. Minami and Neue 1994; Sass et al. 1999; Forster et al. 2007). CH_4 fluxes in rice fields are strongly regulated by levels of organic input (e.g. Minami and Neue 1994; Wassmann et al. 1996). Denier van der Gon (1999) studied the impact of changes in fertilizer practice on CH_4 emissions in China and found that declining use of organic fertilizer in rice agriculture probably reduced Chinese CH_4 emissions by approximately 2.5–5% $year^{-1}$ from the 1970s to the 1990s. Since the late 1960s, expanded use of chemical fertilizer has led to decline in the use of organic materials in many Asian countries (e.g. Hossain and Singh 2000). The rapid rise in chemical fertilizer use in China is consistent with concurrent reductions in organic amendments that are more labor-intensive (Denier van der Gon 1999).

Changing management of water resources also has likely contributed to reduced emissions from rice agriculture. Field studies indicate that mid-season drainage

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reduces CH_4 emissions by 15–80% (e.g. Wassmann et al. 2000). Combining this information with regional statistics on management practices, Li et al. (2002) estimate that the practice of midseason paddy drainage in China could have lowered CH_4 fluxes by about 2% year^{-1} from 1980 to 2000. Here, we estimated the changing CH_4 source strength of Chinese rice agriculture over time using a modified empirical model with historical rice cultivation and climate data in China. We also evaluated the impact of chemical fertilizer application and water management (WM) practice in rice fields to the CH_4 flux after the 1960s.

2. Method

To estimate decadal CH_4 emissions from rice paddies in China, we applied an empirical model. The empirical model was based on Huang et al. (1998a,b). In previous studies, the Huang model was validated against flooded rice field measurements in various regions, including the United States, China, and Italy (Huang et al. 1998a,b; Sass et al. 2002). In this study, we modified the rice field environments in the Huang model by adding two modules to include the effects of fertilizer application and WM. We also compiled a database of major variables controlling CH_4 emission from rice fields around the world from published literature. We began by developing several scenarios to evaluate the impacts of these environmental variables. Then, we estimated the CH_4 fluxes from 1961 to 2007 using historical rice data sets from the International Rice Research Institute (IRRI) (2008).

2.1. The Huang model

The original empirical model (Huang et al. 1998a, b) assumed that methanogenic substrates were primarily derived from rice plants and added organic matter. The model was developed primarily from statistical analyses of crop data and information from field measurements in continuously flooded rice fields (Huang et al. 1998a,b). The annual CH_4 flux (FX) was estimated using the equation:

$$FX_{cf} = [E_{cf} \times (1 - f_{om}) + E_{cfom} \times (f_{om})] \times A \times DF \tag{1}$$

where E_{cf} (g CH_4 m^{-2} d^{-1}) is the daily rate of CH_4 emission in a continuously flooded (CF) rice field, f_{om} is the fraction of the rice area with additional organic matter amendments (OM). E_{cfom} (g CH_4 m^{-2} d^{-1}) is the daily rate of CH_4 emission with additional OM in CF rice field, A (m^{-2}) is the production area of CF rice agriculture, and DF (days) is the flooding period. f_{om} was assumed to be 0.30 (Huang et al. 1998b).

The daily rate of CH_4 emission from CF rice agriculture was estimated by the daily rate of gross CH_4 production (Huang et al. 1998b):

$$E_{cf} = 0.35 \times \left[P_{rp} + P_{dom}\right] \tag{2}$$

where the P_{rp} (mg m^{-2} d^{-1}) and P_{dom} (mg m^{-2} d^{-1}) are the daily amount of carbohydrates derived from rice plants, and from incorporated organic amendments, respectively. The constant of 0.35 represents a fraction of CH_4 emitted to the atmosphere as compared with gross production, and represents the efficiency of CH_4 oxidation. The daily amount of carbohydrates derived from rice plants was linked to grain yield, cultivar character, and soil environment (Huang et al. 1998b):

$$P_{rp} = 0.27 \times [14.1 \times T \times S \times V \times G^{0.95}] \tag{3}$$

$$\begin{aligned} P_{dom} = 0.27 \times \{&OM_N \times [1 - \exp(-k_1 \times S \times T \times DF) + OM_S \\ &\times [1 - \exp(-k_2 \times S \times T \times DF)]\} \times 10^3/DF \end{aligned} \tag{4}$$

