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Methane emission from Texas rice paddy soils. 1. Quantitative multi-year dependence of CH_4 emission on soil, cultivar and grain yield

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Abstract

Methane emissions at different rice productivity levels were observed from Texas rice paddy soils during the years 1991–95. Analysis of field measurements showed that seasonal methane emission (E) was strongly dependent on soil, cultivar, and rice grain yield. The relationship can be quantitatively described by E (g m^{-2}) = 0.048 × SI × VI × GY. SI is a soil index to characterize the relative effect of soil texture on emission and is linked with soil sand percentage. VI is a variety index to identify the intervarietal difference in methane emission and is related to the amount of methane emission per unit grain yield. GY is grain yield (g m^{-2}). Constant 0.048 was derived from the measurements of 10 cultivars planted in 1993. Computed emission applying the relationship is well matched with measured data. The comparison of computed with measured seasonal methane emission over an 80-day period using a total of 32 data sets yields a correlation coefficient r^2 of 0.800. In addition, the ratio of seasonal methane emission to net primary productivity was calculated on a carbon to carbon basis, which produces an average value of 2.8%, ranging from 1.2% to 5.4%. A further investigation indicated that the ratio is soil and variety dependent and can be quantitatively explained by $C[CH_4]/C[NPP]$ (%) = 3.21 × SI × VI + 0.12 ($r^2 = 0.738$, $n = 32$). Under the condition of 30% soil sand, this ratio is ≈ 3% for the majority of cultivars.

Keywords: CH_4 emission, cultivar, grain yield, quantitative dependence, soil texture, Texas rice paddy soils

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1 Introduction

Methane (CH_4), one of the most important radiatively active trace gases, is considered to have 25 times more infrared sorbing capability per molecule than carbon dioxide as a source of potential global warming (Rodhe 1990). Atmospheric methane concentration has been increasing at a rate of about 1% per year and currently is increasing at ≈ 0.5% per year (Steele *et al.* 1992). Worldwide, irrigated rice cultivation is recognized as a major source of atmospheric methane (Schütz *et al.* 1991; Neue *et al.* 1994). Recent global estimates of methane emission from wetland rice fields range from 20 to 100 Tg per year (IPCC 1992). With growing global populations, the world's annual rough rice production must increase (IRRI 1989), which will likely result in an increase of global methane emissions (Bouwman 1991; Anastasi *et al.* 1992).

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Since the first *in situ* measurements of methane emissions from rice paddies were obtained by Cicerone & Shetter (1981), several parameters associated with rice agriculture have been identified that affect the rate of methane emission, including soil properties (Neue *et al.* 1994; Sass *et al.* 1994), climate (Schütz *et al.* 1990; Sass *et al.* 1991), agricultural practices, such as water regime and management (Inubushi *et al.* 1990a, b; Sass *et al.* 1992) and organic matter amendment (Schütz *et al.* 1989b; Yagi & Minami 1990; Cicerone *et al.* 1992; Denier van der Gon & Neue 1995), and plant physiology (Nouchi *et al.* 1990; Whiting & Chanton 1993; Nouchi 1994). However, the quantitative relationships of methane emission with these parameters are still far from being understood. To develop mitigation techniques for reducing methane emission from irrigated rice fields, it is required to quantify the contribution of rice agriculture to global methane emissions.

More recent results from fieldwork across a variety of flooded wetlands (Sass *et al*. 1990; Whiting *et al*. 1991; Whiting & Chanton 1993), including irrigated rice, show that methane emission was positively correlated with plant biomass or net ecosystem production, suggesting the net ecosystem production is a master parameter that integrates many factors significant to methane emission from wetlands (Whiting & Chanton 1993). By comparing a variety of methane emission data sets obtained over a four-year period from three different soil types, Sass *et al*. (1994) reported a correlation existed between seasonal methane emission and the percentage sand in the soils. Wide variations in observed methane emissions have been also reported to be rice cultivar related (Parashar *et al*. 1991; Lin 1993; Lindau *et al*. 1995).

Over the past five-year period from 1991 to 1995, we have been conducting experiments under normal cultivational management to determine crucial parameters that affect methane emission from rice paddy soils in the Texas Gulf Coast area. These parameters include soil type (Sass *et al*. 1994), rice cultivar and rice productivity. In this paper, we present a quantitative relationship of methane emission with these parameters. The objective is to investigate the quantitative response of methane emission to multiple parameters and hence, to interpret our five-year experiments in general.

