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A semi-empirical model of methane emission from flooded rice paddy soils

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Abstract

Reliable regional or global estimates of methane emissions from flooded rice paddy soils depend on an examination of methodologies by which the current high variability in the estimates might be reduced. One potential way to do this is the development of predictive models. With an understanding of the processes of methane production, oxidation and emission, a semi-empirical model, focused on the contributions of rice plants to the processes and also the influence of environmental factors, was developed to predict methane emission from flooded rice fields. A simplified version of the model was also derived to predict methane emission in a more practical manner. In this study, it was hypothesized that methanogenic substrates are primarily derived from rice plants and added organic matter. Rates of methane production in flooded rice soils are determined by the availability of methanogenic substrates and the influence of environmental factors. Rice growth and development control the fraction of methane emitted. The amount of methane transported from the soil to the atmosphere is determined by the rates of production and the emitted fraction. Model validation against observations from single rice growing seasons in Texas, USA demonstrated that the seasonal variation of methane emission is regulated by rice growth and development. 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 methane emission can be predicted from rice net productivity, cultivar character, soil texture and temperature, and organic matter amendments.

Keywords: CH_4 emission, flooded rice soils, global warming, model, rice plant control

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Introduction

Atmospheric methane (CH_4) is recognized as one of the most important greenhouse gases. Rodhe (1990) reported that CH_4 has some 15–30 times greater infrared absorbing capability than CO_2 on a mass basis and may account for 15% of anticipated global warming. The concentration of atmospheric CH_4 has been increasing at a rate of about 1% per year and is currently increasing at $\approx$ 0.5% per year (Steele *et al.* 1992).

Worldwide, irrigated rice cultivation is thought to be a major source of atmospheric CH_4 (Schütz *et al.* 1991; Neue *et al.* 1994) and may contribute 10–30% of the total emitted into the atmospheric methane pool (Cicerone & Oremland 1988; Houghton *et al.* 1990). A recent estimate by IPCC (1992) suggests the most probable value of methane emitted from global rice paddies is 60 Tg per year, ranging from 20 to 100. Projections based on population growth rates in countries where rice is the main food crop indicate that rice production must increase 65% by 2020 to meet the rice demand for the growing population (IRRI 1989), which will most likely be accompanied by an increase in methane emissions (Bouwman 1991; Anastasi *et al.* 1992).

Because methane fluxes cannot be measured continuously in all locations of rice growing areas, a reliable estimate is required to evaluate the contribution of rice agriculture to global methane emissions and, hence, to develop mitigation techniques for reducing these emissions. Efforts have been made to estimate methane emissions from rice paddy soils by extrapolating field measurements to a regional or global scale (Cicerone & Shetter 1981; Holzapfel-Pschorn & Seiler 1986; Schütz *et al.* 1989b; Neue *et al.* 1990; Watson *et al.* 1992; Wang *et al.* 1994); by assuming methane emission as a constant

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fraction of rice net primary productivity (Aselmann & Crutzen 1989; Taylor *et al.* 1991; Bachelet & Neue 1993; Bachelet *et al.* 1995); or by correlating methane emissions with rice grain production (Anastasi *et al.* 1992) or with organic matter inputs (Kern *et al.* 1995). However, the available data base on methane emissions from different rice growing regions is insufficient to cope with the multitude of varying climatic and edaphic factors for a reliable extrapolation on a regional or global scale (Shearer & Khalil 1993; Wassmann *et al.* 1993). The carbon emitted as methane is not a constant fraction of rice net primary productivity, but rather is affected by soil properties and rice varieties (Huang *et al.* 1997a).

To obtain reliable estimates of methane emissions from regional or global rice paddies, attention must be focused on an examination of methodologies by which the current high variability in the estimates might be reduced. One possible way to do this is the development of predictive models. The model derived with this objective should be realistically descriptive of observed results and capable of extrapolation to a regional and/or a global scale after necessary calibration. Based on supplies of carbon substrate for methanogens by rice primary production and soil organic matter degradation, and on environmental controls of methanogenesis, Cao *et al.* (1995) developed a model to simulate methane emissions from flooded rice paddy soils. A validation of the model with a field trial from Italian rice paddies suggested that methane emission can be predicted from a set of environmental variables in that particular area (Cao *et al.* 1995).

On the basis of our multiyear studies (Sass *et al.* 1990, 1991a,b, 1992, 1994; Sass & Fisher 1995; Sigren *et al.* 1997a; Huang *et al.* 1997a,b), a semiempirical model is developed to predict methane emission from flooded rice fields. A simplified version of the model is also derived to predict methane emission in a more practical manner. The model is focused on the contribution of rice photosynthetic production to the processes of methane production, oxidation and emission and the influence of environmental factors on these processes. The long-term objectives of this study are (i) to develop methane emission models on a regional and/or global scale by linking remotely sensed crop data and special databases on climate, soils, and land use and management; (ii) to calibrate and/or verify model predictions with reliable experimental data; (iii) to determine how much methane is currently emitted and to predict, by applying the models, how much methane will be emitted in the future from rice paddies without a change in present agronomic practices; and (iv) to develop agricultural practices that can reduce methane emissions without reducing rice production.

Rationale and hypothesis

The processes involved in methane emission from flooded rice paddies to the atmosphere include methane production in the soil by methanogens, methane oxidation within oxic zones of flood water and the soil by methanotrophs, and vertical transport from soil to the atmosphere.

Methane is produced in the terminal step of several anaerobic degradation chains. The biochemical pathways leading to the production mainly 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 methane produced in rice paddies (Burke & Sackett 1986; Schütz *et al.* 1989a; Thebrath *et al.* 1992; Rothfuss & Conrad 1993). The amount of methane 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 derived either from rice plants via root exudation and biomass litter (Holzapfel-Pschorn *et al.* 1986; Schütz *et al.* 1991; Kludze *et al.* 1995) or added organic matter (Schütz *et al.* 1989b; Yagi & Minami 1990; Sass *et al.* 1991b; Cicerone *et al.* 1992; van Denier der Gon & Neue 1995). The environmental factors affecting methane production include soil texture (Neue *et al.* 1994; Sass *et al.* 1994), climate (Schütz *et al.* 1990; Sass *et al.* 1991b), 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 methane from rice paddies, with $\approx$ 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.* 1989a). The rice aerenchymal system not only transports methane from the rhizosphere to the atmosphere but also promotes the movement of atmospheric oxygen into the rhizosphere supporting methane oxidation (De Bont *et al.* 1978; Conrad & Rothfuss 1991; Gerard & Chanton 1993). More than 50% of the generated methane is oxidized during the early phase of the vegetation period, whereas up to 90% is consumed during the late season of rice growing (Schütz *et al.* 1989a; Sass *et al.* 1992). Consequently, the emitted fraction of the produced methane decreases with rice growth and development.

With an understanding of the processes of methane production, oxidation and emission, we believe that rice growth and development is a principal parameter governing these processes in all flooded rice paddies, regardless of where they are located. In the present study, it was hypothesized that methanogenic substrates are mainly derived from rice plants and added organic matter. Rates of methane production in flooded rice soils are dependent upon both substrate supply and the influence of environmental factors. The fraction of methane emitted is controlled by rice growth and development. Rates of methane transported from soil to

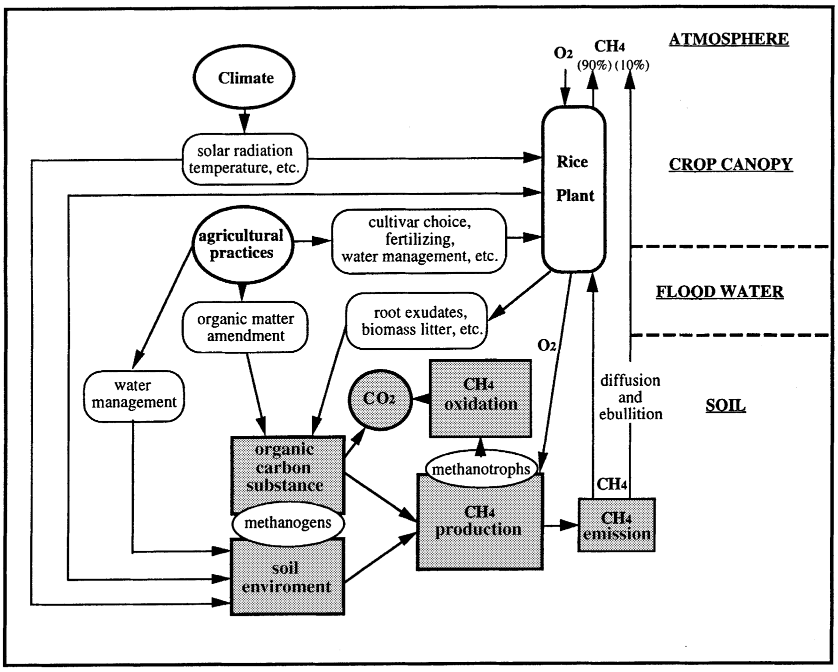

Fig. 1 Conceptual explanation for modelling the processes of methane production, oxidation and emission from flooded rice paddy soils. The arrow lines represent mass flow or interactions between defined quantities

the atmosphere are determined by the rates of production and the emitted fraction. Figure 1 shows the conceptual explanation for modelling the processes of methane production, oxidation and emission from flooded rice paddy soils.

Simulation model

Availability of substrates for methanogens

Carbon sources associated with rice plants. Studies focused on the effect of rice growth on methanogenic substrate supply and hence methane production from irrigated rice fields in Italy (Schütz *et al.* 1989a), the United States (Sass *et al.* 1990; Lewis 1996), and China (Shangguan *et al.* 1993) illustrated that methane production in flooded paddy soils was enhanced by rice growth and development. Methane production in the direct vicinity of rice plants was generally higher than that between the rows of rice plants (Sass *et al.* 1990; Shangguan *et al.* 1993) and enhanced production was associated with rice growth (Schütz *et al.* 1989a; Sass *et al.* 1990; Lewis 1996). More recent studies have shown that rice plants contribute significantly to methanogenic substrates (Kludze *et al.* 1995; Sigren 1996). The soil acetate concentrations from plots of rice-planted field in Texas, the United States, for example, were detected to vary from 14.2 to 1216.5 μM over a 1994 growing season, while those from adjacent plant-free plots were less than 5.5 μM (Sigren 1996). Consistent with this negligible soil acetate concentration, rates of methane production and emission from plant-free plots were negligible (this lab unpublished data).

By comparing a variety of methane emission data sets obtained over a four-year period from three different soils planted with the same cultivar, Sass *et al.* (1994) reported that a correlation existed between seasonal methane emission and the percentage sand in the soils. Measurements also indicated that the intervarietal difference in methane emission is attributable to the different amount of organic carbon associated with rice cultivars (Sigren 1996), which results in the difference in methane production (Lewis 1996), rather than the difference in gas transport (Sigren *et al.* 1997a).