where the constant of 0.27 is a conversion factor of $C_6H_{12}O_6$ to CH_4. The factor of 14.1 and the exponent of 0.95 are empirical constants. T and S are indices of soil temperature and soil texture, respectively. V is an index of rice variety. These indices (T, S, V) are dimensionless. G (g m^{-2}) is rice grain yield. OM_N (g m^{-2}) and OM_S (g m^{-2}) are the amount of nonstructural and structural carbohydrates from organic matter inputs, respectively. The fractions of OM_N and OM_S of the total incorporated organic matter are 0.25 and 0.75, respectively. k_1 (2.7×10^{-2} d^{-1}) and k_2 (2×10^{-3} d^{-1}) are decay rates for nonstructural and structural carbohydrates, respectively. The total organic matter input from incorporated organic materials (e.g. residues of previous crops, green manure, pig-manure and rapeseed cake) was assumed to be 150 (g m^{-2}). As described below, V was as allowed to vary between 1.4 and 1.0 based on rice variety. The soil texture index was determined by a percentage of sand, and the soil temperature index was based on a temperature coefficient and the mean value of soil temperature. These indices were calculated as given by Huang et al. (1998b):

$$S = 0.325 + 0.0225 \times SP \tag{5}$$

$$T = Q_{10}^{(TS-30)/10} \tag{6}$$

where the factors of 0.325 and 0.0225 are empirical constants. SP (%) is a soil sand percentage. Q_{10} (dimensionless) is a temperature coefficient. TS (°C) is a mean soil temperature during the growing season. Following Huang et al. (1998b), we used a Q_{10} of 3.0 and a baseline temperature of 30°C. The daily rate of CH_4 emissions with additional OM in CF rice field was estimated by adjusting the E_{cf} with an enhancement factor (R_{om}). The enhancement factor was determined to account for the contribution of additional organic matter inputs to CH_4 emission. The adjustment of the daily rate of CH_4 emission with additional OM was described as Huang et al. (1998b):

$$E_{cfom} = E_{cf} \times (1 + R_{om}) \tag{7}$$

$$R_{om} = (PE_{om} - PE)\ PE \tag{8}$$

where PE_{om} and PE are previous CH_4 emissions measurements from rice fields with and without additional organic matter amendments, respectively. There are two different rice cropping seasons (single cropping and double cropping) in China. In the system of double cropping (rice is planted twice per year), the CH_4 emissions from the late season crop are generally higher than those from the early season crop (e.g. Wassmann et al. 1993; Huang et al. 1998b and references therein). CH_4 emissions from late season fields were estimated following Huang et al. (1998b):

$$E_{ls} = 0.35 \times P_{rp} \times (1 + R_{ls}) \tag{9}$$

$$E_{lsom} = 0.35 \times P_{rp} \times (1 + R_{om}) \times (1 + R_{ls}) \tag{10}$$

$$R_{ls} = (PE_{ls} - PE_{es})/PE_{es} \tag{11}$$

where PE_{ls} and PE_{es} are previous CH_4 emission observations from late rice season and from early rice season, respectively. E_{ls} (g m^{-2} d^{-1}) is the daily rate of CH_4 emission in the continuously flooded rice field from the late season crop. E_{lsom} (g m^{-2} d^{-1}) is the daily rate of CH_4 emission with additional OM in CF rice field from the late season crop. R_{ls} is an enhancement factor for late season crops; we used a R_{ls} value of 0.47 following Huang et al. (1998b). For the single crop and early season crop, the CH_4 emission rate was calculated using Equations (2) and (7).

2.2. *Our modifications of the Huang model to account for fertilizer application*

Our empirical model was based on the Huang model described in section 2.1. In the Huang model, the fraction of the rice harvested area with additional OM (f_{om}) was assumed to be constant (0.3) for the years of 1994 and 1995 (see equation 1). Here, we allowed f_{om} to vary year by year to estimate CH_4 flux over several decades. We assumed the f_{om} was linked to the availability of inorganic fertilizers. Denier van der Gon (1999) suggested the use of organic matter amendments has declined since the 1960s. He proposed that the decrease in organic fertilizer use was mainly related to the increased availability of chemical fertilizer, and lower labor costs associated with chemical fertilizer application.