2 Materials and methods

2.1 Location and climate

Field experiments were performed from 1991 to 1995 in rice fields at the Texas A&M University Agricultural Research and Extension Centre near Beaumont, Texas, USA, located at longitude 94°30′W, latitude 29°57′N. Rice represents the main crop produced in this area, which has an annual growing season of ≈ 275 days. The average temperature during the rice growing season in April through September is 25.2 °C and annual rainfall averages 1340 mm, ≈ 50% (122 mm month^{-1}) occurring in the same period.

2.2 Soil

Fields represent soil types typical of the Texas coastal prairie (Crout *et al*. 1965). The soils include Beaumont clay, an Entic Pelludert; Lake Charles clay, a Typic Pelludert that is slightly less acid and stronger in structure; and Bernard-Morey, a fine thermic Vertic Ochraqualf. All three soils have poor internal and surface drainage with percolation rates less than 0.5 mm/day after initial saturation (Brown *et al*. 1978).

2.3 Rice cultivational practice

Eleven cultivars were planted during the five-year period. The planting date usually occurred during April. The rice crops were drill-planted at about 112 kg ha^{-1} in rows spaced 20 cm apart. Seedling density ranged from 250 to 300 m^{-2}. The plants emerged about 10 days after planting. Approximately 120 days were required for most cultivars to mature under normal planting. Permanent flooding was within 40–42 days after planting and fields normally remained flooded for about 80 days before being drained in preparation for harvest. 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. Grain yields ranged from a lowest value of 1246 kg ha^{-1} in 1995 to a highest value of 8742 kg ha^{-1} in 1991, with an average value of ≈ 5850 kg ha^{-1}.

2.4 Measurements

In all experiments, methane measurements were taken twice weekly from permanent flooding until draining for harvest, by taking samples of the headspace gas of an open-bottom chamber of known cross-sectional area. Methane mixing ratios were obtained by gas chromatography with a flame ionization detector. The emission was determined from the slope of the mixing ratio change in the five samples (50 cm^3) taken over a 30-min sampling period. Sample sets which did not yield a linear regression value of r^2 greater than 0.90 were rejected. In most cases, plants were harvested by machine. The grain yield was reported as rough rice grain corrected to 14% moisture content. Sand, clay and silt percentage of the soils were analysed by using the standard hydrometer method (Gee & Bauder 1986).

3 Results

3.1 Relationship of methane emission with soil texture

Methane production and eventual emission in wetland rice are influenced by soil micro-environments. Neue *et al*. (1990) summarized conditions for high methane production in wetland rice soils into six crucial parameters: water regime, Eh/pH buffer, carbon supply, temperature, texture and mineralogy, and salinity. Generally, most of these parameters, including texture and mineralogy, salinity, and organic carbon in the soil, represent the fixed characteristics of a given soil. These fixed characteristics can be viewed as static parameters. The rest of these parameters, such as water regime, Eh/pH buffer and temperature, will change with water management and climate. In a given area with a specific climate and agronomic management regime, the variation of methane production potential from different soils could be caused by these static parameters. As a result, the emissions will be different among these soils.

In light of our previous studies from 1989 to 1992 growing seasons, methane emission from three soils planted with the same cultivar, Jasmine, was found to be significantly correlated with soil sand percentage. The total seasonal methane emission, E (g m^{-2}), was described by $E = 10.40 + 0.718 \times$ (% sand) (Sass *et al.* 1994). From this correlation, a general relationship is derived to evaluate the relative effect of soil sand content on methane emission, which is quantified by a dimensionless soil index as follows:

$$SI = \frac{E}{E_R} = \frac{10.40 + 0.718 \times SAND}{10.40 + 0.718 \times 30} = 0.325 + 0.0225 \times SAND, \qquad (1)$$

where SI is the soil index. E and E_R are the seasonal methane emissions (g m^{-2}) under a given sand percentage, SAND, and 30% sand content, respectively. The value of SI is less than one for sand percentage lower than 30 and larger than one for sand percentage higher than 30.

