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A process-based model for methane emissions from irrigated rice fields: experimental basis and assumptions

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Abstract

In this paper, we review the process-level studies that the authors have performed in rice fields of Texas since 1989 and the development of a semi-empirical model based on these studies. In this model, it is hypothesized that methanogenic substrates are primarily derived from rice plants and added organic matter. Rates of methane (CH_4) production in flooded rice soils are determined by the availability of methanogenic substrates and the influence of climate, soil, and agronomic factors. Rice plant growth and added carbon control the fraction of CH_4 emitted. The amount of CH_4 transported from the soil to the atmosphere is determined by the rates of production and the emitted fraction. Model calibration against observations from a single rice-growing season in Texas, USA, without organic amendments and with continuous irrigation demonstrated that the seasonal variation of CH_4 emission is regulated by rice biomass and cultivar type. A further validation of the model against measurements from irrigated rice paddy soils in various regions of the world, including Italy, China, Indonesia, Philippines, and the United States, suggests that CH_4 emission can be predicted from rice net productivity, cultivar character, soil texture, temperature, and organic matter amendments.

Introduction

Atmospheric methane (CH_4) is recognized as one of the most important greenhouse gases. Methane, with some 15-30 times greater infrared-absorbing capability than CO_2 on a mass basis, may account for 20% of anticipated global warming (Rodhe, 1990). The concentration of atmospheric CH_4, currently at 1.73 ppm, has been increasing at a rate of about 1% yr^{-1} but recently has slowed to approximately 0.5% yr^{-1} (Steele et al., 1992) and may be approaching a near steady state (Dlugokencky et al., 1998). The current burden of CH_4 in the atmosphere is approximately 4,700 teragrams (1 $Tg=10^{12}$ g). Recent estimates suggest an annual global CH_4 emission of approximately 550 Tg with 375 Tg from anthropogenic sources. The contribution from rice agriculture is estimated to range from 20 to 100 Tg with an average of 60 Tg (Denier van der Gon, 1996).

Many reports over the past decade have given the magnitudes of the sinks and sources for CH_4. Natural and agricultural wetlands have received particular attention because of their importance in global balances, inverse modeling, and tracer studies. Studies of the last several years have provided a wealth of information on the in situ processes and environmental controls of trace gas production and exchange, but they have done little to reduce the uncertainty in regional and country estimates of the exchange. Advances are needed in how to meaningfully scale measurements from point sources to a regional or larger scale. A first step in scaling field measurements to a regional or global scale is the development of predictive models based on process and environmental factors. In this paper, we review the process-level studies that the authors have performed in rice fields of Texas since 1989 (Sass & Fisher, 1997) and the development of a semi-empirical model based on these studies (Huang et al., 1998a). Rice fields, rather than natural wetlands, were studied because they provide an appropriate system to begin to address these ends. They are primarily composed of a single plant variety; can be tightly managed with respect to key variables such as planting times, flooding, and fertilization, and further, rice agroecosystems are widely distributed throughout many of the world's climate zones.

Model rationale and hypotheses

The processes involved in CH_4 emission from flooded rice fields to the atmosphere include CH_4 production in the soil by methanogens, CH_4 oxidation within oxic zones of the soil and floodwater by methanotrophs, and vertical transport of the gas from the soil to the atmosphere.