Although the methanogenic substrates in the rhizosphere have been connected with rice plants (Holzapfel-Pschorn *et al.* 1986; Schütz *et al.* 1991; Kludze *et al.* 1995; Sigren 1996), the quantitative relationship between them is still poorly known. The observed correlation of methane production with live underground biomass of rice (Sass *et al.* 1990) and the correlation of methane emissions with photosynthetic production in rice (Sass *et al.* 1990; Huang *et al.* 1997a,b), sawgrass (Whiting *et al.* 1991) and across a variety of agricultural and natural wetland ecosystems (Whiting & Chanton 1993) suggest that the carbon emitted as methane is associated with plant photosynthetic production. $^{13}CO_2$ uptake experiments with rice plants by Minoda & Kimura (1994) and Minoda *et al.* (1996) indicated that part of photosynthetically fixed ^{13}C was transferred to plant roots, exuded into the rhizosphere and released as methane within a short time period, typically 3–11 h. We postulate that some portion of photosynthetic carbohydrates, depending on plant metabolism, would be liberated into the rhizosphere via root exudation and/or plant biomass litter. These carbohydrates would then be converted by fermentative and acetogenic bacteria into methanogenic substrates. In the absence of any other organic inputs, the amount of carbohydrates derived from rice plants for fermentative production of methane precursors was assumed as an allometric function of rice biomass by

$$C_R = \beta_0 W^{\beta 1}, \tag{1}$$

where C_R represents carbohydrates (g m^{-2} d^{-1}) derived from rice plants and W is rice above-ground biomass (g m^{-2}) in a given day. Coefficients β_0 and β_1 are empirical parameters. The β_0 (d^{-1}) was assumed to be dependent on rice cultivar and soil texture by

$$\beta_0 = \alpha \times \mathrm{VI} \times \mathrm{SI}. \tag{2}$$

In (2), α (d^{-1}) is an empirical constant. VI is a variety index identifying relative difference in methane production among rice varieties (Huang *et al.* 1997a). SI is a dimensionless soil index to characterize the relative effect of soil texture on methane production/emission and linked with soil sand content (Huang *et al.* 1997a).

$$\mathrm{SI} = 0.325 + 0.0225\mathrm{SAND}, \tag{3}$$

where SAND represents sand percentage in a given soil. The SI is less than one for sand percentage lower than 30 and larger than one for sand percentage higher than 30.

Carbon Sources Associated with Organic Matter Amendments. Incorporated organic matter, such as rice straw and green manure, represents the main component of the initial stock of organic matter in rice soils. Decomposition of these organic materials is thought to be the predominant source of methanogenic substrates in the early stages of the vegetative period (Watanabe & Roger 1985).

The incorporated organic matter was assumed to be comprised of two kinds of components: nonstructural and structural carbohydrates. The nonstructural carbohydrates, such as sugars and starches, are easily decomposed components and the structural carbohydrates refer to those more recalcitrant compounds (Hunt 1977; Murayama 1984). Decomposition of organic matter is affected by soil moisture and temperature (Tate 1987; Parton *et al.* 1993). The decay rate of organic matter was also found to increase as soil sand content increases (Parton *et al.* 1993). In permanently flooded rice soils, the water condition was assumed to be suitable for organic matter decomposition. The process of decomposition was simulated with a first-order kinetics equation (Tate 1987; van Denier der Gon & Neue 1995) as:

$$C_{OM} = \mathrm{SI} \times \mathrm{TI} \times (k_1 \times \mathrm{OM_N} + k_2 \times \mathrm{OM_S}) \tag{4}$$

$$\mathrm{TI} = Q_{10}^{(T_{soil}-30/10)}\ (T_{soil} = 30 \text{ for } 30 < T_{soil} \leqslant 40\ ^{\circ}\mathrm{C}), \tag{5}$$

where C_{OM} is the daily amount of carbohydrate degraded from organic matter amendments (g m^{-2} d^{-1}). The impact of soil texture and soil temperature on decomposition was quantified by the soil index (SI) in (3) and a soil temperature index (TI) in (5), respectively. Q_{10} is a temperature coefficient with a value of 3.0 and T_{soil} is the daily average soil temperature (°C). The optimal temperature for decomposition was assumed to range from 30 to 40 °C (van Denier der Gon & Neue 1995; Parton *et al.* 1993). OM_N and OM_S represent nonstructural and structural components (g m^{-2}), respectively. Constants k_1 and k_2 represent the first-order decay rate for OM_N and OM_S under optimal soil moisture and soil temperature. Referring to studies by Murayama (1984) and van Denier der Gon & Neue 1995), k_1 and k_2 were taken values of 2.7×10^{-2} and 2×10^{-3} d^{-1}, respectively.

Dependence of methane production on substrate supply and environment

Effect of soil redox potential. Flooded soils provide a low redox potential (Eh) and methane is produced only after the Eh has been lowered to sufficiently negative values, typically less than – 100 mv (Masscheleyn *et al.* 1993). Measurements from flooded rice fields (Cicerone *et al.* 1983; Lewis 1996) showed that the Eh values in the top 10 cm depth of soil were relative high and declined slowly during the first three-week period after flooding. Taking a value of −150 mv as a critical Eh for methane production (Wang, Z.P. *et al.* 1993), the effect of soil Eh on methane production was described in (6). The decline of soil Eh after flooding was functioned as (7) on the basis of field measurements by Lewis (1996).

$$F_{Eh} = \exp[\mathrm{C}^{(150+\mathrm{Eh}/150)}]\ (\mathrm{Eh} = -150 \text{ for } \mathrm{Eh} < -150) \tag{6}$$

$$\mathrm{Eh} = 1390\ t^{-0.87} - 250, \tag{7}$$

where F_{Eh} is a reduction factor of soil redox potential, $0 < F_{Eh} \leqslant 1.0$. Coefficient C is an empirical constant and the time variable is expressed by t in days after flooding, respectively.

Influence of soil temperature. Influence of temperature on methane production rates has been shown in culture experiments (Vogels *et al.* 1988) and in measurements with soil samples incubated at different temperature levels (Conrad 1989; Sass *et al.* 1991b). Methane emission was also found to respond to the diel variation of temperature (Schütz *et al.* 1989b; Sass *et al.* 1991b). A close relationship between the mean values of CH_4 emission rates and soil temperatures throughout the rice vegetative period has been reported by Holzapfel-Pschorn & Seiler (1986) from an Italian rice field. However, no apparent seasonal dependence of methane emission on temperature was observed in American rice fields (Cicerone *et al.* 1983; Sass *et al.* 1990, 1992). Chen & Wang (1993) reported that methane emission from a Chinese rice paddy was correlated with air temperature only in sunny days when the cloudiness was less than 3/10 (a cloud amount of 30%). Whalen & Reeburgh (1992), from their multiyear studies on tundra methane emissions, suggested that the effect of temperature is site specific and that the relationship between temperature and methane emission is not straightforward.

Theoretically speaking, however, processes involved in biochemical and microbial activities must be associated with temperature. The response of methane production to temperature in a given area might depend on the long-term adaptation of methanogenesis to the seasonal variation of temperature, or the tolerance of methanogenesis towards high or low temperature in a relative short period. In other words, differences in methane production, when viewed as a whole for a growing season, might exist in regions, although no clear correlation between seasonal temperature and methane production or emission was found from a given region.

To be general for different regions, a mean value of soil temperature during the rice growing period of interest was introduced to the soil temperature index (TI) in (5) for quantifying the influence of temperature on methane production from a given region. Field measurements suggest the temperature coefficient for methane emission (Q_{10}) ranges from 2 (Khalil *et al.* 1991) to 4 (Schütz *et al.* 1989b). A Q_{10} value of 3 was assumed in this study.

Methane production rate. The net reaction of anaerobic carbohydrate fermentation and 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 ≈ 0.27 ($3[CH_4]/[C_6H_{12}O_6] = 0.27$). In an equilibrated rice field, the population size of methanogens is unlikely to be responsible for the variation of methane production over a rice growing season (Schütz *et al.* 1989a). Rate of methane production, P (g m^{-2} d^{-1}), was therefore determined mainly by the availability of methanogenic substrates and the influence of environmental factors as

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

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 4).

Methane emission as modulated by rice growth

Methane is oxidized by aerobic methanotrophs in flooded soils and flood water of rice paddies. Like other vascular plants rooted in anoxic sediments, rice plants mediate the transport of atmospheric oxygen down the rhizosphere through their aerenchymal system (De Bont *et al.* 1978) supporting methane oxidation (Conrad & Rothfuss 1991; Gerard & Chanton 1993). As rice growth and development proceeds, the aerenchymal system becomes well developed and the oxidation is enhanced. The fraction of methane which is emitted declines consequently (Schütz *et al.* 1989a; Sass *et al.* 1992). Experiments from Italian rice fields showed that the emitted fraction in the early season varied from 0.41–0.55 down to 0.03–0.08 at the end of the season (Schütz *et al.* 1989a). Similar seasonal trends were also observed from American rice fields (Sass *et al.* 1990, 1992). Assuming that the proportion of methane emitted decreases with rice growth over the season, the emitted fraction, E_f, was simulated by

$$E_f = \frac{E}{P} = 0.55\left(1 - \frac{W}{W_{max}}\right)^{\beta_2}, \quad (9)$$

where W is rice above-ground biomass at a given day and W_{max} is the maximum above-ground biomass at the end of a growing season (g m^{-2}), respectively. Constant 0.55 is an assumed initial fraction (Schütz *et al.* 1989a) and β_2 is an empirical constant.

Combining (8) with (9), daily methane emission, E (g m^{-2} d^{-1}), was determined by

$$E = P \times E_f. \quad (10)$$

Model parameterization

Assuming that only plant-related methane production and eventual emission occur in the absence of any other organic inputs (i.e. taking C_{OM} in eqn 8 as zero), measurements of both rice biomass production and methane emissions were used to determine the empirical constants β_1 in (1), α in (2), C in (6) and β_2 in (9) by employing a nonlinear method (SYSTAT 1989) to (10). These measurements were conducted in a Texas flooded rice field without any extra organic inputs in 1994 and a total of three cultivars were involved (Huang *et al.* 1997b). The values of α, β_1, β_2 and C were evaluated as 1.8×10^{-3}, 1.25, 0.25 and – 1.7, respectively.

Simplified model

In general, simulation models are used to describe a more detailed process, while more simplified models are expected to interpret field experiments with limited information. A simplified version of the present model was derived to estimate methane emission from flooded rice paddy soils in a more practical manner. The aim of this simplification is to make the model applicable to a wider area with limited data sets.

Average daily rate of methane production

In highly reduced (Eh < 150 mv) paddy soils, the average daily rate of methane production associated with rice plants, $\bar{P}_R$ (g m^{-2} d^{-1}), was given by

$$\bar{P}_R = 0.27\times\bar{T}I\times SI\times VI\times 1.8\times 10^{-3}\times\bar{W}^{1.25}, \qquad (11)$$

where $\bar{T}I$ is an average reduction factor of soil temperature, calculated by substituting an average soil temperature into T_{soil} in eqn (5). $\bar{W}$ represents an average daily weight of above-ground biomass (g m^{-2}) over a growing season. According to field measurements of above-ground biomass in 1994 and 1995 (Huang *et al.* 1997b), $\bar{W}$ was ≈ 55% (± 3%) of the above-ground biomass at the end of the season, W_{max}.