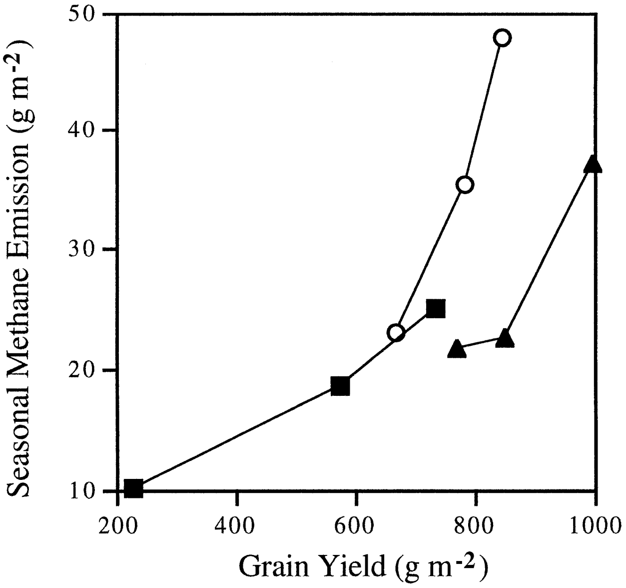

Fig. 1 Methane emission vs. rice grain yield. The solid squares come from a 3-year (1993–95) period records for cultivar Lemont. The open circles and solid triangles, coming from three different planting dates in 1990 for cultivar Jasmine, represent the treatments of straw incorporation and without straw incorporation, respectively.

3.2 Methane emission versus rice grain yield

We have previously reported that the methane emission from a Lake Charles soil paddy was strongly related to above-ground biomass (Sass *et al.* 1990), and that an increase in rice grain yield was accompanied by an increase in methane emission both in no straw application and in straw incorporated rice fields (Sass *et al.* 1991). Recently, a dramatic decrease in both grain yield and methane emission was observed in 1995. For uncertain reasons, the average grain yield and seasonal methane emission from four cultivars this year dropped to 2100 kg ha^{-1} and 12.1 g m^{-2}, respectively, 68% and 48% lower than that in normal harvesting year.

Figure 1 shows the trend of total seasonal methane emission with rice grain yield from two cultivars over four different years. The data sets for cultivar Lemont, represented by three solid squares in the figure, were observed from 1993 to 1995 experiments in which no organic matter was incorporated into the soils. The data sets for cultivar Jasmine were from experiment with three different planting dates in 1990 growing season (Sass *et al.* 1991). The solid triangles and the open circles represent treatments without straw application and with 6 t ha^{-1} straw incorporation in the fields, respectively. Available data sets in Fig. 1 suggest that total seasonal methane emission is in general dependent on rice grain yield over a wide range. The increase in rice grain yield is likely responsible for the increase in methane emission from either organic matter incorporated fields (open circles) or without organic inputs fields (solid squares + solid triangles), although for a given cultivar the methane increase from fields with incorporated organic matter (open circles) is higher than those from fields with no organic application (solid triangles).

3.3 Quantification of varietal difference in methane emission

Wide variations in observed methane emissions have been reported to be cultivar related. Methane emissions from eight different cultivars grown under similar conditions near New Delhi, India showed a variation of as much as an order of magnitude (Parasher *et al.* 1991). A study of five rice cultivars in irrigated fields near Beijing, China indicated that the average daily methane emission varied by a factor of two (Lin 1993).

To investigate the variation of methane emissions among varieties, 10 cultivars were planted under similar soil texture with sand percentage of 21.2 ± 1.2 in 1993. A significant variation in methane emission was observed in this study. The average daily flux from these 10 cultivars ranged from 230.1 to 526.3 mg m^{-2} d^{-1} with a mean value of 326.9 mg m^{-2} d^{-1}, approximately a 2.3-fold difference between the maximum and the minimum. The grain yield, on the other hand, varied from 466.7 to

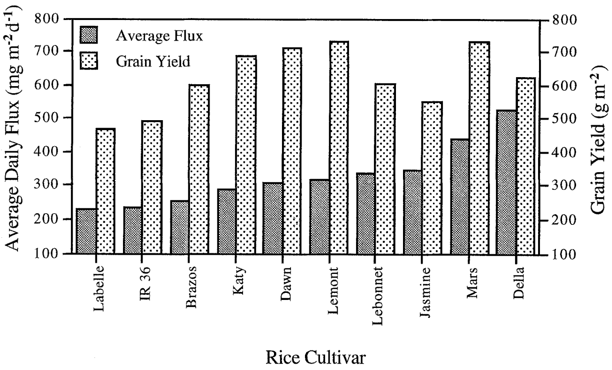

Fig. 2 Varietal differences in methane emission and grain yield of rice plant, Beaumont, Texas, 1993.