Methane is produced in the terminal step of several anaerobic microbial degradation chains. The metabolic pathways leading to CH_4 production include fermentation of methylated compounds and CO_2 reduction with molecular hydrogen (Takai, 1970; Conrad, 1989; Ferry, 1993). Acetate fermentation has been estimated to account for 50-90% of the CH_4 produced in rice fields (Burke & Sackett, 1986; Schütz et al., 1989a; Thebrath et al., 1992; Rothfuss & Conrad, 1993). The amount of CH_4 produced in flooded rice soils is primarily determined by the availability of methanogenic substrates and the influence of environmental factors. The sources of organic carbon for methanogenic substrates are primarily rice plants via root exudation, root senescence, and plant litter (Holzapfel-Pschorn et al., 1986; Schütz et al., 1991; Kludze et al., 1996) or added organic matter for fertilization (Schütz et al., 1989a; Yagi & Minami, 1990; Sass et al., 1991; Cicerone et al., 1992; Denier van der Gon & Neue, 1995). Emissions from soil organic carbon mineralization have been reported from other studies (Holzapfel-Pshorn, et al., 1986) but were essentially unobserved in Texas studies (Sass et al., 1990; Tyler et al., 1997). In these studies, control plots in unplanted fields generally showed little or no CH_4 emissions until short-term bursts of CH_4 were observed late in the season. These emissions were attributed to carbon sources from weeds and/or algal blooms in the floodwater developing at that time. The total seasonal CH_4 emissions from unplanted plots averaged less than 4% of emissions from plots planted to rice. The lack of emissions from soil organic carbon may be due to the management of the Texas fields. In general, they were fallow the season before experimental use and were kept fairly aerated during that time by plowing and disking to reduce weed crop formation. Also, these experimental soils are low in organic carbon (approximately 1.5%). In applying the model to emissions from China (Huang et al., 1998b), the model was modified in terms of emission calculations from the late crop of double cropping situations. This modification was done to take into account residual soil organic carbon remaining from the first crop. The analysis is essentially the same as that which would be required in the general case of soil organic carbon from areas of high soil organic carbon.

The environmental factors affecting CH_4 production include soil texture (Neue et al., 1994; Sass et al., 1994), climate (Schütz et al., 1990; Sass et al., 1991), and agricultural practices, such as water regime and management (Inubushi et al., 1990a,b; Sass et al., 1992; Lewis, 1996; Yagi et al., 1996).

Plant-mediated transport is the primary mechanism for the emission of CH_4 from rice fields, with approximately 90% of CH_4 transported to the atmosphere through the aerenchymal system of the rice plants (Cicerone & Shetter, 1981; Holzapfel-Pschorn et al., 1986; Schütz et al., 1989b). Under high organic fertilization, ebullition can play a significant role in CH_4 transport. Although ebullition does not appear to be significant in Texas soils, the model is not dependent on the specific mode of CH_4 transport.

The rice aerenchymal system not only transports CH_4 from the flooded rice to the atmosphere but also promotes the movement of atmospheric oxygen into the rhizosphere supporting root respiration and CH_4 oxidation (De Bont et al., 1978; Conrad & Rothfuss, 1991; Gerard & Chanton, 1993).

Experimental basis for the model

Simulation model equations

With an understanding of the processes of CH_4 production, oxidation, and emission, it is hypothesized that the rate-determining step in the process is that of CH_4 production with a time lag between production and emission of less than 3 h (Sass et al., 1991). Daily rates of CH_4 production in flooded rice soils are primarily dependent upon the availability of carbon substrates from rice plants and added organic amendments and influenced by the temperature, texture, and redox state of the soil. The emitted fraction of CH_4 is then determined by the extent of bacterial oxidation of the produced CH_4 (Huang et al., 1998a).

In the absence of other organic inputs, the daily amount of carbohydrate derived from rice plants, C_R ($g\ m^{-2}\ d^{-1}$), is postulated to be dependent on the rice cultivar and biomass represented by the allometric function:

$$C_R = \alpha \times VI \times SI \times TI \times W^{1.25} \quad (1)$$

where α ($g^{-.25}$ d^{-1}) is an empirical constant, VI (dimensionless) identifies the dependence on rice variety, SI (dimensionless) characterizes the effect of soil texture, TI (dimensionless) is a soil temperature index, and W (g m^{-2}) is the rice aboveground biomass on a given day (Huang et al., 1998a). The factors SI and TI are explained below. The exponential factor of 1.25 relating carbon substrate to biomass was obtained from a best-fit analysis as an empirical parameter (Huang et al., 1998a).

When organic inputs are present, the additional daily amount of carbohydrates is represented by

$$C_{OM} = SI \times TI \times (k_1 \times OM_N + k_2 \times OM_S) \quad (2)$$

where C_{OM} (g m^{-2} d^{-1}) is the daily amount of carbohydrate degraded from organic amendments, OM_N and OM_S (g m^{-2}) represent the amount of nonstructural and structural components, respectively, and k_1 and k_2 (d^{-1}) represent the first-order decay rates of the two components (Huang et al., 1998a). If the model is applied to situations where an appreciable amount of soil organic carbon is present and is mineralized during the season, this source could possibly be handled by this same treatment since organic amendments are the ultimate source of this carbon. Different values of k_1 and k_2 may need to be applied in these cases.