Using an integration form of first-order kinetics equation (Tate 1987), the average daily rate of methane production derived from incorporated organic matter within a permanent flooding period, $\bar{P}_{OM}$ (g m^{-2} d^{-1}), was calculated by

$$\bar{P}_{OM} = 0.27\times\{OM_{No}[1 - \exp((-k_1\times SI\times\bar{T}I\times D)] + OM_{So}[1 - \exp(-k_2\times SI\times\bar{T}I\times D)]\}/D, \qquad (12)$$

where OM_{No} and OM_{So} represent the initial amount of nonstructural and structural carbohydrates from incorporated organic matter, respectively. The constant *D* is the duration in days of permanent flooding over a rice growing season.

Average daily rate of methane emission

In consideration of the influence of soil redox potential on methane production and the fraction of methane oxidation prior to emission, an average emission factor of 0.35 was estimated by running the term $F_{Eh}\times[0.55(1-\{W/W_{max}\})^{0.25}]$ over a growing season. The value of 0.35 can be approximately viewed as the average fraction of methane emitted from the total methane produced.

The average daily rate of methane emission, $\bar{E}$ (g m^{-2} s^{-1}), was simulated by

$$\bar{E} = 0.35\times(\bar{P}_R + \bar{P}_{OM}). \qquad (13)$$

Model validation

The present model was validated against methane emission measurements made near Beaumont, Texas (USA) during the years 1991–95, and the measurements in an outdoor pot experiment, Rice University, Houston, Texas in 1995. These measurements involved 11 cultivars, three soil types with sand percentage ranging from 4.3% to 32.5%. Nitrogen fertilization as urea (total of 150–300 kg N ha^{-1}) was applied as needed at planting (35%), just before permanent flooding (35%) and at panicle differentiation (30%). No organic matter was incorporated to the soils in these experiments. More detailed information was described elsewhere by the authors (Sass *et al.* 1990, 1991a,b, 1992, 1994; Huang *et al.* 1997a,b).

Methane emission rates in various regions of the world, including Italy (Holzapfel-Pschorn & Seiler 1986; Holzapfel-Pschorn *et al.* 1986; Schütz *et al.* 1989a,b), China (Chen *et al.* 1993; Wang *et al.* 1994; Li *et al.* 1994), Indonesia (Nugroho *et al.* 1994), Philippines (Denier van der Gon & Neue 1995, Denier van der Gon & Neue 1995; Denier van der Gon & Neue 1995) and USA (Banker *et al.* 1995), were used to compare with the modelling results. These emission rates were measured from irrigated rice paddies without organic matter amendments.

The effect of organic matter amendment on methane emission was validated against the observations from Texas, USA by Sass *et al.* (1991b) and Vercelli, Italy by Schütz *et al.* (1989b). The measurements from Italy were made in the Po River Valley (45°20′N, 8°25′W), during the years 1984–86. The soil consisted of a sandy loam made up of 60% sand, 25% silt, 12% clay and 2.5% organic matter (Schütz *et al.* 1989b).

The simulation model (eqn 10) was employed to compute methane production and eventual emission with a daily step and the simplified model (eqn 13) was applied to simulate average daily methane emission. Total seasonal methane emission was determined either from the summation of daily simulated values (eqn 10) over a flooding period or by multiplying the computed average daily values (eqn 13) by the duration of permanent flooding in days (*D*).

Model inputs

Model inputs include rice biomass growth, variety index, soil sand percentage and temperature, amount of organic matter amendments, fraction of nonstructural and structural carbohydrates of the incorporated organic matter.

Rice growth can be simulated with different kinds of models. However, simulations of such complexity require detailed information on climate conditions, soil nutrition supply, fertilizer application, plant photosynthetic characteristics and, etc. (McMennamy & O'Toole 1983; Ritchie *et al.* 1987; Williams *et al.* 1989; Singh *et al.* 1993; Huang *et al.* 1996), which is unlikely to be suitable for linking to the general databases currently available. To be applicable to large data sets, rice growth in the present model

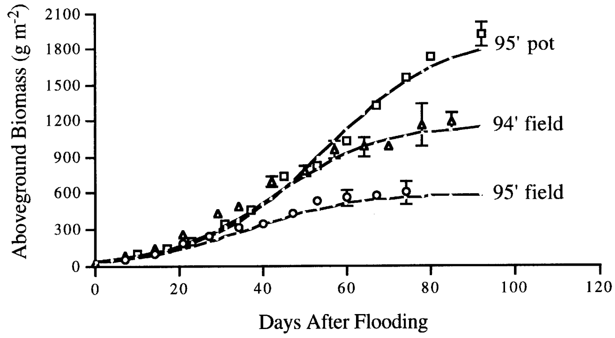

Fig. 2 Rice above-ground biomass accumulation with time. Dashed curves are simulated by employing a logistic growth equation. Open triangles and circles are data sets measured from rice fields near Beaumont, Texas. Open squares are data sets measured from an outdoor pot experiment at Rice University, Houston, Texas. The vertical bars are standard deviations from 2 to 3 sampling replicates. Cultivar used was Lemont. Details of these experiments were described by the authors (Huang *et al.* 1997b)

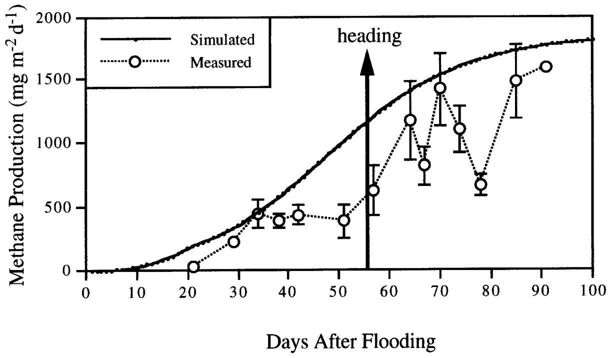

Fig. 3 Comparison between simulated and measured methane production. Solid curve is simulated and open circles are measured by incubation of soil cores from the top 10 cm depth flooded soil without additional organic inputs. The vertical bars are standard deviations from 3 sampling replicates (Lewis 1996)

was computed by applying a logistic growth equation as follows

$$W = \frac{W_{max}}{1 + B_0 \times \exp(-r \times t)} \tag{14}$$

$$B_0 = \frac{W_{max} - W_0}{W_0} \tag{15}$$

$$W_{max} = 9.46GY^{0.76}. \tag{16}$$

Rice growth in above-ground biomass at a given day is represented by W (g m^{-2}) in (14). W_o and W_{max} are above-ground biomass (g m^{-2}) at the beginning of permanent flooding and at the end of a growing season, respectively. Variable t is the time scale in days after flooding. W_{max} was correlated with grain yield GY (g m^{-2}) as in (16) (Huang *et al.* 1997a). Constant r is an intrinsic growth rate for above-ground biomass and averages 0.08 ($\pm$ 0.02) d^{-1} in a total of 17 cases, with 10–13 measurements of above-ground biomass for each case. Measurements were conducted weekly in Texas rice paddy soils during 1994 and 1995 growing seasons and five cultivars were involved (Huang *et al.* 1997b). Figure 2 shows a comparison of measured and simulated above-ground biomass at different productivity levels by employing the logistic growth equation (14). The correlation of computed against measured biomass results in an r^2 of 0.988 (n = 36, $P < 0.001$).

Assuming that soil temperature at the seasonal level (time scale not less than a day) correlates with air temperature, temperature in flooded rice soils was estimated by a relationship as $T_{soil} = 4.4 + 0.76T_{air}$ for those regions where soil temperature data are not available. T_{soil} and T_{air} represent flooded soil and air temperature in °C, respectively. The relationship was derived from measurements made in Texas rice paddy soils. The initial fraction of nonstructural and structural carbohydrates of the incorporated straw, according to a straw decomposition experiment in 1991 (this lab unpublished data), are $\approx$ 0.25 and 0.75, respectively.

Validation of methane production and emitted fraction

Figure 3 shows a comparison between simulated (eqn 8) and measured methane production. The measurement of methane production was made by incubation of soil cores from the top 10 cm depth flooded paddy at $\approx$ 29 °C. Soil samples were collected from plots of the cultivar Lemont, 1/4 of the way between two rows of rice plants (Lewis 1996). This cultivar was planted in a Texas rice field in 1994, without any organic incorporation. The seasonal pattern of observed methane production (open circles) shows a sharp increase after heading, approximately twice that before heading, while simulated pattern (solid line) shows that the production increases sharply before heading but slowly after heading and levels off during the late season. The comparison of simulated with measured methane production yields an r^2 of 0.756 (n = 14, $P < 0.001$).

Simulation of the emitted fraction (eqn 9) was validated against results obtained by Schütz *et al.* (1989a). Agreement between predictions and observations is presented in Fig. 4, which results in an r^2 of 0.997 ($n = 4$, $P < 0.001$).

Validation of methane emission from flooded paddy soils without organic amendments in Texas, USA

Simulations of methane emission (eqn 10) at three distinct rice productivity levels, low, medium and high, were validated against field measurements in 1993 and 1995

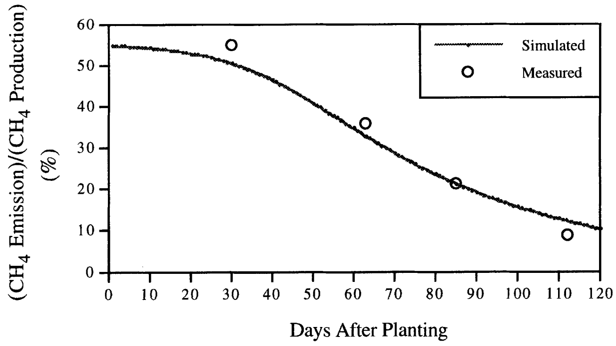

Fig. 4 Comparison between simulated and measured fraction of CH_4 emitted from the total CH_4 produced. Solid curve is simulated and open circles are data points from Schütz *et al.* (1989a), respectively

and a pot experiment in 1995. Mean value and standard deviation were calculated for the above-ground biomass of cultivars Mars, Della and Lemont. These values were 1367 ± 92, 542 ± 154 and 1874 ± 58 (g m^{-2}) for the 1993 and 1995 field studies and 1995 pot study, respectively, approximately a 3.5-fold difference between the maximum and the minimum. The average and standard deviation of methane flux from these three observations were, respectively: 426 ± 106, 131 ± 42 and 562 ± 117 (mg m^{-2} d^{-1}), approximately a 4.3-fold difference between the highest and the lowest. Comparisons between simulated and observed methane emissions at low, medium and high rice productivity levels are shown in Fig. 5(a);. (b) and (c), respectively. The simulated seasonal patterns at different rice productivity levels in general agree with the observations.