731.5 g m^{-2} with a mean value of 618.9 g m^{-2}. Similar to the trend in Fig. 1, methane emission increased with increasing grain yield for most cultivars. However, a high methane emission was not always observed with high grain yield. Figure 2 presents the methane flux and grain yield for all 10 cultivars. Among these, cultivars Della & Mars exhibit high methane emission values of 526.3 and 436.7 mg m^{-2} d^{-1}, 1.61-fold and 1.34-fold higher than the average, respectively. In comparison, the average grain yield of these two cultivars is only about 11% higher than the mean value of all 10.

On the assumption that the amount of methane emitted by a given cultivar can be characterized by the methane emission per unit grain yield, we calculated the ratio of seasonal methane emission over an 80-day period to grain yield for all 10 cultivars. The calculation results in an average ratio of 0.058 ± 0.010 g CH_4 g^{-1} grain for these two high emission cultivars (Mars & Della) and 0.038 ± 0.005 g CH_4 g^{-1} grain for the remaining eight, indicating that the high emission cultivars release more methane than the majority cultivars do at the same productivity level. The standard deviation for the eight cultivars is seen to be relatively small (0.005 g CH_4 g^{-1} grain), suggesting the quantity of methane emission in terms of rice productivity is nearly constant for the majority of the cultivars studied.

Analogous to the soil index, a variety index to identify the relative difference in methane emission among cultivars is defined as

$$VI = \frac{(E/GY)/SI}{RRATIO}, \qquad (2)$$

where VI is the dimensionless variety index. E/GY represents the ratio of seasonal methane emission to grain yield for a particular cultivar in a soil of given percentage sand. To be general for different soils, the soil index, SI, is introduced in this expression. RRATIO is a reference value and characterized by an average ratio of E/GY for a given group of cultivars corrected to 30% sand soil condition. As calculated above, the average ratio of E/GY for the majority of the cultivars studied is 0.038 g CH_4 g^{-1} grain under the condition of 21.2% sand. The RRATIO therefore takes a value of 0.048 (0.038/SI = 0.038/0.80 = 0.048). Using eqn (2), we calculated the variety index for all 10 cultivars. The average VI for the eight cultivars, as expected, is characterized by a value of 1.0 with a standard deviation of 0.14, while the mean value for the cultivars Mars and Della is ≈ 1.5.

3.4 Relationship of methane emission with soil, variety, and rice grain yield

It is noteworthy that grain yield is only a measure of the economically useful part of the net photosynthetic productivity, mainly determined during the reproductive period, while total dry matter is a measure of a crop's net photosynthetic productivity over the whole growth season. In this point, rice biomass at the end of growing season would be expected to be a much better parameter corresponding to total seasonal methane emission than grain yield. However, the measurements of rice biomass are not always available while the grain yield is usually recorded in rice agriculture. To be practical and applicable to large data sets, grain yield was used to approximately characterize rice net photosynthetic productivity.

Assuming that soil index, variety index and rice grain yield are independent of each other and that only plant-mediated methane emission occurs in the absence of any other organic inputs, seasonal methane emission is hypothesized to be a multiple function of soil index, variety index and grain yield as follows:

$$E = \alpha \times SI \times VI \times GY, \qquad (3)$$

where E represents seasonal methane emission (g m^{-2}) and GY is rice grain yield (g m^{-2}). Constant α is an experimental coefficient.

Comparing eqn (3) with eqn (2), one can easily find that the constant α in eqn (3) will be equal to the reference value RRATIO in eqn (2), if the hypothesis in eqn (3) is reasonable. To evaluate this, the RRATIO value of 0.048 derived from the variety investigation was extrapolated to all 5-year data sets. Table 1 shows the measured data of soils, rice grain yield, and methane emissions from the experiments conducted at Beaumont, Texas during the years 1991–95. By employing eqn (3), seasonal methane emission over an 80-day period was computed. The value of VI here is simply characterized by 1.0 for the majority cultivars and 1.5 for the high emission cultivars, respectively. Table 1 and Fig. 3 show the comparison of computed with measured methane emission. The comparison results in a correlation coefficient r^2 of 0.800 (n = 32) with a

Table 1 Soil, cultivar, rice grain yield, and methane emissions from Texas rice paddy soils, 1991– 1995