As mentioned in section 2.1, rice fields where additional organic matter inputs have been applied will produce higher CH_4 emissions than fields where there are no organic amendments. As a consequence, if the use of organic matter has decreased, it would cause a reduction in CH_4 fluxes per unit area of rice agriculture. Therefore, it is important to consider the change of organic fertilizer use to provide a better understanding of CH_4 emissions. However, the changes in organic fertilizer use have been difficult to monitor, and there were no statistical data available on the use of organic inputs in rice fields (Denier van der Gon 1999). To account for the changes of organic fertilizer inputs, we assumed an inverse linear relationship between the increasing chemical fertilizer use and the decreasing organic fertilizer consumption. The modified equations to account for the fertilizer application are written as:

$$FX_{fu}(t) = [E_{cf}(t) \times (1 - f_{om}(t)) + E_{cfom}(t) \times f_{om}(t)] \times A(t) \times DF \tag{12}$$

$$f_{om}(t) = 1 - FU(t)/FU_{max} \tag{13}$$

where t is yearly time step (from 1961 to 2007), FX_{fu} (Tg/year) is the annual CH_4 flux with a variable fraction of organic matter amendment. FU (t/ha) is the amount of chemical fertilizer application per unit rice area. FU_{max} (t/ha) is the maximum level of fertilizer application (2.2 t/ha) that was assumed to correspond to no organic amendment. The values of f_{om} are shown in Table 1. The f_{om} was assumed to range from 0.1 to 1.0. Calculations of the enhancement factor (R_{om}) show an average value of 1.15 ± 0.42 at 6t/ha of organic amendment input using a linear regression model (Table 2). This R_{om} value is in good agreement with the estimate (1.05) by Huang et al. (1998b).

Table 1. Model parameters related to fertilizer use, water management, and rice variety for China.

Year	1965	1970	1975	1980	1985	1990	1995	2000	2005
f_{om}^{a}(%)	0.96	0.93	0.90	0.75	0.70	0.54	0.35	0.34	0.10
f_{md}^{b}(%)	0.00	0.00	0.07	0.18	0.28	0.39	0.49	0.60	0.71
V^{c}	1.40	1.40	1.40	1.34	1.29	1.20	1.11	1.07	1.03

[a] We used Equation (13) to calculate the fraction of the rice area with additional OM.

[b] We used Equation (18) to calculate the fraction of the rice area with water management treatment.

[c] The transition from traditional variety ($V = 1.4$) to modern rice variety ($V = 1.0$) was estimated using the percentage of area with modern rice (IRRI 2008).

Table 2. CH_4 emissions from rice fields with and without organic amendments.

Region, Country	Year	CH_4 flux (mg m^{-2} h^{-1}) With OM	CH_4 flux (mg m^{-2} h^{-1}) Without OM	OM (t/ha)	R_{om}	Reference
Manila, Philippines	1992–1993	9.0 ± 1.9	2.3 ± 1.6	12.0	2.84	Wassmann et al. (1996)
Nueva Eeija, Philippines	1996	24.0 ± 11.5	9.10 ± 2.6	4.0	1.63	Corton et al. (2000)
Nueva Eeija, Philippines	1996	11.2 ± 5.0	9.10 ± 3.2	2.5	0.23	Corton et al. (2000)
Cuttack, India	1997	1.2 ± 0.2	0.6 ± 0.1	2.0	0.84	Adhya et al. (2000)
New Delhi, India	1993	2.1	0.5	12.0	3.20	Debnath et al. (1996)
New Delhi, India	1999–2000	1.7 ± 0.6	0.8 ± 0.5	6.0	1.24	Pathak et al. (2003)
Varanasi, India	1993–1994	7.7 ± 3.8	4.6 ± 2.6	10.0	0.67	Singh et al. (1996)
Suwon, Iksan, Milyang, Korea	1993–1997	12.8 ± 5.8	5.7 ± 3.5	5.0	1.23	Kwum et al. (2003)
Central Lampung, Indonesia	1992–1995	28.2 ± 5.0	20.3 ± 4.1	5.0	0.39	Nugroho et al. (1996)
Central Lampung, Indonesia	1993–1995	21.6 ± 13.2	14.2 ± 9.0	5.0	0.52	Lumbanraja et al. (1998)
Chiayi, Taiwan	2000	14.5 ± 17.9	6.7 ± 7.4	9.8	1.16	Liou et al. (2003)
Best Fit R_{om}					1.15[a] ± 0.42	

[a] The best fit R_{om} represented the enhancement factor at 6 t/ha of added organic amendments, the relationship between the amount of added organic matter (OM) and R_{om} was estimated using a linear regression model.