Figure 6 shows the comparisons between computed and measured methane emissions from cultivars with different phenological development in a normal harvest year. Cultivar Labelle, exhibiting the shortest growth duration, headed at 81 days and was harvested at 113 days after planting. Cultivar Jasmine, having the longest growth duration, headed at 99 days and was harvested at 142 days after planting. Cultivar Dawn, with an average growth duration for most cultivars involved in this study, headed at 93 days and was harvested at 129 days after planting.

With a total of 295 data sets measured from 11 cultivars in 1993 and 1995 experiments, the comparison between simulated and measured daily methane emissions (Fig. 7) results in a correlation coefficient (r^2) of 0.874 with a slope of 0.906 and an intercept of 44.2 (n = 295, P < 0.001). Consistent with rice productivity levels, the daily methane emissions from 1995 rice field (open squares) are mainly concentrated in the range of 0 and 300 mg m^{-2} d^{-1}, those from 1993 rice field (crosses) are in the range of 300 and 800 mg m^{-2} d^{-1}, and those from 1995 pot experiment (open circles) are in the range of 700 and 1200 mg m^{-2} d^{-1}.

Simulations of total seasonal methane emissions were tested against measurements from Texas flooded paddy soils during the period from 1991 to 1995. The regression of computed against observed emissions (Fig. 8) yields an r^2 of 0.905 (n = 36, P < 0.001) and 0.893 (n = 36, P < 0.001) when the simulation model (eqn 10) and the simplified model (eqn 13) were employed, respectively. Detailed information about cultivars, soils, rice productivity levels and methane emissions are given in Table 1. The total seasonal methane emissions during the 5-year period show an average of 24.99 ± 12.15 g m^{-2} with 36 observations. In consonance with the observations, simulations with the present simulation model and simplified model result in the average value of 25.08 ± 12.59 and 26.33 ± 13.41 g m^{-2}, respectively (Table 1).

Validation of methane emission from flooded paddy soils without organic amendments in various regions of the world

Model performance was further validated against methane emission rates in various regions of the world. These emission rates were measured from irrigated rice paddy soils without organic matter amendments. By substituting $0.55W_{max}$ for the average above-ground biomass ($\bar{W}$) in (11) and then inserting (11) into (13), seasonal average of daily methane emission rates (g m^{-2} d^{-1}) can be simulated by $0.35 \times 0.27 \times 1.8 \times 10^{-3} \times \bar{TI} \times SI \times VI \times (0.55W_{max})^{1.25}$. According to the relationship between maximum above-ground biomass (W_{max}) and rice grain yield (GY) in (16), the average emission rate was eventually computed by $1.34 \times \bar{TI} \times SI \times VI \times GY^{0.95}$ (mg m^{-2} d^{-1}). From available information on soil sand percentage and temperature, the soil index (SI) and the temperature index ($\bar{TI}$) can be calculated. However, the variety index (VI) for identifying the intervarietal differences in methane emission rates is not always known. Assuming that the VI is 1.0 for the majority of cultivars (Huang *et al.* 1997a) and its coefficient of variation (CV), a measure of relative variation, is 30% (Huang *et al.* 1997b), the average emission rate would vary between $1.34 \times \bar{TI} \times SI \times 0.7 \times GY^{0.95}$ and $1.34 \times \bar{TI} \times SI \times 1.3 \times GY^{0.95}$ according to the model.

Table 2 shows available information on soil sand percentage, temperature and rice grain yield in different regions of the world. The average daily methane flux from a total of 20 cases ranged from 85 in the Philippines to 662 mg $m^{-2}d^{-1}$ in Sichuan, China with a mean value of 322 ± 144 mg $m^{-2}d^{-1}$. In comparison with these measurements, simulations with three assumed VI values of 0.7, 1.0 and 1.3 resulted in the means of 219 ± 97, 312 ± 138 and 406 ± 180 mg $m^{-2}d^{-1}$, respectively (Table 2). As shown in Table 2, 80% (16 out of 20 cases) of the

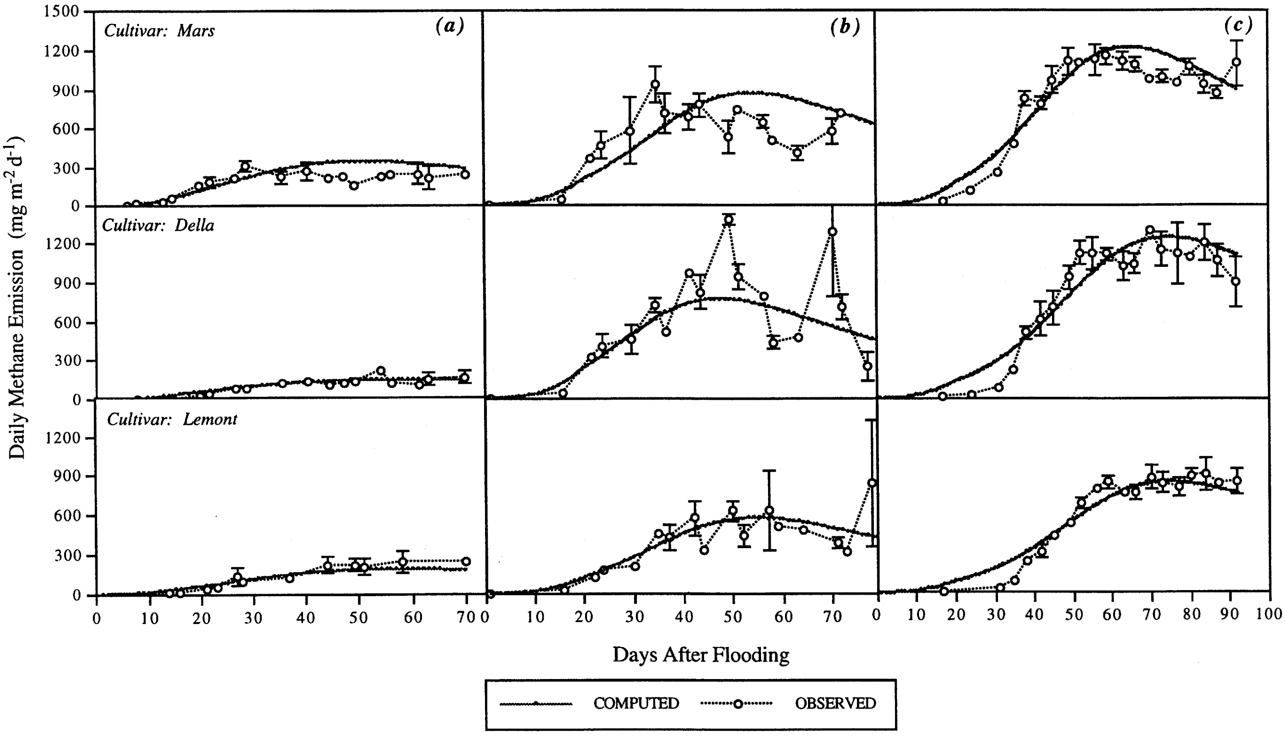

Fig. 5 Comparisons of computed with observed seasonal patterns of methane emission at three distinct rice productivity levels: (a) low rice productivity in 1995 field experiment, Beaumont, TX; (b) medium in 1993 field experiment, Beaumont, TX; and (c) high in 1995 pot experiment, Rice University, Houston, TX. The vertical bars are standard deviations from 2 to 3 sampling replicates. The average and standard deviation of shoot biomass for cultivars Mars, Della and Lemont were, respectively: 542 ± 154, 1367 ± 92 and 1874 ± 58 g m^{-2} from these three experiments. That of corresponding methane flux were, respectively: 131 ± 42, 426 ± 106 and 562 ± 117 mg m^{-2} d^{-1}

measured emission rates fall within the range of estimates with VI values of 0.7 and 1.3. Of these four cases which fall beyond the estimates, only one from unfertilized field in Vercelli of Denier van der Gon & Neue 1995) varies greatly from the estimated (Table 2). The comparison of measured with computed methane emission rates (VI = 1.0) results in a correlation coefficient r^2 of 0.733 (n = 20, $P < 0.001$). These results suggest that the VI values for the cultivars involved in these cases are likely close to 1.0 with a variation range of ± 0.30, or the relative variation of estimates with the present model is ≈ 30%.

Validation of methane emission from flooded paddy soils with organic amendments

According to the present model, methane production and eventual emission from flooded rice soils are derived from two sources of methanogenic substrates, rice plants and organic matter amendments. Assuming that the field measurements could be separated into two parts, emissions associated with rice plants (E_R) and with organic matter incorporation (E_{OM}), the E_{OM} would be equal to the total emission (E_T) minus the E_R, i.e. $E_{OM} = E_T - E_R$. The E_T and E_R represent methane emissions from soils with and without organic matter amendments, respectively.

Figure 9(a) shows a comparison of computed and measured seasonal methane emission with a 6 t ha^{-1} grass straw (*Paspalum* spp.) incorporation in an American rice field (Sass *et al.* 1991b). The contribution of incorporated organic matter to methane emission (E_{OM}) is shown in Fig. 9(b). Solid curve is the simulated and open circles is the observed $E_{OM,}$ suggesting that the decomposition of organic matter in the first month after incorporation is important to methane emissions.

Simulated methane emissions (E_{OM}) derived from organic matter amendments were validated against the field measurements made in Texas, USA and Vercelli, Italy. The rate of organic matter application ranged from 3 t ha^{-1}–12 t ha^{-1}. The comparisons between observed and computed emissions with the simulation model and the simplified model result in an r^2 of 0.597 (n = 14, $P < 0.01$) and 0.588 (n = 14, $P < 0.01$), respectively. More detailed information of fertilizer, organic matter application and methane emission in these two locations

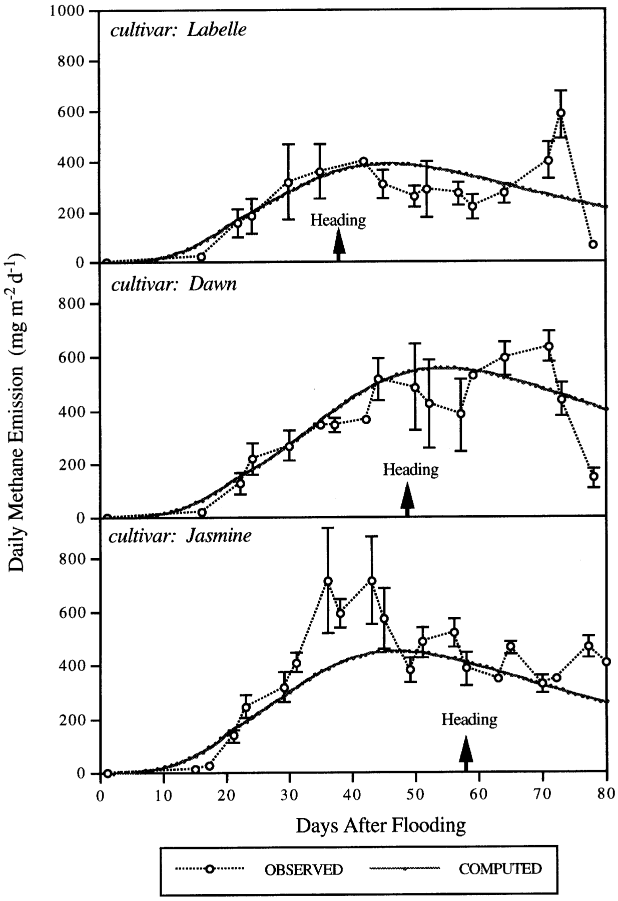

Fig. 6 Comparison of computed with observed seasonal patterns of methane emission from three cultivars with different phenological development in a normal harvest year, Beaumont, Texas 1993. The vertical bars are standard deviations from 2 sampling replicates

