CH4MOD: A MODEL FOR SIMULATING METHANE EMISSION FROM IRRIGATED RICE CULTIVATION WITH VARIOUS AGRICULTURAL PRACTICES

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ABSTRACT

Focusing on the effect of water regime on CH_4 production/emission and the CH_4 transport via bubbles, modification to the model developed by Huang et al. (1998) was made to simulate the processes of CH_4 production, oxidation and emission. The modified model, named as CH4MOD, was validated against a total of 89 field observations conducted in China. These observations covered main rice cultivation regions from northern (Beijing, 40º30´N, 116º25´E) to southern (Guangzhou, 23º08´N, 113º20´E) China, and from eastern (Hangzhou, 30º19´N, 120º12´E) to southwestern (Tuzu, 29º40´N, 103º50´E) China. Single rice and double rice cultivations are mainly distributed in these regions with different irrigation patterns and various types of organic matter incorporation. The validation indicated that model simulations in general agreed with the observations. The observed seasonal amount of CH_4 emission ranged from 3.1 to 761.7 (kg C hm^{-2}) with an average of 199.4 (kg C hm^{-2}). In consonance with the observations, simulations with the model resulted in an average value of 233.9 (kg C hm^{-2}), ranging from 16.7 to 824.3 (kg C hm^{-2}). Comparison between the computed and the observed total seasonal CH_4 emission yielded a correlation coefficient r^2 of 0.891 with a slope of 1.004 and an intercept of 33.7 (n=89). It was concluded that the CH4MOD could well simulate CH_4 emission from irrigated rice cultivation under various soils, climates and agricultural practices.

1.0 INTRODUCTION

To reduce CH_4 emissions with increasing rice production, we must know how many amounts of CH_4 are released at present and will be released in the future from regional/global rice paddies. Simulation models are thought to be good manner to reliably estimate CH_4 emission on regional/global scale and have been gaining international interesting (IPCC, 2000). A number of models have been developed in recent years to estimate CH_4 emission from rice paddies (e.g. Li et al. 1994; Cao et al. 1995; Huang et al. 1998; Matthew et al. 2000). However, few models were able to validate against field measurements with various parameters of soil, climate and agricultural practice because sufficient observations associated with these parameters were not available. Fortunately, scientists have made great efforts in the field observations of CH_4 emission from Chinese rice paddies (e.g. Wang et al. 1994; Cai et al. 1995a, 1995b; Khalil et al. 1998) since 1988, which offered a great opportunity to validate present models.

With an understanding of the processes of CH_4 production, oxidation and emission, Huang et al. (1998) developed a model to predict CH_4 emission from rice paddy soils. The model associated these processes with rice growth, organic C depletion and environmental factors. In tropical and subtropical regions, double-rice cropping is a prevailing manner for intensifying rice production. Methane emission from the late-rice season was found to be much higher than that from the early-rice season (Huang et al. 1998). Many studies (e.g. Yagi et al. 1996) demonstrated that water management such as periodic drainage and intermittent irrigation during rice growing period significantly reduced CH_4 emissions. Decomposition of incorporated organic materials is thought to be the predominant source of methanogenic substrates in the early stages of rice growing (Watanabe & Roger 1985) and the CH_4 emission via ebullition contributed significantly to the total emissions (Shangguan et al. 1993). However, Huang's model was mainly focused on single-rice cropping system and primarily developed for the permanent flooding rice paddies. Moreover, the CH_4 emission via ebullition was not taken into account in their model. All of these shortages might make big errors when the model is employed to estimate CH_4 emission from rice paddies with various agricultural practices.

In this paper, modification to Huang's model was made to simulate CH_4 emission from rice cultivation with various agricultural practices. The main objective was to lay a foundation for the estimates of CH_4 emission from regional/global rice paddy soils.

2.0 MODEL DESCRIPTION AND MODIFICATION

Based on the original model developed by Huang et al. (1998), we paid more attention to the effect of the water regime to CH_4 production, CH_4 emission via the ebullition, and the double-rice cropping system.