2.3. *Our modifications of the Huang model to account for water management*

Conducting WM in rice fields, such as mid-season drainage and aeration during the rice growing season, has been shown to reduce CH_4 emissions substantially. The mid-season drainage practice has not affected or even increased rice yield (e.g. Yagi et al. 1996; Wassmann et al. 2000, Li and Barker 2004). In China, mid-season drainage is considered a way to conserve water, and has gained popularity among farmers in different Chinese provinces during the past 2 decades (Li et al. 2002 and references therein).

To estimate the effect of practicing mid-season drainage treatment in rice fields, a reduction factor and a fraction of the rice fields with WM were determined. We assumed the decadal changes in the fraction of paddies with mid-season drainage (f_{md}) were inversely linked to the water availability for agricultural use (FAO 2008). We linearly extrapolated the water consumption values for those time periods without data. The modified equations are described as:

$$FX_{md}(t) = [E_{cfom}(t) \times (1 - f_{md}(t)) + E_{mdom}(t) \times f_{md}(t)] \times A(t) \times DF \tag{14}$$

$$E_{md}(t) = E_{cf}(t) \times (1 + R_{md}) \tag{15}$$

$$E_{mdom}(t) = E_{cfom}(t) \times (1 + R_{md}) \tag{16}$$

$$R_{md} = \left(PE_{md} - PE_{cf}\right)/PE_{cf} \tag{17}$$

$$f_{md}(t) = f_{md}(2000) \times [(f_{aw}(1961) - f_{aw}(t))/(f_{aw}(1961) - f_{aw}(2000))] \tag{18}$$

where FX_{md} (Tg year^{-1}) is the annual CH_4 flux while the factor of WM is included. PE_{md} and PE_{cf} are previous CH_4 emission observations from fields with mid-season drainage practice and with continuous flooded treatment, respectively. f_{md} is the fraction of the rice harvested area practicing mid-season drainage treatments (Table 1). $f_{aw}(t)$ is the fraction of agricultural water withdrawal to total water withdrawal for that year (FAO 2008). We assumed that $f_{md}(2000)$ was 0.60 in 2000, which was a mean of previous estimates that ranging from 0.40 (Li and Barker 2004) to 0.8 (Li et al. 2002) during that time period. Table 3 shows the previous CH_4 flux

Table 3. CH_4 emissions from rice fields with and without water management.

Region, Country	Year	CH_4 flux (mg m^{-2} h^{-1}) Continuous	Intermittent	R_{md}	Reference
Nanjin, Beijing, Hangzho, China	1995, 1999	8.9 ± 3.3	5.4 ± 2.8	−0.40	Huang et al. (2004)
Beijing, China	1995	15.2	6.3	−0.59	Wang et al. (2000)
Nueva Eeija, Philippines	1997	9.0 ± 6.5	6.5 ± 5.9	−0.30	Corton et al. (2000)
Cuttack, India	1997	1.0 ± 0.5	0.8 ± 0.3	−0.22	Adhya et al. (2000)
New Delhi, India	1994–1997	0.9 ± 0.3	0.7 ± 0.3	−0.25	Jain et al. (2000)
New Delhi, India	1999–2000	1.6 ± 0.7	0.8 ± 0.4	−0.48	Pathak et al. (2003)
Suwon, Iksan, Milyang, Korea	1993–1997	10.9 ± 6.5	8.4 ± 5.2	−0.23	Kwun et al. (2003)
Central Lampung, Indonesia	1993–1995	22.6 ± 5.1	15.2 ± 3.1	−0.33	Lumbanraja et al. (1998)
Ryugasaki, Japan	1991, 1993	4.3 ± 1.5	2.6 ± 1.0	−0.40	Yagi et al. (1996)
Average				−0.35 ± 0.12	

measurements from two different types of WM fields. Calculations of the reduction factor show an average value of -0.35 ± 0.12 with a range from -0.22 to -0.59 (Table 3).