The daily production rate of CH_4 by methanogenic bacteria, P (g m^{-2} d^{-1}) is then represented by

$$P = 0.27 \times F_{Eh} \times (C_R + C_{OM}) \quad (3)$$

where F_{Eh} (dimensionless) describes the time development of the soil redox potential and 0.27 assumes that three moles of CH_4 is derived from one carbohydrate unit and is the ratio of their molecular weights (0.27 = 3 $CH_4/C_6H_{12}O_6$) (Huang et al., 1998a).

Having determined the daily CH_4 production rate, the emission rate, E (g m^{-2} d^{-1}), is given by

$$E = P \times E_f \quad (4)$$

where E_f is the emitted fraction of CH_4 determined by the rate of CH_4 oxidation and is simulated by

$$E_f = 0.55 \times (1 - W/W_{max})^{0.25} \quad (5)$$

where W_{max} (g m^{-2}) is the seasonal maximum aboveground biomass. The constant 0.55 represents the initial fraction of produced CH_4 which is emitted (Huang et al., 1998a).

Data needed to use the model

Emission values are calculated on a daily basis and summed over the season to give a seasonal estimate of CH_4 emission. To evaluate the model, one needs daily estimates of rice crop aboveground biomass and soil temperature; the relative emission potential of the rice cultivar used; the percent sand in the field soil; and the amount, timing, and composition of the organic amendments. Huang et al. (1998a) suggest that daily biomass, W, can be approximated by using the logistic growth equation:

$$dW/dt = r \times W \times (W_{max} - W)/ W_{max} \quad (6)$$

where r is the intrinsic growth rate for aboveground biomass and W_{max} can be approximated from the grain yield, GY, by the equation (Huang et al., 1997b):

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

The intrinsic growth rate, r, was experimentally determined to be 0.08 ± 0.02 d^{-1} based on 17 cases from four different cultivars and with 10–13 biomass measurements in each case (Huang et al., 1998a).

A simplified version of the model is also presented (Huang et al., 1998a) in which seasonal emission values can be estimated using integrated or average values of the time-dependent parameters.

Explicit and implicit assumptions in the model

Several assumptions have been incorporated into this model, both explicit and implicit. The explicit assumptions are easily recognized in that they appear as factors in the above equations. The implicit assumptions are less easily recognized but nevertheless are quite important in understanding how the model can be constructed based on experimental evidence.

Methane is produced by bacterial activity in a highly reduced soil environment. The primary driving force assumed in the model for the production of CH_4 is the availability and quantity of organic substrate supplied by the rice plant and other organic additions. A part of the produced CH_4 is reoxidized in oxidizing zones of the soil while the rest is transported to the atmosphere, mainly via the rice plants (Nouchi et al., 1990) with a lesser amount emitted by diffusion and ebullition through the soil-water system except in systems with very high or very decomposable organic amendments.

Equations 1, 2, and 3 assert that under conditions of constant soil temperature, soil composition, and soil redox potential, daily CH_4 production is proportional to the daily carbon substrate production derived from two sources: rice plants and added organic amendments. Implicit in this statement is the assumption that the conversion time from substrate formation to CH_4 production and emission is less than 1 d. In our studies, we have measured soil acetate turnover times ranging up to 7–10 h during the first 5 wk of the season, dropping to less than 1 h during the later half of the growing season (Sigren et al., 1997a). These values are less than the 10-16 h estimated by Schütz et al. (1989a) and 16 h estimated by Krumböck & Conrad (1991). However, all three estimates suggest that soil substrate pools in rice fields are turned over in less than 1 d. Temperature studies of CH_4 production and emission indicate that CH_4 production is the rate-determining step and that emission through the rice plant occurs effectively instantaneously (Sass et al., 1991).

The model also assumes that acetate is the major precursor of CH_4 in rice fields. Stable isotope measurements suggest that in our fields the percentage of CH_4 produced from acetate fermentation ranges from 57 to 80% (Tyler et al., 1997). Schütz et al. (1989a) estimated that acetate accounted for 50–70% of CH_4 production, whereas Thebrath et al. (1992) said it accounted for 80–90%. Regardless of the magnitude of this fraction, the model results will be valid if the ratio of CH_4 production from acetate to that from carbon dioxide reduction remains constant in all rice fields and during the whole season. The similarity of these three findings from different areas of the world suggests that this may be a reasonable assumption.