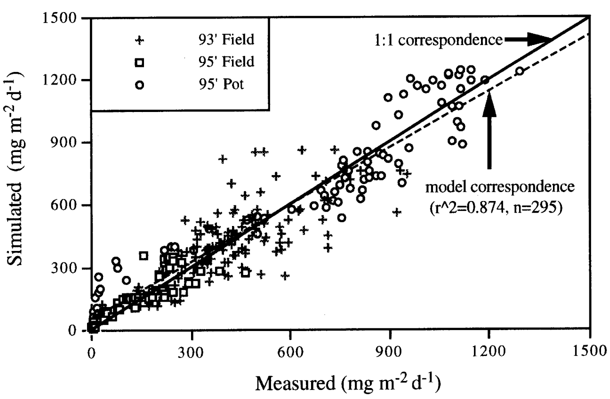

Fig. 7 Comparison of simulated with measured daily methane emissions from Texas flooded rice soils during 1993 and 1995 growing seasons. A total of 11 cultivars were involved in the 2-year period. Model correspondence is the regression line of simulated vs. measured methane emissions

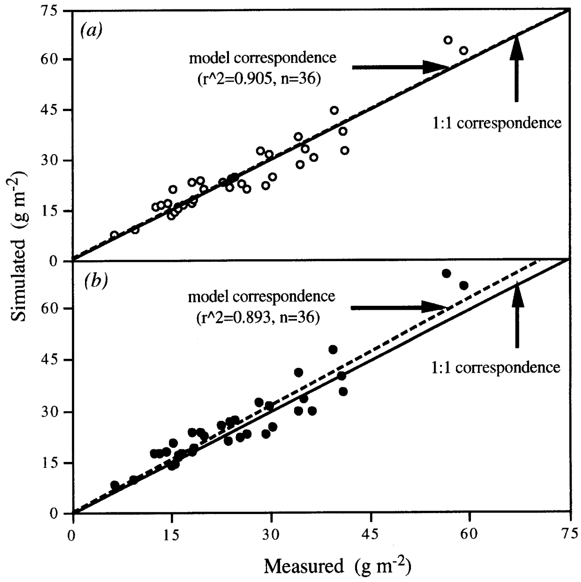

Fig. 8 Comparison of simulated with measured total seasonal methane emissions from Texas flooded rice paddy soils during 1991–95 growing seasons by employing the simulation model (a) and the simplified model (b), respectively. Model correspondence is the regression line of simulated vs. measured methane emissions

is shown in Table 3. The computed emissions with the simulation model and the simplified model from a total of 14 cases averaged 25.4 ± 12.6 and 23.1 ± 10.9 g m^{-2}, respectively. These values are close to the measured average of 23.0 ± 15.5 g m^{-2} (Table 3).

Discussion

Carbon substrates associated with rice plants

The amounts of methanogenic substrates associated with rice plants were quantified through rice biomass production in the model. To evaluate the possible relationship between the carbon sources that are incorporated in rice biomass and that might be released into the rhizosphere, a 45% C ratio in plant dry matter (Aselmann & Crutzen 1989) and a root/shoot ratio of 0.1 (Yoshida 1981) were assumed.

Under the soil conditions of 30% sand and temperature of 25 °C, carbon substance derived from rice plants was calculated with the simulation model (eqn 8). Calculations show that the carbon substances released into the rhizosphere from rice plants over an 80-day period are equivalent to 101%, 10%, and 9% of the root, shoot and whole plant carbon, respectively. Prikryl & Vancura (1980) reported that the amount of organic carbon exuded from the roots of wheat plants was about the same as that incorporated in the root biomass during a 12-day cultivation. Experiments by Barber & Martin (1976) showed

Table 1 Simulated and measured methane emissions from irrigated rice paddy soils (without organic matter amendments) in Texas, USA 1991–95

Planting Date (M/D)	Cultivar	Soil Type	Sand (%)	Temp.[a] (°C)	Grain yield (g m^{-2})	Flooded days	VI	SI	TI	W_{max}[b] (g m^{-2})	Total seasonal CH_4 emission M[c]	COMP[d] (g m^{-2})	COMP[e]
1991													
4/3	Jasmine	Beaumont Clay	4.3	25.4	853.2	85	1.0	0.42	0.60	1598	16.51	16.60	17.64
4/3	Jasmine	Beaumont Clay	4.3	25.4	832.0	85	1.0	0.42	0.60	1567	13.11	16.20	17.23
4/3	Jasmine	Beaumont Clay	4.3	25.4	802.5	85	1.0	0.42	0.60	1525	15.81	15.80	16.65
4/3	Jasmine	Beaumont Clay	4.3	25.4	859.5	85	1.0	0.42	0.60	1607	18.01	16.70	17.77
4/3	Jasmine	Beaumont Clay	4.3	25.4	874.2	85	1.0	0.42	0.60	1627	14.22	16.90	18.06
5/7	Jasmine	Beaumont Clay	4.3	25.4	698.5	85	1.0	0.42	0.60	1372	15.33	14.10	14.59
5/7	Jasmine	Lake Charles Clay	21.8	25.4	625.6	85	1.0	0.82	0.60	1262	30.13	25.00	25.41
1992													
4/23	Jasmine	Lake Charles Clay	18.8	24.9	529.4	93	1.0	0.75	0.57	1112	15.10	21.04	20.59
4/23	Jasmine	Lake Charles Clay	19.4	24.9	537.3	93	1.0	0.76	0.57	1124	23.60	21.69	21.26
4/23	Jasmine	Lake Charles Clay	19.1	24.9	605.5	93	1.0	0.75	0.57	1231	19.20	23.79	23.61
4/23	Jasmine	Lake Charles Clay	21.0	24.9	529.6	93	1.0	0.80	0.57	1112	25.40	22.44	21.97
4/23	Jasmine	Bernard Morey	32.3	24.9	591.9	93	1.0	1.05	0.57	1210	28.20	32.52	32.20
4/23	Jasmine	Bernard Morey	32.5	24.9	543.3	93	1.0	1.06	0.57	1134	36.30	30.37	29.81
4/23	Jasmine	Bernard Morey	31.0	24.9	589.4	93	1.0	1.02	0.57	1206	29.60	31.51	31.18
4/23	Jasmine	Bernard Morey	29.6	24.9	651.0	93	1.0	0.99	0.57	1301	35.00	33.21	33.21
1993													
4/27	Lebonnet	Lake Charles Clay	21.2	25.7	604.5	78	1.0	0.80	0.62	1230	26.22	21.30	22.94
4/27	Lemont	Lake Charles Clay	21.2	25.7	731.5	78	1.0	0.80	0.62	1421	24.52	24.60	27.49
4/27	Dawn	Lake Charles Clay	21.2	25.7	707.9	78	1.0	0.80	0.62	1386	23.86	24.00	26.65
4/27	Katy	Lake Charles Clay	21.2	25.7	685.4	78	1.0	0.80	0.62	1353	22.50	23.40	25.84
4/27	Della	Lake Charles Clay	21.2	25.7	624.8	78	1.5	0.80	0.62	1261	41.05	32.70	35.50
4/27	IR 36	Lake Charles Clay	21.2	25.7	490.0	78	1.0	0.80	0.62	1048	18.18	18.10	18.79
4/27	Mars	Lake Charles Clay	21.2	25.7	730.5	78	1.5	0.80	0.62	1420	34.06	36.90	41.19
4/27	Brazos	Lake Charles Clay	21.2	25.7	597.1	78	1.0	0.80	0.62	1218	19.84	21.10	22.67
4/27	Labelle	Lake Charles Clay	21.2	25.7	466.7	78	1.0	0.80	0.62	1010	17.95	17.40	17.94
4/27	Jasmine	Lake Charles Clay	21.2	25.7	550.4	85	1.0	0.80	0.62	1145	29.20	22.10	22.87
1994													
4/5	Mars	Bernard Morey	27.9	25.1	518.5	70	1.5	0.95	0.58	1094	34.26	28.60	29.68
4/5	Lemont	Bernard Morey	27.9	25.1	559.8	77	1.0	0.95	0.58	1160	17.97	23.40	23.41
4/5	Labelle	Bernard Morey	27.9	25.1	499.8	63	1.0	0.95	0.58	1064	15.95	15.40	17.20
1995													
4/18	Lemont	Bernard Morey	23.1	26.9	228.4	71	1.0	0.84	0.71	587	9.21	9.10	9.95
4/18	Mars	Bernard Morey	23.1	26.9	272.0	71	1.5	0.84	0.71	670	12.31	15.80	17.62
4/18	Della	Bernard Morey	23.1	26.9	124.6	71	1.5	0.84	0.71	370	6.31	7.40	8.39
4/18	Cypress	Bernard Morey	23.1	26.9	215.2	71	1.5	0.84	0.71	561	14.89	13.10	14.11
1995 Outdoor Pot Experiment, Rice University, Houston, Texas (Huang *et al.* 1997b)													
5/10	Lemont	Bernard Morey	23.1	25.4		92	1.0	0.84	0.60	1922[f]	39.39	44.40	47.73
5/10	Labelle	Bernard Morey	23.1	25.4		92	1.0	0.84	0.60	1670[f]	40.75	38.20	40.04
5/10	Mars	Bernard Morey	23.1	25.4		92	1.5	0.84	0.60	1810[f]	59.15	62.50	66.42
5/10	Della	Bernard Morey	23.1	25.4		92	1.5	0.84	0.60	1890[f]	56.60	65.40	70.11
Average					585.3	83	1.11	0.78	0.61	1258	24.99	25.08	26.33
SD					184.0	9	0.21	0.18	0.04	350	12.15	12.59	13.41

[a]A mean value within permanent flooding period; [b]Maximum above-ground biomass at the end of the growing season, computed with $9.46GY^{0.76}$, GY is rice grain yield (g m^{-2}; [c]Measured; [d]Computed by applying the simulation model (eqn 10) with a daily step, see text in detail; [e]Computed by employing the simplified model (eqn 13), see text in detail; [f]Above-ground biomass measured at the end of the growing season.