Planting Date (M/D)	Cultivar	Soil type	Sand (%)	Grain yield (g m^2)	SI	VI	CH$_4$ Emission^a (g m^2)		$\frac{C[CH4]}{C[NPP]} \times 100^d$
							M^b	COMP^c	
1991									
4/3	Jasmine	Beaumont Clay	4.3	853.2	0.42	1.0	15.5	17.3	1.47
4/3	Jasmine	Beaumont Clay	4.3	832.0	0.42	1.0	12.3	16.8	1.19
4/3	Jasmine	Beaumont Clay	4.3	802.5	0.42	1.0	14.9	16.2	1.48
4/3	Jasmine	Beaumont Clay	4.3	859.5	0.42	1.0	17.0	17.4	1.60
4/3	Jasmine	Beaumont Clay	4.3	874.2	0.42	1.0	13.4	17.7	1.25
5/7	Jasmine	Beaumont Clay	4.3	698.5	0.42	1.0	14.4	14.1	1.59
5/7	Jasmine	Lake Charles Clay	21.8	625.6	0.82	1.0	28.4	24.5	3.41
1992									
4/23	Jasmine	Lake Charles Clay	18.8	529.4	0.75	1.0	13.0	19.0	1.77
4/23	Jasmine	Lake Charles Clay	19.4	537.3	0.76	1.0	20.3	19.6	2.74
4/23	Jasmine	Lake Charles Clay	19.1	605.5	0.75	1.0	16.5	21.9	2.03
4/23	Jasmine	Lake Charles Clay	21.0	529.6	0.80	1.0	21.8	20.3	2.97
4/23	Jasmine	Bernard Morey	32.3	591.9	1.05	1.0	24.3	29.9	3.04
4/23	Jasmine	Bernard Morey	32.5	543.3	1.06	1.0	31.2	27.5	4.17
4/23	Jasmine	Bernard Morey	31.0	589.4	1.02	1.0	25.5	28.9	3.21
4/23	Jasmine	Bernard Morey	29.6	651.0	0.99	1.0	30.1	31.0	3.51
1993									
4/27	Lebonnet	Lake Charles Clay	21.2	604.5	0.80	1.0	26.9	23.3	3.32
4/27	Lemont	Lake Charles Clay	21.2	731.5	0.80	1.0	25.1	28.2	2.68
4/27	Dawn	Lake Charles Clay	21.2	707.9	0.80	1.0	24.5	27.3	2.68
4/27	Katy	Lake Charles Clay	21.2	685.4	0.80	1.0	23.1	26.4	2.59
4/27	Della	Lake Charles Clay	21.2	624.8	0.80	1.5	42.1	36.1	5.06
4/27	IR 36	Lake Charles Clay	21.2	490.0	0.80	1.0	18.6	18.9	2.69
4/27	Mars	Lake Charles Clay	21.2	730.5	0.80	1.5	34.9	42.2	3.73
4/27	Brazos	Lake Charles Clay	21.2	597.1	0.80	1.0	20.3	23.0	2.53
4/27	Labelle	Lake Charles Clay	21.2	466.7	0.80	1.0	18.4	18.0	2.76
4/27	Jasmine	Lake Charles Clay	21.2	550.4	0.80	1.0	27.5	21.2	3.64
1994									
4/5	Mars	Bernard Morey	27.9	518.5	0.95	1.5	39.2	35.6	5.43
4/5	Lemont	Bernard Morey	27.9	559.8	0.95	1.0	18.7	25.6	2.44
4/5	Labelle	Bernard Morey	27.9	499.8	0.95	1.0	20.3	22.9	2.89
1995									
4/18	Lemont	Bernard Morey	23.1	228.4	0.84	1.0	10.4	9.3	2.69
4/18	Mars	Bernard Morey	23.1	272.0	0.84	1.5	13.9	16.5	3.14
4/18	Della	Bernard Morey	23.1	124.6	0.84	1.5	7.1	7.6	2.91
4/18	Cypress	Bernard Morey	23.1	215.2	0.84	1.5	16.8	13.1	4.54
AVE.			20.0	585.3	0.77	1.1	21.5	22.4	2.85
S.D.			8.5	184.0	0.19	0.2	8.2	7.7	1.04

(a) Over an 80-day period; (b) Measured; (c) Computed by 0.048×SI×VI×GY; (d) Calculated carbon ratio of CH$_4$ emission to NPP (see text in detail)

slope of 0.956 and an intercept of 0.02, strongly supporting the above hypothesis.