In Equation 1, the daily amount of carbon substrate and hence the daily amount of carbon substrate derived from rice plants of a particular variety is indicated to be directly related to the current aboveground biomass. This assumption has been evaluated and validated from several studies (Huang et al., 1997b).

In Equation 4, daily CH_4 emission is related to CH_4 production by multiplying by a time-dependent factor defining the fraction of CH_4 not oxidized. This assumption is discussed at length in Huang et al. (1998a). In the model, oxidation is assumed to range from 55% early in the season to approximately 80% during the late season. Some research suggests that more than 50% of the generated CH_4 is oxidized during the early phase of the vegetation period, whereas up to 90% may be consumed during the late season of rice maturation (Schütz et al., 1989b; Sass et al., 1992; Sigren et al., 1997a). Other studies suggest a lower amount of oxidation. Epp and Chanton (1993) reported that CH_4 oxidation in the rhizosphere of 3-mo-old rice plants ranged from 14 to 52%. A good review of the difficulties inherent in measuring the extent of methanotrophy in rice ecosystems is presented by Denier van der Gon (1996).

Correlations between CH_4 emission and aboveground biomass have been reported in subtropical sawgrass system (Whiting et al., 1991) and across a variety of agricultural and subarctic natural wetland ecosystems (Whiting & Chanton, 1993). Seasonal CH_4 emissions over a 5-yr period have been quantitatively described over a wide range of conditions (Huang et al., 1997a,b). In experiments carried out in Texas in 1994 and 1995, Huang et al. (1997b) showed that, over a 10-wk period after permanent flooding, total seasonal CH_4 emission was positively correlated with rice aboveground biomass ($r^2 = 0.845$, $n = 11$). A very strong dependence of daily CH_4 emission on aboveground vegetative biomass ($r^2 = 0.887$, $n = 93$) and on root biomass ($r^2 = 0.816$, $n = 33$) was also observed. Calculation from three developmental periods (vegetative, reproductive, and ripening) of rice plants indicated that more than 75% of total seasonal CH_4 was emitted during the last 5-wk period in concert with reproductive and ripening stages, while rice biomass production during the same period amounted to approximately 50% of the seasonal total. Carbon released as CH_4 was found to be approximately equivalent to 3% and 4.5% of photosynthetically fixed carbon in the biomass for low- and high-emitting cultivars.

Little attention has been paid to the relationship between CH_4 production and aboveground biomass. Sass et al. (1990) reported that daily CH_4 emissions from a flooded rice soil is highly correlated with rice aboveground biomass ($r^2 = 0.92$) and that CH_4 production is correlated with root biomass ($r^2 = 0.56$). A reanalysis of the data from the 1990 study shows a correlation between CH_4 emission and aboveground biomass with $r^2 = 0.79$. During an extended study of the effects of soil redox potential on CH_4 production and emission (Lewis, 1996), extensive data were collected in 1994 on CH_4 production levels as a function of soil depth. These data have been examined against aboveground biomass data collected concurrently from

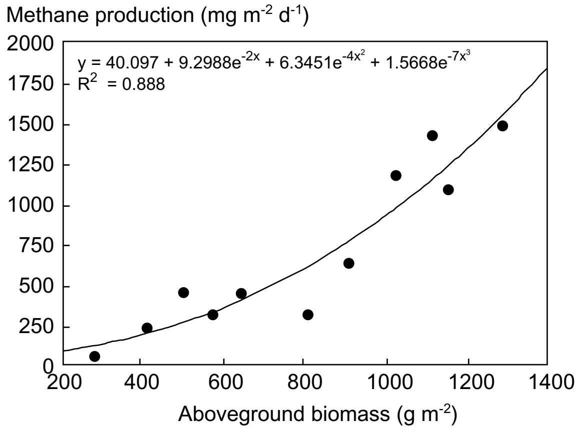

Figure 1. Correlation between CH_4 production and aboveground biomass data collected in 1994. Solid circles represent experimental measurements. The curve shown is a best-fit third-order polynomial of these data with accompanying equation

the same field plots (Huang et al., 1997b). The results, presented in Figure 1, indicate a good correlation between CH_4 production and aboveground biomass. A linear best-fit correlation results in an r^2 of 0.86. The curve shown is a best-fit third-order polynomial (r^2= 0.89). The model postulates a relationship between daily CH_4 production and aboveground biomass raised to the 1.25 power, which closely resembles the shape of the polynomial shown in Figure 1 and results in an r^2 value of 0.89.