2.4. Scenarios and model inputs

To assess the CH_4 flux from rice fields with various agricultural practices during 1961–2007, we developed four scenarios consisting of different environmental factors. The scenarios were (1) a control, (2) fertilizer use only, (3) WM only, and (4) combined fertilizer use and WM. The details of these scenarios are described as follows.

The control scenario simulated CH_4 fluxes from rice fields without considering time-varying chemical fertilizers or WM. We applied the original model with different assigned parameters. The annual CH_4 flux was calculated using Equation (1). The f_{om} was assumed to be 1.0. To estimate the rice net productivity, we used rice production and rice yield (IRRI 2008). For the model inputs of flooding period, soil texture and temperature, we assembled those parameters from literature (Table 4). Considering the air temperature in China has increased over the past few decades, we allowed the soil temperature to change based on the Chinese air temperature anomalies (http://www.cru.uea.ac.uk/cru/data/temperature/; Brohan et al. 2006). Since the original model was developed for flooded rice fields, an adjustment factor needs to be applied to the rice harvested area from IRRI (which includes irrigated, rainfed, deepwater, and upland rice crop area). The adjustment factor is calculated as a ratio of the sum of irrigated, rainfed and deepwater area to the total rice crop area (IRRI 2008) (Table 4). For the rice variety index (V), Denier van der Gon (2000) showed that because of the development of high-yielding rice varieties (one of the drivers of the Green Revolution), the ratio of plant biomass to yield has substantially decreased since 1961. He indicated that tradition varieties have a mean harvest index (HI = weight of the panicles/total dry matter) of 0.3, compared to a higher HI for modern varieties (0.5). To account for differences in carbohydrate production for a given grain yield, we assumed the traditional rice variety has higher a V index (1.4) than modern rice variety (1.0) (Huang et al. 1997; Denier van der Gon 2000). The changes in the V index (Table 1) were then estimated using the percentage of modern rice areas (IRRI 2008). There are three types of rice-cropping

Table 4. Model parameters of distribution of rice crop areas, soil characteristics, and flooded period.

Cropping system	Area (%)				SP (%)	TS (°C)	DF (days)
	Irrigated	Rainfed	Deepwater	Upland			
Single cropping	$93^{a,b}$	$5^{a,b}$	$0^{a,b}$	$2^{a,b}$	24.4 ± 15.1^{c}	22.5 ± 2.3^{c}	108 ± 6^{c}
Early cropping	$93^{a,b}$	$5^{a,b}$	$0^{a,b}$	$2^{a,b}$	24.4 ± 15.1^{c}	23.2 ± 1.7^{c}	82 ± 3^{c}
Late cropping	$93^{a,b}$	$5^{a,b}$	$0^{a,b}$	$2^{a,b}$	24.4 ± 15.1^{c}	22.0 ± 1.9^{c}	94 ± 6^{c}

SP is a soil sand percentage; *TS* is a mean soil temperature in 1994; *DF* is the flooded period.

[a] Distribution of rice crop area by environment between 2004 and 2006 (IRRI 2008).

[b] Assumed different cropping systems in China have the same distribution of rice crop environment.

[c] Huang et al. (1998b) and references therein.

fields (single-rice cropping, early-rice cropping, and late-rice cropping). We assumed the annual grain yield (G = rice production/rice area) in Equation (3) was a combined result from three types of rice-cropping fields. Three rice area adjustment factors (RA_S, RA_E, RA_L) were calculated for the single-rice cropping, early-rice cropping and late-rice cropping areas in China, respectively (Table 5). For the rice production in China, we also applied three rice production adjustment factors (RP_S, RP_E, RP_L) for these rice-cropping fields (Table 6).