3.5 Carbon ratio of methane emission to NPP with soil and variety

The net primary productivity, NPP, of rice plants has been related to methane emission (Sass *et al*. 1990; Whiting & Chanton 1993). On a carbon to carbon basis, Aselmann & Crutzen (1989) suggested methane emission to NPP ratios ranging from 3 to 7%. This range was calculated from the emission rates by Cicerone *et al*. (1983) and Holzapfel-Pschorn & Seiler (1986) when related to the mean plant production of rice in the U.S. and Italy, where these measurements were made. A value of 5% has been recently used to estimate the methane emission from regional or global rice paddies (Taylor *et al*. 1991; Bachelet & Neue 1993; Bachelet *et al*. 1995).

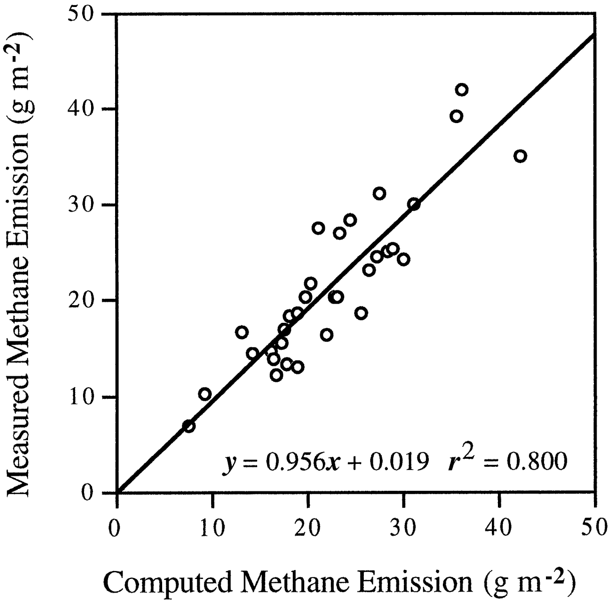

Fig. 3 Correlation of computed with measured seasonal methane emission over an 80-day period, Beaumont, Texas, 1991–95.

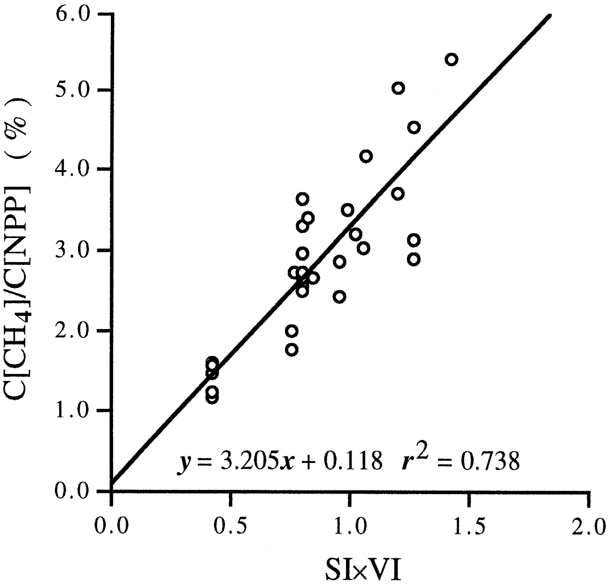

Fig. 4 Measured ratios of methane emission to NPP (on a carbon to carbon basis) as a function of soil index (SI) and variety index (VI) over a 5-year period experiments conducted at Beaumont, Texas.

NPP of rice plants in this study was deduced from grain yield records, since very few NPP data were available for this category. Based on observed data (Table 2) from five cultivars planted in 1994 and 1995 growing seasons, total above-ground biomass, TAGB, was correlated with grain yield, GY, by the following equation:

$$\mathrm{TAGB} = 9.46 \times \mathrm{GY}^{0.76}. \qquad (4)$$

Root biomass was assumed to be ≈ 0.1 of the TAGB (Yoshida 1981) and therefore NPP of rice was estimated as $1.1\times\mathrm{TAGB}$ or $10.4\times\mathrm{GY}^{0.76}$ (g m^{-2}).

Similarly, a 45% C ratio in plant dry matter (Aselmann & Crutzen 1989) was assumed to calculate the carbon ratio of methane emission to NPP ($C[CH_4]/C[NPP]$) in our investigation. The calculation shows an average $C[CH_4]/C[NPP]$ ratio of ≈ 2.8%, ranging from 1.2% to 5.4% (Table 1).