Although a strong correlation can be shown to exist between CH_4 production and biomass for a single cultivar, the absolute relationship varies from cultivar to cultivar. That is, some cultivars appear to allocate more of the products of photosynthesis to root exudation than others do. In 1993, CH_4 emissions from 10 cultivars commonly used in Texas were investigated (Sass & Fisher, 1997). The period of maturation ranged from 114 d (Labelle) to 140 d (Jasmine). Semidwarf and conventional cultivars are represented with plant heights ranging from 90 cm (Lemont) to 140 cm (Dawn). Cultivars with yield potentials from medium to high as well as medium and long grain length are represented. Seasonal CH_4 emissions were found to vary from 17.95 to 41.05 g m^{-2}. A nonparametric test of medians was performed on the seasonal emissions of the 10 cultivars. The cultivars were sorted into three groups with the low emission group (Labelle and IR36) significantly different from the high emission group (Mars and Della), but not from the intermediate emission group (Lemont, Lebonnet, Dawn, Katy, Brazos, and Jasmine).

In 1994, the CH_4 emission from three of these cultivars were again measured (Sass & Fisher, 1997), one from each group: Mars, Labelle, and Lemont. The emission data were very similar to the 1993 study. The integrated seasonal emissions in 1994 vs 1993, respectively, were 34.26 g vs 34.06 g for Mars; 15.95 g vs 17.95 g for Labelle; and 17.97g vs 24.52 g for Lemont.

Other studies of CH_4 emissions from different cultivars have been reported. Methane emissions from eight different cultivars grown under similar conditions near New Delhi, India, differed by as much as an order of magnitude (Parashar et al., 1991). A study of five rice cultivars in irrigated fields near Beijing, China, indicated that CH_4 emission during the tillering-flowering stage varied by a factor of two (Lin, 1993).

Organic amendments such as rice straw or green manure increase CH_4 production and emission (Neue & Sass, 1994) by enhancing the reduction of soils and providing additional carbon sources. Different organic amendments vary considerably in their effectiveness in the production of CH_4 (Cicerone et al., 1992; Watanabe et al., 1993). Yagi & Minami (1990) show that the effectiveness of various organic amendments in producing CH_4 depends on the percentage of readily mineralized carbon (RMC). As shown in Equation 2, the model accounts for differences among various added amendments by dividing the available carbon substrate into two components in a first-order decay: a faster decomposing ($k_1 = 0.027\ d^{-1}$) portion of “nonstructural” or RMC and a slower decomposing ($k_2 = 0.002\ d^{-1}$) portion of “structural” carbon (see Murayama, 1984). In field studies (Sass, unpubl.), we have investigated the decomposition of rice straw during an entire flooded rice-growing season. Decomposition was measured by weighing soil-submerged nylon mesh bags of rice straw at various intervals during the season. Comparison of decomposition rates measured in this study with the rates given in Equation 2 results in a strong correlation ($r^2 = 0.96$) by assuming a rapidly decomposing straw fraction of 16%.

The bacterial processes involved in the processes leading to CH_4 emission should be temperature- and soil structure-dependent. These dependencies are represented in the model (Equations 1 and 2) by a temperature index, TI, and a soil index, SI.

The model accounts for soil temperature through TI, defined by the Arrhenius relationship:

$$TI = Q_{10}^{(Tsoil\text{-}30/10)} \text{ with } T_{soil} = 30 \qquad (8)$$
$$\text{for } 30 \le T_{soil} \le 40\ °C$$

Values of Q_{10} for methanogenesis range widely in various wetland ecosystems (Segers, 1998). Field measurements in irrigated rice systems suggest a Q_{10} range from 2 (Khalil et al., 1991) to 4 (Schütz et al., 1989a). A model value of 3 was assigned to Q_{10} (Huang et al., 1998a) based on field and incubation measurements (Sass et al., 1991). In this study, it was shown that both CH_4 production (anaerobic laboratory incubations) and CH_4 emission (diel field experiments) followed the same temperature relationships with good agreement with the Arrhenius relationship. In the same study, diel soil temperatures varied by as much as 4 °C before canopy closure and by 3 °C after canopy closure later in the season. There was no observable time shift between trends in the measured soil temperature and CH_4 emission, indicating a rapid CH_4 production and emission response to temperature. Daily mean soil temperatures ranged by approximately the same amount throughout the season, but daily CH_4 emission values did not directly correlate with daily mean soil temperature, possibly due to the influence of other overriding factors such as plant growth and development.