For the Fertilizer Use (FU) scenario, we calculated the CH_4 fluxes using Equation (12). This scenario is used to account for a transition of rice fields with traditional organic fertilizer use to rice fields with modern chemical fertilizer application after the 1960s. Since the long-term data of organic fertilizer use in rice agricultures were not available, we calculated f_{om} (Table 1) using published chemical fertilizer consumption based on International Fertilizer Industry Association (IFA) (http://www.fertilizer.org/ifa/ifadata/) during 1961–2006. The fertilizer consumption for 2007 was not available, and it was estimated using 2007 rice yield and the 2000–2006 slope of the relationship between fertilizer application and rice yield. For the

Table 5. Distribution of rice area for cropping systems (single, early and late-rice cropping) (Mha).

Year	Total rice area	Rice cropping systems						
		Single	Early	Late	RA_S^a	RA_E^b	RA_L^c	Reference
1994–1995	30.2	12.2	8.0	10.0	0.40	0.27	0.33	Huang et al. (1998b)
2004	28.4	16.1	5.9	6.4	0.57	0.21	0.22	State Statistical Bureau (2005)
2005	28.8	16.3	6.0	6.5	0.56	0.21	0.23	State Statistical Bureau (2006)
Average	29.1	14.8	6.7	7.6	0.51	0.23	0.26	
SD	0.9	2.3	1.2	2.1	0.09	0.03	0.06	

[a] Fraction of single-rice cropping area in the total cultivated area.
[b] Fraction of early-rice cropping area in the total cultivated area.
[c] Fraction of late-rice cropping area in the total cultivated area.

Table 6. Distribution of rice production for cropping systems (single, early and late-rice cropping) (Mt).

Year	Total rice production	Rice cropping systems						
		Single	Early	Late	RP_S^a	RP_E^b	RP_L^c	Reference
1994–1995	173.9	75.4	42.2	56.4	0.43	0.24	0.23	Huang et al. (1998b)
2004	179.1	113.9	32.2	33.0	0.64	0.18	0.18	State Statistical Bureau (2005)
2005	180.6	114.1	31.9	34.6	0.63	0.18	0.19	State Statistical Bureau (2006)
Average	177.9	101.1	35.4	41.3	0.57	0.20	0.23	
SD	3.5	22.3	5.8	13.1	0.12	0.04	0.08	

[a] Fraction of single-rice cropping production in the total rice production.
[b] Fraction of early-rice cropping production in the total rice production.
[c] Fraction of late-rice cropping production in the total rice production.

WM scenario, we evaluated the potential impact of practicing mid-season drainage treatment in rice fields to the CH_4 flux. We estimated the CH_4 flux using Equation (14) with a reduction factor (R_{md}) of -0.35 (Table 3). Because of limited statistical data describing the practice of mid-season drainage treatment, we calculated f_{md} (Table 1) using available water consumption data for agricultural use (FAO 2008). For the fertilizer use and water management (FU-WM) scenario, we combined the factors of fertilizer use and of WM together. The new annual CH_4 flux (FX_{new}) for this scenario was described as:

$$FX_{new}(t) = \{[E_{cf}(t) \times (1 - f_{om}(t)) + E_{cfom}(t) \times f_{om}(t)] \times (1 - f_{md}(t)) + [E_{md}(t) \times (1 - f_{om}(t)) + E_{mdom}(t) \times f_{om}(t)] \times f_{md}(t)\} \times A(t) \times DF \tag{19}$$

3. Results and discussion

Based on our model results, CH_4 flux from rice fields has declined since the 1980s mostly because of the influence of chemical fertilizer use, application of modern rice variety, and WM in rice harvested areas (Figure 1a). In the control scenario, if the FU and WM factors were not included in the model, the CH_4 flux would have risen rapidly from 8.2 Tg/year to 19.7 Tg/year during 1961–2007. However, this control scenario is less realistic because numerous studies have shown that rice agricultural practices have evolved over the past decades, and these changes have affected CH_4 fluxes emitted from local rice fields (see section 2.2 and 2.3). In the FU-WM scenario, CH_4 flux started at about 8.1 Tg/year in 1961, and gradually increased to around 16.8 Tg/year in 1982. Thereafter, the CH_4 flux decreased steadily to it lowest value at about 7.6 Tg/year in 2007. The decrease in the global flux was connected to the