2.1 SUBSTRATES FOR METHANOGENS AND METHANE PRODUCTION

Methanogenic substrates are primarily derived from the decomposition of added organic matter and rice plants (Sass et al., 1991; Minoda et al.,1996). Decomposition of organic matter in soil was simulated with a first-order kinetics equation (Huang et al., 1998) as:

$$C_{OM} = 0.65 SI \times TI \times (2.7 \times 10^{-2} OM_N + 2 \times 10^{-3} OM_S) \qquad (1)$$

where C_{OM} is the daily amount of carbohydrate degraded from organic matter amendments. The constant 0.65 is a reduction factor of flooding on decomposition (Huang et al., 2002). The OM_N and OM_S represent nonstructural and structural components of incorporated organic matter, respectively. Initial fraction of the OM_N and OM_S was calculated by the contents of nitrogen and lignin for different types of organic matter (Huang et al., 2003). The impact of soil texture and soil temperature on decomposition was quantified by the soil index (SI) and the temperature index (TI) as follows (Huang et al., 1998):

$$SI = 0.325 + 0.0225SAND \qquad (2)$$

$$TI = Q_{10}^{\frac{T_{Soil}-30}{10}} \qquad (T_{soil} = 30 \text{ for } 30 < T_{soil} = 40°C) \qquad (3)$$

The SI is associated with soil sand percentage (SAND) and the TI related to soil temperature (T_{soil}, **℃**). The temperature coefficient Q_{10} was assumed to be 3.0 (Huang et al., 1998).

The amount of carbohydrates derived from rice plants was simulated by (Huang et al., 1998):

$$C_R = 1.8 \times 10^{-3} \times VI \times SI \times W^{1.25} \qquad (4)$$

where C_R represents carbohydrate derived from rice plants and W is rice aboveground biomass in a given day. The VI is a variety index identifying relative difference in CH_4 production among rice varieties (Huang et al. 1997). The rice aboveground biomass (W) was computed by a logistic growth equation as (Huang et al. 1998):

$$W = \frac{W_{\max}}{1 + B_0 \times \exp(-rt)} \qquad (5)$$

$$B_0 = \frac{W_{\max} - W_0}{W_0} \qquad (6)$$

$$W_{\max} = 9.46GY^{0.76} \qquad (7)$$

where W_0 and W_{max} are aboveground biomass of rice plants at transplanting and at harvesting, respectively. Time variable t is the days after transplanting. The GY represents rice grain yield. Constant r is an intrinsic growth rate for aboveground biomass (Huang et al. 1998).

The net reaction of anaerobic carbohydrate fermentation with methanogenesis was assumed to be an overall reaction of $C_6H_{12}O_6 => 3CH_4 + 3CO_2$. From this reaction, a conversion factor on a mole weight basis of $C_6H_{12}O_6$ to CH_4 is approximately 0.27 ($3[CH_4]/[C_6H_{12}O_6]=0.27$). Rate of CH_4 production (P) was determined mainly by the availability of methanogenic substrates and the influence of environmental factors as (Huang et al. 1998):

$$P = 0.27F_{Eh} \times (TI \times C_R + C_{OM}) \qquad (8)$$

Effect of soil temperature on methane production associated with organic matter amendments (C_{OM}) was assumed to have already been built into the decomposition process (eqn. 1). The F_{Eh} is a reduction factor of soil redox potential (Eh) which is described as (Huang et al. 1998):

$$F_{Eh} = \exp(-1.7 \times \frac{150 + V_{Eh}}{150}) \qquad \text{(Eh = -150 for Eh < -150)} \qquad (9)$$

where the V_{Eh} is soil Eh in a given day. Based on the field measurements by Lewis (1996), changes in the Eh after initial flooding in the early season were modeled by a power function of the days after flooding (Huang et al. 1998). Field measurements during rice growing season at Nanjing indicated that the soil Eh increased rapidly when drained and decreased after re-flooded (this group unpublished data). We simulated the soil Eh change by following differential equations:

$$V_{Eh}^{(t+1)} = V_{Eh}^{(t)} - D_{Eh} \times (A_{Eh} + \min(1, C_{OM})) \times (V_{Eh}^{(t)} - B_{Eh}),$$

$$\text{for flooding process} \qquad (10)$$

$$V_{Eh}^{(t+1)} = V_{Eh}^{(t)} - D_{Eh} \times (A_{Eh} + 0.7) \times (V_{Eh}^{(t)} - B_{Eh}), \text{ for drainage process} \qquad (11)$$

where $V_{Eh}^{(t)}$ represents the soil Eh value in time t, the days after flooding or days since drainage. The A_{Eh} and D_{Eh} are the differential coefficients and taken values of 0.23 and 0.16, respectively. The B_{Eh} is a limiting criterion, taking a value of –250 (mv) for flooding and 300 (mv) for drainage period, respectively.