Soil bacterial activity and hence CH_4 production, oxidation, and emission are found to be influenced by soil substrate conditions, mainly texture. Sass et al. (1994) compared a variety of CH_4 emission data sets obtained over a 4-yr period from three adjacent different soil types at the Texas Agricultural Experiment Station near Beaumont, Texas. A variety of physical and chemical properties of the soils were compared with CH_4 emissions from fields planted with a single rice cultivar. It was observed that seasonal CH_4 emissions directly correlated with the percent sand in the soils. Soil percent sand ranged from 4.3 to 32.5%, while seasonal CH_4 emission values ranged from 13.6 to 36.3 g m^{-2}. The results of this study were directly incorporated into the model (Huang et al., 1998a) through the soil index, SI, as

$$SI = 0.3225 + 0.0225*\text{sand }\% \qquad (9)$$

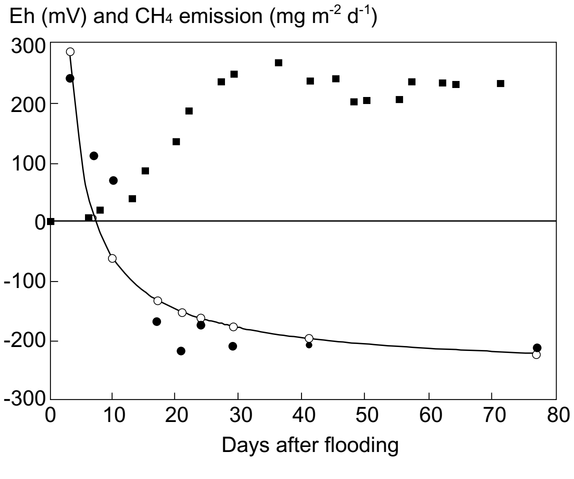

Figure 2. Methane emission in mg m^{-2} d^{-1} (solid squares) and soil Eh in mV (solid circles) measured in a Texas rice field in 1994. The Eh values are compared with the analytical expression Eh = 1390 $t^{-0.87}$-250 (see text) represented by the open circles and corresponding solid line

This relationship has been modified in the model to scale the effect of soil texture to be unity when the soil sand percentage is 30%. Although the experimental evidence for this effect was based on CH_4 emission studies (Sass et al., 1994; Huang et al., 1997a), it is applied in the model in calculating CH_4 production. This application is justified by the observation that production and emission are very tightly coupled, with production being the rate-determining step in the process (Sass et al., 1991).

The temporal development of CH_4 production and emission is dependent on the reducing condition of the bacterial soil environment. The flooding of rice fields begins a series of events that lead to reduced soil conditions in which methanogenic activity can occur, beginning with the consumption of molecular oxygen by aerobic soil bacteria (Bohn et al., 1985). After oxygen depletion, a series of other terminal electron acceptors (NO_3^-, Mn^{+4}, Fe^{+3}, and SO_4^{-2}) are bacterially reduced, lowering the soil Eh from +250 to –100 mV. The critical soil Eh for the initiation of CH_4 production in laboratory incubations has been reported to be between –150 and –160 mV (Wang et al., 1993). Field soils are more heterogeneous than slurries due to the presence of microsites and soil aggregate structures; therefore in situ critical Eh values may be higher and CH_4 emissions may be observed even though the measured soil Eh has not reached a critical value. At any rate, as seen in Figure 2, initial CH_4 emission and critical soil Eh both develop over approximately the same time interval; approximately 2–3 wk after permanent flooding (Sigren et al., 1997b). The observed Eh is represented analytically by the best-fit equation