Table 2 Simulated and measured methane emission rates from irrigated rice paddy soils (without organic matter amendments) in various regions of the world

				Soil			CH_4 emission rate ($mg\ m^{-2}\ d^{-1}$)[b]					
								COMP[d]				
Region, country	Latitude, longitude	Year(s)	No. of OBS[a]	Sand (%)	Temp. (°C)	Grain yield ($g\ m^{-2}$)	M[c]	VI = 0.7	VI = 1.0	VI = 1.3	Field description	Source
Texas, USA	29°57′N, 94°30′W	91′	6	4.3	25.4	820	182	140	200	260		this paper
Texas, USA		92′	4	31.4	24.9	594	347	238	341	443	soil sand of 29.6–32.5%	this paper
Texas, USA		91′-93′	15	20.8	25.3	601	301	194	277	360	soil sand of 18.8–21.8%	this paper
Texas, USA		94′	3	27.9	25.1	526	326	201	287	373		this paper
Texas, USA		95′	4	23.1	26.9	210	150	91	129	168	low grain yield	this paper
Louisiana, USA	29°37′N, 91°15′W	93′	1	17.0	28.1[f]	620[g]	370	242	346	450	first crop	Banker *et al.* (1995)
Vercelli, Italy	45°20′N, 08°25′W	83′	1	60.0	21.6	400[h]	434	185	264	344	unfertilized	Holzapfel-Pschorn & Seiler (1986)
Vercelli, Italy		83′	1	60.0	20.6	585[i]	468	238	340	442		Holzapfel-Pschorn & Seiler 1986
Vercelli, Italy		84′	1	60.0	22.0	585[i]	303	278	396	515		Holzapfel-Pschorn *et al.* 1986
Vercelli, Italy		84′-86′	14	60.0	22.0	585[i]	252	278	396	515	different fertilizers	Schütz *et al.* (1989a), 989b)
Nanjing, China	32°00′N, 118°48′E	90′	1	8.2	25.1[f]	668	161	134	192	249		Li *et al.* 1994
Beijing, China	40°30′N, 116°25′E	90′	1	69.1[e]	20.9[f]	494	420	235	336	437		Chen *et al.* 1993
Sichuan, China	29°40′N, 103°50′E	88′-94′	7	78.5	25.0	538	662	445	636	826		MAK Khalil, unpublished data
Hangzhou, China	30°19′N, 120°12′E	88′-89′	2	8.5	22.9[f]	500	187	81	116	151	early crop	Wang *et al.* (1994)
Taman Bogo, Indonesia	06°30′N, 106°30′E	92′	1	51.0	24.5[f]	580	515	320	457	594	Urea + $(NH_4)_2SO_4$	Nugroho *et al.* 1994
Taman Bogo, Indonesia		92′	1	51.0	24.5[f]	550	415	304	435	565	Urea	Nugroho *et al.* 1994
Taman Bogo, Indonesia		92′	1	51.0	24.5[f]	570	403	315	450	584	$(NH_4)_2SO_4$	Nugroho *et al.* 1994
IRRI, Philippines	14°35′N, 120°59′E	92′	1	6.0	24.8[f]	350	85	64	91	119	wet season	Denier & Neue 1994, 1995; Aduna *et al.* (1995)
IRRI, Philippines		92′	1	6.0	25.6[f]	555	163	108	154	200	dry season	Denier & Neue 1995; Aduna *et al.* 1995
IRRI, Philippines		92′	1	39.0	25.6[f]	555	285	282	402	523	dry season	Denier *et al.* 1996; Aduna *et al.* 1995
Average				36.6	24.3	544	322	219	312	406		
SD				24.1	2.0	123	144	97	138	180		

[a]Number of observations; [b]Seasonal average of daily methane emission rates; [c]Measured. Methane emissions after being drained in preparation for havest were not included when the seasonal average methane emission rates were calculated; [d]Computed with $1.34 \times \bar{T}I \times SI \times VI \times GY^{0.95}$, see text in detail; [e]Deng *et al.* (1990); [f]Values were estimated from air temperature for those regions where soil temperature are not available; [g]Same grain yield level as in Texas was assumed; [h]30% lower than fertilized field was assumed; [i]Alexandratos, N. (1995)

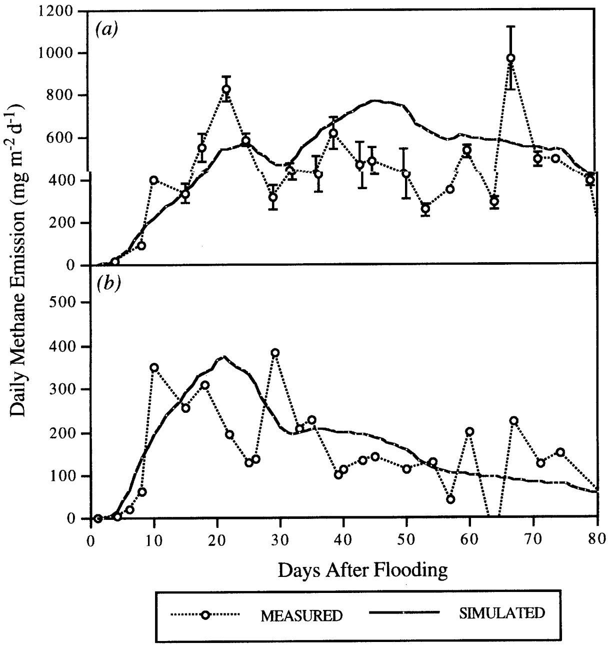

Fig. 9 Comparison between simulated and measured methane emissions with 6 t ha^{-1} straw incorporated into the soil, Beaumont, TX 1990. (a) methane emissions associated with both rice plants and organic matter amendment (E_T). The vertical bars are standard deviations from 2 sampling replicates. (b) contribution of organic matter incorporation to methane emission ($E_{OM} = E_T - E_R$). The measured E_{OM} in (b) is an average value of two fields. See text for details

that the water-soluble and insoluble ^{14}C-labelled carbon released by the roots of wheat and barley plants amounted to up to 26–47%, 11–17%, and 8–12% of that in roots, shoots and whole plants during a 3-week period, respectively. Our calculation suggests that ≈ 50% of the carbon transferred to roots would be released into the rhizosphere, which is in agreement with the values of 35–60% obtained from carbon economy studies of annual crops (Keith *et al.* 1986; Martin & Kemp 1986; Buyannvsky & Wagner 1987; Lambers 1987).

The quantification of seasonal carbon substrates associated with rice growth and development has only recently been studied at the International Rice Research Institute by Kludze *et al.* (1995). From three rice cultivars grown in a greenhouse, the authors reported that the magnitude of root exudation rates, not including the nondiffusible materials such as sloughed-off root cells and probably polysaccharides released by root-cap cells, followed the sequence as flowering > maturity > panicle initiation > seedling stage during rice growing season. However, the present model (eqn 1) shows the rice-related carbon substrates is an allometric function of rice above-ground biomass, suggesting that the substrates would follow the magnitude sequence as maturity > flowering > panicle initiation > seedling stage during rice growing season. One possible interpretation might be that dead biomass and sloughed-off root cells would provide additional substrates during plant growth and development, particularly after flowering when rice roots begin senescence.

The allometric relationship between plant derived methanogenic substrates and rice above-ground biomass was illustrated by the available data on methane production and rice above-ground biomass from the American and Italian rice fields. Above-ground biomass and methane production from American rice field were simultaneously measured in Beaumont, Texas in 1994 (Huang *et al.* 1997b; Lewis 1996). Methane production data from the Italian rice field are from Schütz *et al.* (1989a). Due to no available biomass data from the Italian rice field, a logistic growth function expressed in (14) was employed to estimate above-ground biomass. To be general for different locations, the data of rice biomass and methane production were normalized by taking a ratio of the values at a given time to the maximum value. When the measured methane production was plotted against the above-ground biomass, the allometric relationship between these two becomes obvious (Fig. 10). Moreover, the data points (open circles and solid squares) in Fig. 10 show the same response of methane production to biomass production in the two regions.

By running the present model, we simulated methane production from Texas flooded rice paddy soils over the 1994 and 1995 growing seasons on the basis of our seasonal biomass measurements (Huang *et al.* 1997b). When these estimates (right *Y*-axis vs. top *X*-axis, Fig. 10) were overlaid with the measured data points (left *Y*-axis vs. bottom *X*-axis, Fig. 10), the same relationship of methane production vs. rice biomass is clearly exhibited in both cases, which suggests that the presented relationship of methanogenic substrates with rice biomass production is realistic.

Uncertainties and future research needs

Factors involved in the processes of methane production, oxidation and emission include soil, climate, cropping system and agricultural management. A detailed understanding of those factors significant to the methane cycle is required to modify the present model and then extrapolate it to a regional and global scale.

Soil. Neue *et al.* (1990) summarized conditions for methane production in wetland rice soils into six crucial parameters: water regime, Eh/pH buffer, carbon supply, temperature, texture and mineralogy, and salinity. Observations from three upland soils in India by Parashar *et al.* (1991) indicate that methane emissions were generally highest in sandy loam puddled soil, lower in sandy loam soil, and lowest in the silty clay loam soil. Yagi &

Table 3 Comparison of computed with measured methane emission from flooded rice fields with organic matter incorporation

Year	Fertilizer+Organic Matter	Application Rate	Measured Emission ($g\ m^{-2}$)	CH_4 Emission (E_{OM}) $E_{OM} = E_T–E_R$ ($g\ m^{-2}$)[a] M[b]	COMP[c]	COMP[d]
Data cited from Schütz *et al.* (1989b) (Vercelli, Italy)						
1984	none + none	0 + 0	33.0			
	none + rice straw	0 + 5 t ha^{-1}	68.4	35.4	17.5	15.9
	$CaCN_2$ + none	200 kg N ha^{-1} + 0	35.4			
	$CaCN_2$ + straw	75 kg N ha^{-1} + 5 t ha^{-1}	50.7	15.3	17.5	15.9
1985	none + none	0 + 0	16.8			
	none + rice straw	0 + 3 t ha^{-1}	24.2	7.4	10.2	9.0
	none + rice straw	0 + 6 t ha^{-1}	32.6	15.8	20.4	18.0
	none + rice straw	0 + 12 t ha^{-1}	39.9	23.1	40.8	36.0
	$(NH_4)_2SO_4$ + none	200 kg N ha^{-1} + 0	15.8			
	$(NH_4)_2SO_4$ + straw	200 kg N ha^{-1} + 12 t ha^{-1}	54.6	38.8	40.8	36.0
1986	none + none	0 + 0	36.1			
	none + rice straw	0 + 6 t ha^{-1}	38.4	2.3	20.8	18.7
	none + rice straw	0 + 12 t ha^{-1}	76.7	40.6	41.5	37.3
	$(NH_4)_2SO_4$ + none	200 kg N ha^{-1} + 0	13.5			
	$(NH_4)_2SO_4$ + straw	200 kg N ha^{-1} + 12 t ha^{-1}	53.0	39.5	41.5	37.3
	urea + none	200 kg N ha^{-1} + 0	21.4			
	urea + straw	200 kg N ha^{-1} + 6 t ha^{-1}	54.2	32.8	20.8	18.7
	urea + straw	200 kg N ha^{-1} + 12 t ha^{-1}	67.7	46.3	41.5	37.3
Data cited from Sass *et al.* 1991 (Texas, USA)						
1990	urea + none (field1)	190 kg N ha^{-1} + 0	37.3			
	urea + grass straw(field1)	190 kg N ha^{-1} + 6 t ha^{-1}	47.9	10.7	14.4	14.8
	urea + none (field2)	190 kg N ha^{-1} + 0	22.9			
	urea + grass straw(field2)	190 kg N ha^{-1} + 6 t ha^{-1}	35.6	12.7	13.8	14.3
	urea + none (field3)	190 kg N ha^{-1} + 0	22.0			
	urea + grass straw(field3)	190 kg N ha^{-1} + 6 t ha^{-1}	23.2	1.2	13.4	13.9
Average				23.0	25.4	23.1
SD				15.5	12.6	10.9

[a]E_T, E_{OM} and E_R represent CH_4 emissions derived from both rice plants and organic matter incorporation, from organic matter incorporation, and from rice plants, respectively; [b]Measured E_{OM}; [c] Computed with the simulation model; [d] Computed with the simplified model.