2.2 METHANE TRANSPORT, OXIDIZATION AND EMISSION

It is well recognized that plant-mediated transport is the primary mechanism for the emission of CH_4 (Nouchi, 1994). The emitted fraction via plants (F_p) was simulated by (Huang et al., 1998):

$$F_p = 0.55 \times (1 - \frac{W}{W_{\max}})^{0.25} \qquad (12)$$

The W and W_{max} have the same meaning as in eqn. (5). The CH_4 emission via plants (E_p) was then computed as:

$$E_p = F_p \times P \qquad (13)$$

Methane release via bubbles in flooded fields was reported by many researchers (e.g. Denier van der Gon & Neue, 1995). The ebullition occurs dominantly in the early phase of rice growing, and trails off as rice growing. We adopt the equation by Li (1999) to simulate this process.

$$E_{bl} = a \times (P - P_0) \times \ln(T_{soil}) / B_{root} \qquad (14)$$

where E_{bl} represents the CH_4 emission rate via bubbles. The P represents CH_4 production rate (eqn. 8). The P_0 is a critical CH_4 production rate when the bubbles occur and taken a value of 0.002. Coefficient a was taken a value of 0.7. The B_{root} is rice root biomass and was estimated by (Yoshida, 1981):

$$B_{root} = 0.136 \times (B_{root} + W)^{0.936} \qquad (15)$$

3.0 MODEL VALIDATION

The model was validated against independent CH_4 emission measurements over the year from 1988 to 1999. These measurements were made in 9 sites covering five main rice cultivation regions in China, including different water regime, organic matter incorporation, and rice cropping system. A summary of the observations is given in table 1.

Table 1 Summary of the observations for validating the CH4MOD

Observational Site	Location	Soil sand (%)	Observational seasons	Rice cultivation	Cases	Reference
Nanjing, Jiangsu	31°51´ N, 118°49´ E	4.8	1999	Single	4	Program of TECO/NASA by this group
Hangzhou, Zhejiang	30°19´N, 120°12´E	23.0	1995 - 1998	Single Double	23	Lu et al. 1998; 2000
Taoyuan, Hunan	28°55´N, 110°30´E	21.2	1992	Double	8	Shangguan et al. 1993
Changsha, Hunan	28°09´N, 113°06´E	62.0	1995 - 1997	Double	15	Cai et al. 1995a; 1995b; Cai & Yan 1996; Cai et al. 1998; Cai 1999a; 1999b; Cai et al. 2000
Fengqiu, Henan	35°24´N, 114°24´E	2, 20, 80	1993 - 1994	Single	6	
Chongqing	29°48´N, 106°18´E	57.0	1995 - 1997	Single	11	
Guangzhou, Guangdong	23°08´N, 113°20´E	46.3	1994	Double	4	Institute of Atmospheric Physics, CAS
Tuzu, Sichuan	29°40´N, 103°50´E	78.5	1988 - 1994	Single	7	Khalil et al. 1998
Beijing	40°30´N, 116°25´E	55.0	1995 - 1997	Single	11	Wang et al. 1998

3.1 MODEL INPUT

Model inputs include rice grain yields, initial aboveground biomass at rice transplanting, variety index, soil sand percentage, amount of organic amendments, fraction of structural and non-structural carbohydrates of the incorporated organic matter, daily air temperature and water management pattern.

Since the initial aboveground biomass at transplanting (W_0) was not available, a value of 15 g m^{-2} was assumed. The intrinsic growing rate of rice plants (r in eqn. 5) was assumed to be 0.08 for the single rice (Huang et al., 1998) and 0.1 for the early/late rice, respectively. According to Huang et al. (1999), the rice variety index (VI) was assumed a constant of 1.0 for all cases. The soil temperature (T_{soil}) was estimated by the air temperature (T_{air}) as $T_{soil} = 4.4+0.76T_{air}$ (Huang et al. 1998).