$$Eh = 1390\, t^{-0.87} - 250 \qquad (10)$$

where t is the time in days after flooding and the constant 250 represents the normal Eh in mV at the time of flooding (Huang et al., 1998a). This function is compared with experimental values in Figure 2. The development of redox conditions appropriate for methanogenesis depends on the amounts of other terminal electron acceptors in the soils such as iron and manganese. Equation 10 was able to describe the Eh development in soils which contained between 6,570 and 11,348 µg g^{-1} dw soil of total iron and between 905 and 1697 µg g^{-1} dw soil of manganese. During the rice-growing season, the concentration of ferrous iron in these submerged soil increased to steady-state values ranging from 500 to 3,000 µg g^{-1} dw soil (Lewis, 1996). These values compare with studies by Ponnamperuma (1981) in which ferrous concentrations increased to values as high as 600 µg g^{-1} within 1–3 wk of flooding and by Patrick (1981) in which ferrous ion concentrations increased to values greater than 2,000 µg g^{-1}.

The critical effect of the soil redox condition on CH_4 production and emission is thus during the early season. Once the critical value is reached, CH_4 production is dependent on other factors. This effect is treated in the model by a factor F_{Eh} where

$$F_{Eh} = \exp[-1.7\,(150 - Eh)/Eh] \quad \text{with } Eh = -150 \text{ for } Eh < -150 \tag{11}$$

which ranges from 0 to 1 in the early season and equals 1 after a critical value of –150 has been reached or exceeded (Huang et al., 1998a).

In the model, daily CH_4 emission rates are calculated by multiplying production rates by E_f, the emitted fraction of produced CH_4 (Equation 4). If one knows the daily fraction of the produced CH_4 which is oxidized, then E_f would simply be equal to [1 – (fraction oxidized)]. In the model, E_f is approximated by a function of the daily and maximum aboveground biomass (Equation 5). The rationale behind this hypothesis lies in the assumption that soil bacterial activity, including both CH_4 production and oxidation, are coupled to rice plant development. Evidence of the validity of this assumption is presented in Figure 3. Experimentally determined ratios of CH_4 production (laboratory incubations) and emission (in situ field measurements) determined at various times during the growing season are presented from two locations and during four seasons: Vercelli, Italy, 1985 and 1986 (Schütz et al., 1989a) and Beaumont, Texas, 1991 and 1994 (Sass et al., 1992; Lewis, 1996). The same ratio ($E/P = E_f$) was calculated by Equation 5 using biomass data for the Beaumont, Texas 1994 field. Although there is considerable spread in the experimental ratios, there is generally good agreement between them and with calculated values. A gradual decrease with time is noted in the ratio, indicating that the fraction of CH_4 that is oxidized increases during the season. Since the model-calculated E_f for 1994 is in reasonable agreement with all four data sets, it may be reasonable to assume that, in the absence of reliable biomass data, general E_f values may be used in calculating CH_4 emission values. Conversely, if one knows the grain yield, one can calculate the biomass using Equation 7 to obtain the maximum biomass and then Equation 6. The validity of these relationships has been documented by Huang et al. (1997b).

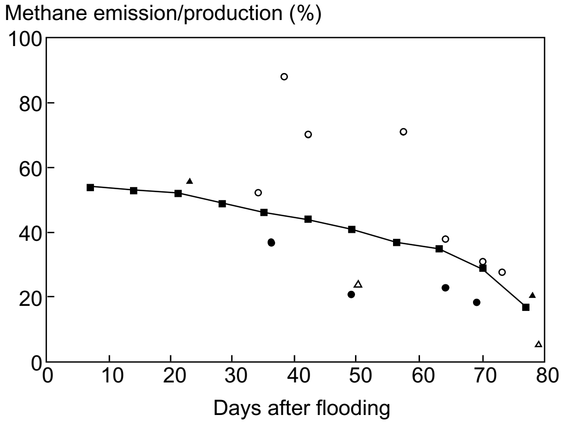

Figure 3. Experimentally determined ratios of CH_4 emission/production (%) determined at various times during the growing season in Vercelli, Italy, 1985 (closed triangles) and 1986 (open triangles) and Beaumont, Texas, 1991 (closed circles) and 1994 (open circles). The same ratio ($E/P = E_f$), calculated by the model equation $E_f = 0.55 \times (1\text{-}W/W_{max})^{0.25}$ using biomass data collected in Texas in 1994 is depicted by the line (closed squares)