Examining these ratios in Table 1, it is apparent that the values from the Beaumont clay soil, characterized by a lowest sand percentage of 4.3, are the smallest among the three soils. The ratios of cultivar Della and Mars are comparably high with respect to other cultivars in the same soil in 1993. Furthermore, when these ratios are plotted against the product of soil index and variety index (Fig. 4), a strong dependence is found. Equation (5) shows such a linear relationship suggesting that factors significant to methane emission must be included in any attempt to extrapolate the ratio to regional or global scales.

$$\frac{C[CH_4]}{C[NPP])} (\%) = 3.21\times \mathrm{SI}\times \mathrm{VI} + 0.12 \qquad (n = 32,\ r^2 = 0.738). \qquad (5)$$

Regardless of the non-zero intercept of 0.12 in eqn (5), the slope of 3.2 represents a ratio of methane emission to NPP for the majority cultivars under the condition of 30% sand content in the soil. In other words, if the multiplication of SI and VI, representing the combined effects of soil and variety on methane emission, is taken as a value of 1.0, the ratio of methane emission to NPP will be ≈ 3.2%. This value is consistent with Whiting and Chanton's value of 3.3% (Whiting & Chanton 1993).

4 Discussion

4.1 Effect of soil texture on methane emission

The fact that methane emission is dependent on soil type opens the question of what process, production or oxidation of methane, is related to soils and which parameters in the soil are dominant.

Table 3 shows the seasonal change in methane production and emission from an Italian (Schütz *et al.* 1989a) and an American rice field (Sass *et al.* 1992). The data reveal a higher methane production from the Italian than the American rice field by a factor of ≈ 6.5 when their average daily values were compared each other. Accompanied with this high production, the average daily methane emission from the Italian field is ≈ 3-fold higher than that from the American field, though the average daily percentage of oxidation from the former

Table 2 Total above-ground biomass of rice at different grain yield levels

Grain yield ($g\ m^{-2}$)			TAGB[a]) ($g\ m^{-2}$)		
Range	Average	SD	Average	SD	Sample size
< 300	267.3	21.4	655.6	58.3	4
300–400	341.6	26.4	805.1	107.8	6
400–500	463.5	27.9	1000.1	104.1	12
500–600	545.0	25.4	1144.5	86.8	11
600–700	648.9	29.5	1293.7	85.5	6

[a] TAGB-Total Above-Ground Biomass

Table 3 Seasonal change in methane production and emission

Date (m/d/y)	Methane Production ($mg\ m^{-2}\ d^{-1}$)	Methane Emission ($mg\ m^{-2}\ d^{-1}$)	Percent Oxidized (%)	Soil Sand (%)	Organic Carbon (%)
Schütz *et al.* (1989a,b) (Vercelli, Italy)*					
6/6/85	342	188	44	60	2.5
7/9/85	1148	411	64		
7/31/85	3291	488	79		
8/27/85	6393	545	91		
6/11/86	1003	411	59		
7/3/86	2759	656	76		
8/1/86	6222	346	94		
9/2/86	5091	142	97		
Sass *et al.* (1992) (Texas, USA)					
6/25/91	1	1	0	30	1.11
7/10/91	151	125	18		
7/23/91	583	143	63		
8/5/91	971	202	79		
8/20/91	582	136	76		
8/25/91	823	154	81		

*Production and emission data taken from Schütz *et al.* (1989a) have been converted to units of $mg\ m^{-2}\ d^{-1}$. Soil information is from Schütz *et al.* (1989b).

case (76.5%) is higher than that from the latter (51.5%). Also, it must be noticed from these limited data that sand content in the Italian rice field is higher than that in the American field. However, the soil index, when calculated for these two cases, would result in the value of 1.68 ($SI = 0.325 + 0.0225 \times 60 = 1.68$) for the Italian field and 1.00 ($SI = 0.325 + 0.0225 \times 30 = 1.00$) for the American field, only yielding a factor of 1.68 between these two. Note that not only the sand content but also the organic carbon in the Italian rice field is higher than that in the American field (Table 3), which suggests that the high methane production and eventual emission from the Italian field may be also enhanced by the high organic carbon in the soil. The varietal effect on methane emission from these two cases is unknown as well.