3.2 VALIDATION FOR SINGLE RICE CULTIVATION

Single rice cultivation is prevailing in the western, northern, and most of the eastern China. Rotations of wheat-rice, green manure-rice, rapeseed-rice and fallow-rice are main cropping systems in these regions. A total of 46 observations made in Beijing, Jiangsu, Zhejiang, Chongqing, Sichuan and Henan were simulated. Figure 1 shows the computed and the observed seasonal variations in CH_4 emission under different water regimes with or without organic matter amendments, indicating that the model can well capture the seasonal pattern of CH_4 emissions.

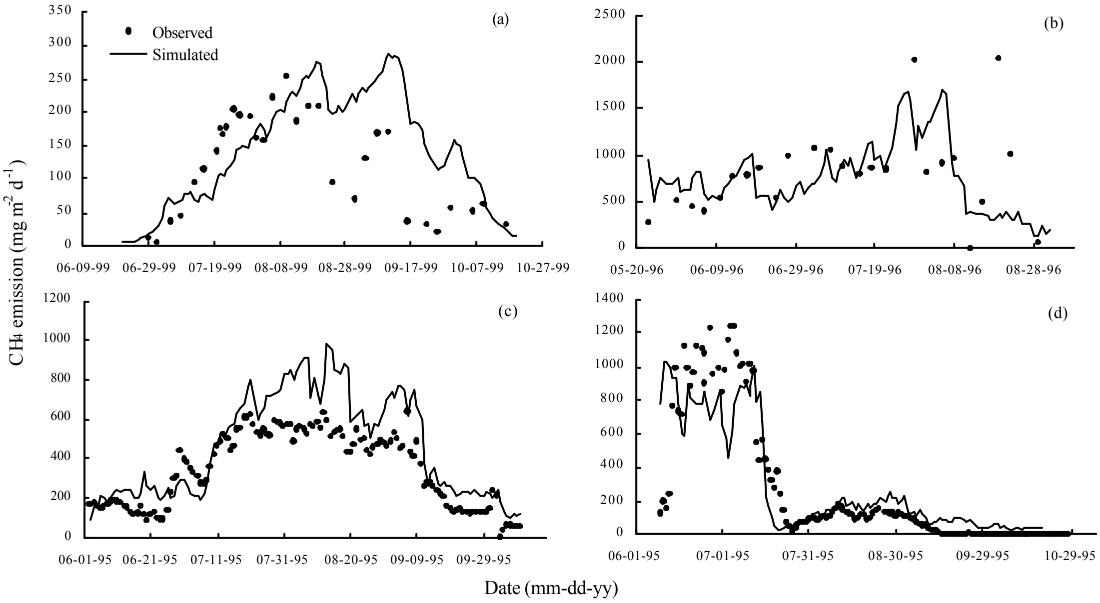

Fig. 1 Observed and simulated seasonal variations in CH_4 emission from single rice season. (a) Continuous flooding without OM incorporation, Nanjing of Jiangsu province. (b) Waterlogged during previous winter season and continuous flooding in rice-growing season, Chongqing. (c) Continuous flooding with incorporation of 1.1 t hm^{-2} green manure, Hangzhou of Zhejiang province. (d) Incorporation of 2.6 t hm^{-2} crop straw with water regime as flooded-drainage-intermittent irrigation, Beijing.

3.3 VALIDATION FOR DOUBLE RICE CULTIVATION

Double rice cropping system is mainly distributed in the southern, southwestern and southeastern China where the hydrological and thermal resources are abundant. A total of 43 observations made in Guangdong, Hunan, Sichuan and Zhejiang were simulated. Figure 2 gives the simulated and the observed CH_4 emissions from these regions. The results in Fig. 2 also demonstrated that the present model could well simulate CH_4 emissions from the early- and the late-rice cultivation under the treatments of with and without organic matter application.

3.4 VALIDATION OF TOTAL SEASONAL METHANE EMISSION

A total of 89 cases were simulated with a daily step. The modeled total amount of seasonal CH_4 estimation was obtained by accumulating the daily simulation for each case. The comparison between computed and observed CH_4 emission (Fig. 3) resulted in an r^2 of 0.891 with a slope of 1.004 and an intercept of 33.7 (n=89). The observed seasonal amount of CH_4 emission ranged from 3.1 to 761.7 (kg C hm^{-2}) with an average of 199.4 (kg C hm^{-2}). In consonance with the observations, simulations with the model resulted in an average value of 233.9 (kg C hm^{-2}), ranging from 16.7 to 824.3 (kg C hm^{-2}).