Model usage

The model was tested by comparing calculated and reported observed values of seasonal CH_4 emissions from 20 studies in Texas and Louisiana, USA; Vercelli, Italy; Nanjing, Beijing, Sichuan, and Hangzhou, China; Taman Bogo, Indonesia; and IRRI, Philippines (Huang et al., 1998a) with considerable success. These studies were used because literature reports were available which contained the necessary model parameters of soil percent sand, average temperature, and grain yield. The variety used was generally not characterized, so the variety index was set to 1. The average calculated CH_4 emission value was 312 ± 138 mg m^{-2} d^{-1} while the average observed value was 322 ± 144. In a subsequent paper (Huang et al., 1998b), the model was used to calculate CH_4 emission values from China on a provincial scale. The resulting total calculated country emission value was reported to be 9.66 Tg with a range from

7.19 to 13.62 Tg, based on estimates of uncertainties in available data on soils, temperature, grain yields, and rice cultivars. To test the model using readily available data, we have calculated daily and seasonal emissions from a field in Texas and compared the results with data collected in 1994 (Sigren, 1996). The only parameters used were average soil temperature (25.1 °C), variety index (1.0), soil sand content (27.9%), and grain yield (570 g m^{-2}). Calculated and observed daily CH_4 emission values are shown in Figure 4. The calculated seasonal CH_4 emission was 17.50 g m^{-2} and the observed seasonal CH_4 emission was 17.97 g m^{-2} (Sigren, 1996). Before the model can be used with confidence in other regions of the world, it will be necessary to compare daily as well as seasonal calculated and observed emission values. This should be done as more complete information becomes available in the literature or as other scientists attempt to apply this and other models to their data.

Future extensions of the model

The current state of the model makes it particularly applicable to the simulation of CH_4 emissions from irrigated rice fields with a minimal amount of available data on climate, soil texture, rice cultivar, and grain yields. Modifications will be required to account for the effects of field drainage, a normal management practice used by farmers in many parts of the world and a potential strategy for the mitigation of CH_4 emissions (Sass et al., 1992). Also, systems of variable floodwater application such as in rainfed rice agriculture will need to be more carefully characterized before modeling of the process can be accomplished. The model dependence of CH_4 production and emission on rice cultivar as well as biomass is problematic in applying it on a large scale. Recent work in our laboratory indicates that plant height or certain aspects of the rice canopy geometry may be an indicator of the variety index, which would allow the model to be more easily applied in cases where varietal data are lacking. In cases where organic amendments have been applied or where indigenous soil organic carbon is an important source of carbon, CH_4 emissions are very dependent on specific composition and decomposition properties as well as on field management. More work is necessary to be able to simulate CH_4 emissions from such fields, particularly with respect to the pre-treatment (such as composting) the timing of such application (early or late treatment leading to possible partial aerobic decomposition), and the use of animal wastes (which have a much different rate of decomposition than plant matter). The ultimate goal of this type of model is to be able to accurately calculate CH_4 emissions on a regional or larger scale based on available geographic information system data sets and remotely sensed data. This model offers a solid beginning to this goal and a base for future development.

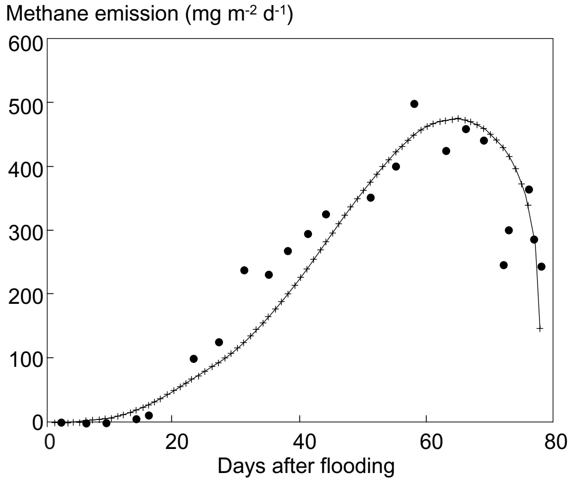

Figure 4. Comparison between observed (closed circles) and calculated (cross and corresponding line) CH_4 emission values from data collected in Texas in 1994

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