Minami (1990) reported that methane emission fluxes from Japanese paddy soils varied widely with soil types in the order of peaty > alluvial > andosol and the flux rates from the peat soils were 40 times greater than the andosol soils. In a more detailed study on methane production with different soils, 20 soils representing the Philippines rice growing areas were investigated by Neue *et al.* (1994). The authors reported that the soil organic carbon content is the only soil property significant to methane production. Nevertheless, a stepwise regression analysis on these data by Huang *et al.* (1997a) indicated that ≈ 85% of the variation of methane production can be interpreted by the content of sand and organic carbon in the soil, while the pH, cation exchange capacity and clay percentage was not found to be statistically significant in this particular case.

Sand fraction in the soil was identified as a dominant parameter for methane production in the present model. From methane measurements in soils with sand content of 4–78% (Schütz *et al.* 1989a,b; Chen *et al.* 1993; Sass *et al.* 1994; Li *et al.* 1994; Wang *et al.* 1994; van Denier der Gon & Neue 1995), we believe that rice grown in soils with a high sand content result in higher methane emission than more clay- or silt-rich soils. Whether the sand fraction is uniquely significant to methane emission remains a question.

The fact that methane emission is dependent on soil texture opens the question as to why methane emission is higher in sand-rich soils than in more clay- or silt-rich soils. With respect to methane production in flooded soils, both methanogenic substrate supply and the conversion efficiency of organic carbon to methane are important. Calculation from 29 soils by Neue & Roger (1993) indicated that both number of methanogens and methane

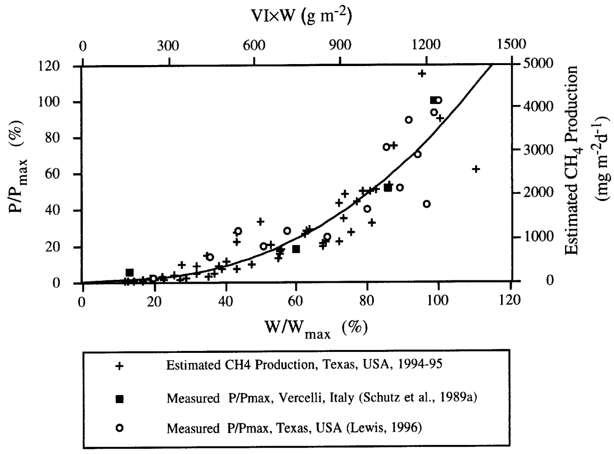

Fig. 10 Methane production as an allometric function of rice above-ground biomass. Data points of rice biomass and methane production were normalized by taking a ratio of values at a given time to the maximum value, i.e. W/W_{max} and P/P_{max}, respectively. Measured methane production (open circles, Lewis 1996) vs. above-ground biomass (Huang *et al.* 1997a) were obtained from Texas rice fields in 1994 growing season. Methane production (solid squares) from Italian rice field was cited from Schütz *et al.* (1989a) and above-ground biomass was estimated by employing a logistic growth equation $W/W_{max} = 1/[1 + Bo\times exp(-rt)]$. Cross points are computed methane production vs. above-ground biomass (VI×W), Texas 1994–95. The simulated response of methane production to above-ground biomass (cross points) exhibits the same manner as that of measured (open circles and solid squares). See text for details

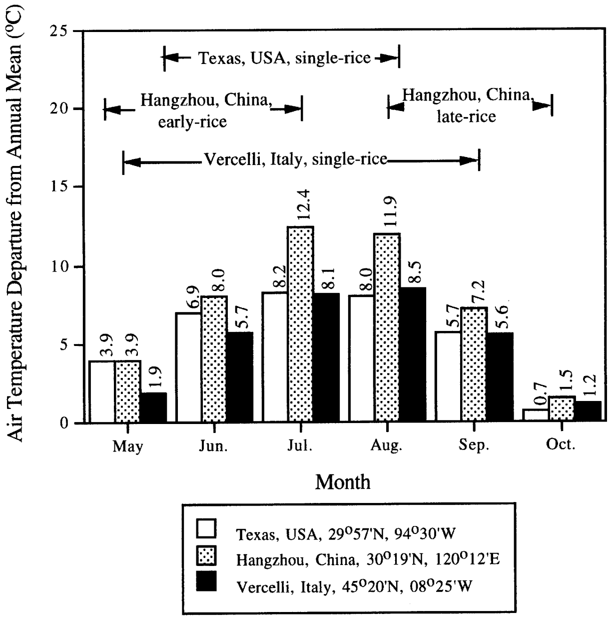

Fig. 11 Seasonal pattern of air temperature departure from annual mean and observation periods of methane emission from Beaumont, Texas, USA (single-rice, 6/01–8/20), Hangzhou, China (early rice, 5/05–7/15; late-rice, 8/15–10/15) and Vercelli, Italy (single-rice, 5/15–9/15) flooded paddy soils

production potential are positively correlated with soil sand content within the range of 1.7–82%, significant at 1% probability level. Experiments by Sass *et al.* (1994) indicated that the contents of the trace elements magnesium, calcium, copper and iron in three Texas soils were proportional to their clay percentage in a range of from 24 to 65%. A higher concentration of trace elements such as iron in clayey soils might provide more potential terminal electron acceptors and hence, reduce the conversion efficiency of organic carbon to methane.

Soil texture may also affect the movement of produced methane. Dissolved methane must diffuse towards the root surface along a concentration gradient, and then release back to the atmosphere through the rice plant (Nouchi 1994). Soil pores differ in size and shape as a result of textural and structural arrangement. Based on the diameter at the narrowest point, pores are classified as macropores (> 100 μm), mesopores (30–100 μm), and micropores (< 30 μm) (Koorevaar *et al.* 1983). More macropores and mesopores are anticipated in sandy soils than in clay- and silt-rich soils and therefore the resistance to the movement of dissolved methane would be smaller in sandy soils.

Climate and cropping systems. The seasonal course of methane emission observed by several authors cannot directly be attributed to temperature changes (Cicerone *et al.* 1983; Seiler *et al.* 1984; Sass *et al.* 1990, 1992). Yet, a close relationship between the mean values of methane emission and soil temperature at different times of the vegetation period from an Italian rice field was reported by Holzapfel-Pschorn & Seiler (1986). Experiments from Chinese rice fields with double-rice cropping system showed an increasing trend of methane emissions with time during the early rice growing season but a decreasing trend during the late-rice growing season (Wang *et al.* 1990), which was thought to be attributed to the seasonal variation of air temperature (Wang *et al.* 1996). Very similar trends over the first and ratoon rice cropping seasons were reported from America rice fields (Lindau *et al.* 1995; Banker *et al.* 1995).

It is noteworthy that the seasonal variation of air temperature is site-specific and that the response of seasonal methane emission to temperature is likely dependent on the magnitude of temperature variation. Figure 11 shows the multiyear average of monthly air temperature departure from the annual mean in three different regions of Texas (USA), Hangzhou (China) and Vercelli (Italy). In Texas, methane emission measurements were generally made during the period from late May/ early June to August. The variation of monthly air temperature is only about 1.3 °C during this period

(Fig. 11). In consonance with this small variation in temperature, no apparent seasonal dependence of methane emission on temperature was observed (Sass *et al.* 1990, 1992). In contrast with the Texas case, a wide variation of air temperature during the methane observation periods can be found in both Hangzhou and Vercelli (Fig. 11) where methane emissions were reported to be temperature related (Holzapfel-Pschorn & Seiler 1986; Wang *et al.* 1990, 1996). The air temperature during the transplanting period of early rice in Hangzhou was about 20 °C (early May) and then increased to 29 °C at maturity (mid July), approximately a 9 °C difference (Fig. 11). For the late-rice season, the air temperature in the transplanting period was about 28.5 °C (mid August) and then dropped to 18.5 °C at maturity (mid October), approximately a 10 °C difference (Fig. 11). The air temperature in Vercelli, Italy varied from 17.5 °C in the early season (mid May) up to 24.1 °C in the heading-flowering period (mid August) and dropped to 20 °C at harvest (mid September), approximately a 6.6 °C in difference between the maximum and the minimum (Fig. 11).

These typical trials suggest that short-term temperature changes may not affect microbial activities and are not responsible for the seasonal fluctuation of methane emission, while a wide variation of temperature during the observation period may affect the processes of methane production and emission. Considering the possible long-term adaptation of methanogens to the local temperature and the tolerance of methanogens towards high or low temperature in a relative short period, it would be more logical to take the mean value of the seasonal soil temperature for those regions where the temperature variation is small, or the mean value of the temperature within a certain time interval of interest, such as every continuous one-week or 10-day period, for those regions where the seasonal variation of temperature is wide, when the temperature index (TI) is calculated using the present model.

Investigations of methane emissions from flooded rice fields are mostly focused on a single-rice cropping system. In tropical and subtropical regions, however, double-rice cropping is a prevailing manner for intensifying rice production. Observations from double-rice cropping systems in Hangzhou and Hunan (China) and in Louisiana (USA) indicated that the seasonal methane emissions from late/ratoon rice seasons were higher than that from the early/first rice seasons. The average increase in emission from Chinese paddies, calculated from 14 observations over 1988–92 growing seasons (Chen & Wang 1993; Shangguan & Wang 1993; Wang, M. *et al.* 1993), was 1.53($\pm$0.23)-fold, while an average increase of 2.82($\pm$0.09)-fold can be found from American fields with a total of 7 observations (Lindau *et al.* 1995; Banker *et al.* 1995). These results raise a question of what factors caused this significant difference, though the enhanced methane emissions during the late/ratoon seasons were thought to be partially attributed to early/first rice crop straw left in field after harvest (Lindau *et al.* 1995). More detailed investigation on the relationship between rice growth, soil, climate and methane emissions from double-rice cropping system are required.