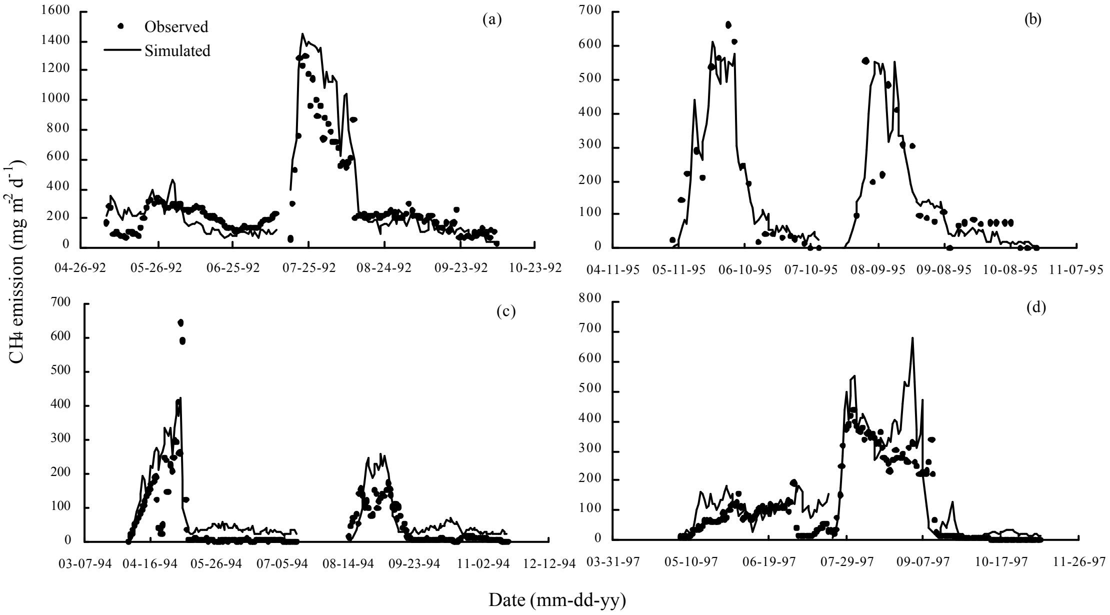

Fig. 2 Observed and simulated seasonal variations in CH_4 emission from double rice seasons. (a) Continuous flooding with incorporations of 3t hm^{-2} green manure for the early-rice and 0.9t hm^{-2} pig manure for the late-rice, respectively, Taoyuan of Hunan province. (b) Continuous flooding with incorporation of 0.75t hm^{-2} green manure for the early-rice, Changsha of Hunan province. (c) Continuous flooding without OM incorporation, Guangzhou of Guangdong province. (d) Continuous flooding with incorporations of 0.6t hm^{-2} bio-gas residues for the early- and the late-rice season, respectively, Hangzhou of Zhejiang province.

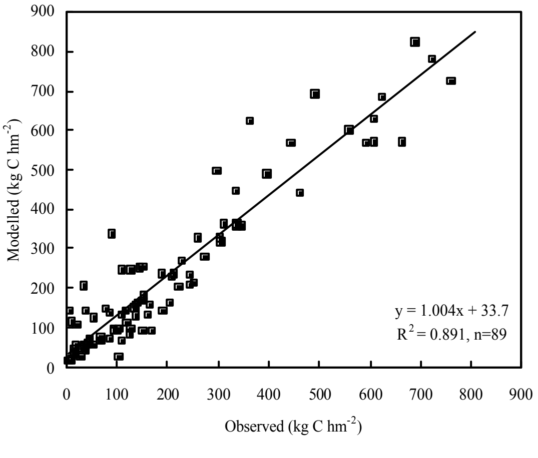

Fig. 3 Correlation of modeled with observed seasonal total CH_4 emission from rice paddies in China.

4.0 CONCLUSIONS

Modification to the original CH_4 emission model indicated that the present model CH4MOD could well describe the processes of CH_4 production and emission from rice cultivation under various soils, climates and agricultural practices including water regime and organic matter application. Reliable estimates of CH_4 emission from rice paddies on regional scale would be possible when the database of soils, climates and agricultural practices are available.

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