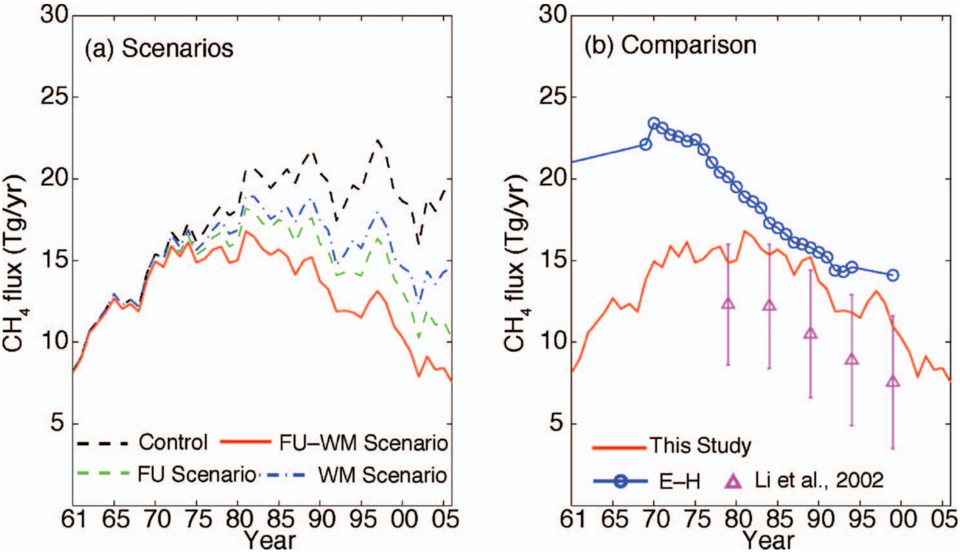

Figure 1. (a) Simulated results of control, fertilizer use (FU) scenario, water management (WM) scenario, and fertilizer use and water management (FU-WM) scenario in China. (b) Comparison of this study (FU-WM scenario) with EDGAR-HYDE (E-H) and Li et al. (2002).

influences of fertilizer use, the impact of WM treatment, the development of rice variety, and the decrease in the rice areas.

Sources of uncertainties in our analysis mainly arise from the limited field measurements related to the use of organic amendments and the practice of mid-season drainage, and the use of an empirical model to scale the impacts of these management changes over time. We applied available rice and water consumption statistics to deduce the changes in CH_4 flux affected by the development of agricultural management and technology at the regional scale. In this study, the estimate of the organic amendment use (f_{om}) is consistent with previous studies showing a decreasing trend in organic inputs to rice fields over time (Denier van der Gon 1999; Gao et al. 2006). The deduced increasing trend of practicing mid-season drainage treatment (f_{md}) is comparable to previous estimates (Li et al. 2002; Li and Barker 2004). Our CH_4 flux estimates (FU-WM scenario) agree well with results estimated by another biogeochemical model (Figure 1b). Li et al. (2002) applied the DNDC (DeNitrification and DeComposition) process-based model to evaluate the CH_4 emissions in China during 1980–2000. Our results are comparable to the upper range of the DNDC results and somewhat lower than the estimates of E-H (Olivier and Berdowki 2001; EDGAR-HYDE v1.4; van Aardenne et al. 2001; EDGAR 32FT2000; Olivier et al. 2005), particularly during the 1960s. Importantly, all these three estimates show a similar decreasing trend in CH_4 flux from Chinese rice fields after the 1980s. In the future, the use of satellite measurements (e.g. from SCIAMACHY or GOSAT) will improve our understanding of large-scale patterns of anthropogenic and natural CH_4 emissions, seasonal variation, and transport of regional sources (e.g. Frankenberg et al. 2005; Bloom et al. 2010).

4. Conclusions

A modified empirical model was applied for simulating the CH_4 flux from rice fields in China during 1961–2007. We evaluated the possible environmental impacts of fertilizer use and WM on CH_4 emissions from rice paddies after the 1960s. We estimate that CH_4 flux was about 8 Tg/year in 1961, and it gradually reached its peak to about 17 Tg/year in the early 1980s. Then, the CH_4 flux went down to about 8 Tg/year in the early 2000s. The decreases after the 1980s were linked closely to changes in agricultural practices, such as mid-season drainage treatments, diminishing organic matter fertilizer consumption, application of modern rice variety, and shrinking rice areas in China.

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