Since most of the available data were obtained from subtropical regions, it is not yet clear whether significant differences exist between methane emission rates in tropical, subtropical and temperate rice growing areas. We suggest in the present model that a temperature index (TI) could be used to quantify the effect of temperature on methane production/emission from a given area. However, the impact of climate on methane emissions is far from understood. Observation periods covering one or two-years might yield misleading results due to specific weather conditions that differ from the long-term average, especially when different cultivational practices are conducted, such as mineral fertilization, organic matter amendments, and water management. Long-term observations from different climate zones or cropping systems should focus on those climatic factors which are significant to methane emissions in that particular region. Solar radiation and air moisture may be important to the emissions from rice cropping regions where dry and wet seasons are distinctive, while temperature might be responsible for the seasonal trends of emissions in double-rice cropping regions.

Agricultural practices. Agricultural practices associated with rice production, including cultivar choice, fertilizer application, irrigation and drainage vary in different regions. Successful development and implementation of mitigation strategies for rice agricultural sources of methane require an understanding of the effects of agricultural practices on methane fluxes and on controlling mechanisms.

Cultivar choice. Cultivar choice in rice agriculture is generally matched with the local climate, soil and cropping calendar. Intervarietal differences in methane emission have been reported from India (van Denier der Gon & Neue 1995), China (Lin 1993), and the United States (Lindau *et al.* 1995; Sass & Fisher 1995). Previous research indicated that the differences were neither correlated with above-ground biomass nor root biomass and grain yield (Huang *et al.* 1997b). A study of substrates for methanogenesis and methane production during the rice growing season indicated that both soil acetate concentrations and rates of methane production were much higher from plots of the cultivar Mars than plots of the cultivar Lemont grown under the same conditions (Sigren 1996; Lewis 1996). As a result, Mars exhibited higher seasonal methane emissions than Lemont (Sigren *et al.* 1997a). Experiments on rice root exudation and its impact on methane production in the International Rice Research Institute by Kludze *et al.* (1995) showed that the amount of root exudates from a local variety Dular was ≈ 3-fold higher than that from a new plant type of IR-65598. Such studies might be expected to provide quantitative links among root exudates, methanogenic substrates and rates of methane production as concerned with the intervarietal differences in methane emission.

There are currently some 80 000 different rice cultivars available through the germplasm bank at the International Rice Research Institute in the Philippines and others are being sought. Most of these are developed for specific areas of the world and many are in current use. In the present model, a variety index (VI) was introduced to identify the intervarietal difference in methane production. However, one must note that this index was derived from *in situ* measurements of methane emission (Huang *et al.* 1997a). It is not likely to be possible to evaluate substances released by rice plants or methane emissions for all of the cultivars currently used. Further efforts therefore should be focused on general relationships between methane production and substrate availability, not only in quantity but also in quality, and relationships between substrate availability and cultivar characteristics in genotype, physiology and morphology.

Fertilizer applications Mineral nitrogen fertilizers like urea and ammonium sulphate $(NH_4)_2SO_4$ are commonly used in rice cultivation to provide nutrition for plant growth. Application of mineral fertilizer strongly influenced methane emission rates, depending on the type, rate, and application mode (Schütz *et al.* 1989b). However, measurements on the effects of these mineral fertilizers on methane production and emission are difficult to interpret.

Lindau *et al.* (1991) showed an increased methane emission rate with increased urea application. Maximum emissions were given for applications of 200 and 300 kg urea-N ha^{-1} and lower emissions for 0 and 100 kg urea-N ha^{-1} in flooded Louisiana (USA) rice fields, while information from Schütz *et al.* (1989b) indicated that the seasonal methane emissions were 33.0, 27.1 and 27.1 g m^{-2} with the application rates of 0, 100 and 200 kg urea-N ha^{-1} over a 1984 growing season in Italian rice fields.

The effect of ammonium sulphate application on methane emission also appears contradictory. Cicerone & Shetter (1981) reported a five-fold increase in methane emission rate from an American rice field after ammonium sulphate addition, while measurements from a Japanese rice field showed a decrease (Yagi & Minami 1990). Measurements from Italian rice fields in 1985 by Schütz *et al.* (1989b) showed the seasonal methane emissions of 16.8, 18.9, 22.1 and 15.8 g m^{-2} with the ammonium sulphate application rates of 0, 50, 100 and 200 kg N ha^{-1}, respectively.

Wang *et al.* (1992) tested the influence of three kinds of different fertilizers on methane production in soil incubations, they found no change over the control for urea, a decrease in production with ammonium nitrate, and a lesser decrease with ammonium sulphate. The methane emission rates with deep application of mineral fertilizer, compared with surface application, were some 40% and 60% lower after deep incorporation of 200 kg urea-N ha^{-1} and 200 kg $(NH_4)_2SO_4$-N ha^{-1}, respectively (Schütz *et al.* 1989b).

Organic matter amendments of flooded rice paddies increase both methane production and emission (Schütz *et al.* 1989b; Yagi & Minami 1990; Sass *et al.* 1991b; Cicerone *et al.* 1992; Neue *et al.* 1994; van Denier der Gon & Neue 1995). As the processes beginning with organic matter decomposition and ending with methane emission are dependent on the contents of organic materials and soil environments, the quantitative relationship between methane emission rates and organic matter amendments becomes complex to simulate.

The application of green manure generally enhanced methane emission (van Denier der Gon & Neue 1995) more than that of rice straw (Neue *et al.* 1994) in tropical paddies in the Philippines. Methane emissions with incorporated rice straw were enhanced more than those from either compost or mineral plots (Yagi & Minami 1990). By assessing published information, van Denier der Gon & Neue (1995) demonstrated that rice straw and fermented residues have a similar effect on methane emissions after correction for differences in easily decomposable carbon content, which suggests that the identification of nonstructural and structural carbohydrates in various organic amendments, such as rice straw, green manure, rapeseed cake, aerobic compost and anaerobic compost, might be essential to model methane emission associated with organic matter applications.

Few studies to date have dealt with the carbon conversion of added organic matter to methane emitted from different soils. Addition of 6 t ha^{-1} grass straw resulted in an average increase in methane emission of 30% from subtropical rice fields with 30% sand in USA (Sass *et al.* 1991b) while an average increase of 68%, with the same addition of 6 t ha^{-1} rice straw, can be found from temperate rice fields with 60% sand in Italy (Schütz *et al.* 1989b). A dramatic increase of methane emission rates with rice straw incorporation in California rice fields was reported by Cicerone *et al.* (1992). With rice straw added at 0, 250 and 500 g m^{-2}, the seasonal total methane emissions were reported as 2.88, 9.10 and 42.8 g m^{-2}, respectively. From available measurements of methane

Table 4 Carbon conversion of added organic matter as methane under different soil conditions

Organic matter	No. of OBS[a]	Total OM application[b] (g m^{-2})	ΔCH_4[c] (g m^{-2})	C[OM][d] (g C m^{-2})	C[ΔCH_4][e] (g C m^{-2})	$\frac{C[\Delta CH_4]}{C[OM]}$ (%)	Soil Sand (%)	Soil Temp. (°C)	Source
Fresh Green Manure	4	82000	150.0	7544.0	112.5	1.49	6.0	25.2	van Denier der Gon & Neue (1995), Philippines
Grass Straw	2	1200	23.4	540.0	17.6	3.25	30.0	25.3	Sass *et al.* 1991, USA
Rice Straw	11	9100	293.7	4095.0	220.3	5.38	60.0	22.0	Schütz *et al.* (1989b), Italy

[a]Number of observations; [b]Summation of all observations; [c]Difference of methane emissions from organic matter treatments and without organic matter application fields; [d]Carbon from OM. 40% C and 23% dry matter was assumed in fresh green manure (Wen 1984) and 45% C was assumed in dry rice straw (Aselmann & Crutzen 1989) and grass straw; [e]Carbon from ΔCH_4.

emission from soils with organic matter application in the Philippines (van Denier der Gon & Neue 1995), the United States (Sass *et al.* 1991b) and Italy (Schütz *et al.* 1989b), the carbon conversion of added organic matter to methane emitted was found to increase with soil sand content (Table 4). This enhancement might be due to an increased decay of organic matter or an improvement in the conversion efficiency of degraded substances to methane.

The main function of fertilizer application is to provide nutrients for rice plant growth and development and to sustain soil resources. It is therefore necessary to make parallel measurements of methane emission and plant net primary productivity when one tries to investigate the dependence of methane emission on fertilizer applications. Comparison of methane emissions with different kinds/rates of fertilizers without a comparison of corresponding plant net primary productivity is unlikely to yield reliable conclusions.

Water management. Water management is one of the most important practices in rice cultivation. To reduce ineffective tillers, remove toxic substances and maintain healthy roots under reduced soil conditions, short periods of drainage for soil aeration during the vegetative growth period and intermittent irrigation during the reproductive growth period are commonly practiced in Japan (Yoshida 1981) and China (Gao *et al.* 1992). The intensity of drainage and the interval between the cycles of irrigation-drainage-reintroduced water vary with soil characteristics and weather conditions. This practice was believed to reduce substrates for methanogens and hence restrict methane production (Sigren *et al.* 1997b).

Periodic drainage of irrigated rice paddies usually results in a significant decrease in methane emissions (Kimura 1992; Sass *et al.* 1992; Lin 1993). However, a large flush of methane, followed by a rapid decrease in methane flux in the intermittently drained plots, was observed immediately after each drainage in a Japanese rice field (Yagi *et al.* 1996). These flushes after every short drainage accounted up to 7–10% of the total methane emitted over the season (Yagi *et al.* 1996). The observations from the Philippines showed that a value of 10% (van Denier der Gon & Neue 1995) and even 20% (Wassmann *et al.* 1994) of the total methane emission was released during the final drainage after harvest.

Drainage and intermittent irrigation is conducted to improve aeration in the rhizosphere also results in a possible reduction of methane production and eventual emission. Therefore, attention must be focused on the general relationship between decreased methane emission and soil aeration. The soil aerobic condition, quantified by redox potential, might be expected to correlate with soil texture, weather conditions, crop canopy status and the duration of drainage.

Conclusion

With an understanding of the processes of methane production, oxidation and emission, a semiempirical model focused on the contributions of rice plants to the processes and also the influence of environmental factors was developed to predict methane emission from flooded rice fields. A simplified version of the model was also derived to predict methane emission in a more practical manner. Model validation against observations from a single rice growing season demonstrated that the seasonal variation of methane emission is regulated by rice growth and development. A further validation of the model against measurements from irrigated rice paddy soils in various regions of the world suggested that methane emission can be predicted from rice net productivity, cultivar character, soil texture and temperature, and organic matter amendments. As an ongoing model, it needs further validation in a wider area and advanced modification is required to extrapolate to a regional and global scale. A successful model can be anticipated to assist in understanding underlying assumptions at process-level, explain field observations, and predict needs for further research. Such a model must be mathematically descriptive of the processes of methane production, oxidation and emission as they occur *in situ*, regardless of where they are located.

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