In a more detailed study, 20 soils representing Philippines rice growing areas were investigated (Neue *et al.* 1994). Table 4 lists methane production values from rice soils of the Philippines and the related soil parameters, including soil pH, organic carbon, cation exchange capacity, sand and clay percentage (Neue *et al.* 1994). By employing a stepwise regression method, we identified both sand percentage and organic carbon as the dominant parameters affecting methane production. The methane production from these 20 soils can be quantitatively expressed by

$$\text{Methane Production} = 3.24 \times \text{SAND} + 176.09 \times \text{OC} - 281.7, \tag{6}$$

where the unit of methane production is in $\mu g\ g^{-1}$ soil. SAND and OC are the sand percentage and organic carbon in the soil. This relationship yields a correlation coefficient R^2 of 0.849, which means that the methane production in this particular case can be ≈ 85% deter-

Table 4 Methane production from rice soils of the Philippines after 10 days incubation[a]

pH	OC (%)	CEC[b] (meg/100 g)	Clay (%)	Sand (%)	CH_4 production ($\mu g\ g^{-1}$ soil)
5.7	1.36	30.30	27	18	0.13
6.3	0.88	16.60	23	30	0.20
6.7	1.64	30.80	31	16	0.48
5.9	1.34	43.40	61	3	0.49
6.8	1.38	29.40	32	8	0.54
5.9	1.38	29.00	44	20	0.58
7.3	1.89	28.40	29	14	0.75
6.0	1.67	42.30	54	4	0.87
5.8	1.51	37.70	50	2	0.92
5.9	1.97	40.20	66	6	1.01
7.8	1.20	49.20	45	15	4.24
4.5	1.84	24.90	56	4	4.57
6.4	0.99	11.10	15	50	4.96
6.4	0.71	7.41	8	70	24.30
6.5	1.28	34.80	43	9	50.40
4.0	1.20	6.09	25	8	93.70
6.5	2.96	38.60	47	15	303.10
4.6	2.86	11.40	28	28	341.00
5.8	2.35	8.03	8	65	388.80
6.0	2.65	11.90	8	79	468.30

[a]adopted from Neue *et al.* (1994); [b]cation exchange capacity

mined by the content of sand and organic carbon in the soil, while the influence of pH, cation exchange capacity and clay percentage on methane production was not found to be statistically significant.

4.2 Understanding of intervarietal difference in methane emission

The wide variation of methane emissions among cultivars provides the possibility for the choice of existing cultivars and the breeding of new cultivars with low emission rates. However, the mechanism of the variation is not yet clear. The data from our cultivar investigation did not show significant differences in rice grain yield between high and low emitting cultivars commensurate with their methane emissions.

A further investigation of root biomass measured weekly from pot culture experiments (Huang *et al.* 1997) shows that there are no significant differences among four cultivars: Mars & Della, representative of high emission varieties, Lemont & Labelle, representative of lower emission varieties. Nevertheless, the average value of emissions over a 70-day period observation is 38.4 g m^{-2} for Mars & Della and 24.7 g m^{-2} for Lemont & Labelle, approximately a 1.5-fold difference between the two groups (Huang *et al.* 1997). A study of substrates for methanogenesis and methane production during the rice growing season indicates that both soil acetate concentration and methane production are much higher from plots of the Mars cultivar than plots of the Lemont cultivar (Sigren 1996; Lewis 1996). As a source of substrates for methanogenesis, the amount and chemical components of root exudates may differ between cultivars Mars and Lemont. This distinction may be eventually recognized as the intervarietal difference in methane emission. More detailed studies are required to determine the mechanism of the difference.

4.3 The role of rice photosynthetic production in methane emission

As we have already mentioned above, grain yield is only a measure of the economically useful part of the net photosynthetic productivity, while total dry matter is a measure of a crop's net photosynthetic productivity over the whole growth season. Through rice grain yield has been used to quantify the contribution of rice productivity to methane emission in this study, careful attention must be focused on the role of rice photosynthetic production in methane emission.

It is well established that rice plants play an important role in the microbial production and oxidation as well as in the emission of methane. Rice plants make at least two main contributions to the process of methane emission. First, rice plants release organic substances into the rhizosphere by biomass litter and root exudation. Second, rice plants provide channels for gas transport. Like other vascular plants rooted in anoxic sediments, rice plants are thought to release oxygen into the rhizosphere (De Bont *et al*. 1978), supporting methane oxidation. Meanwhile, methane produced in the sediment diffuses into the cell-wall water of the root cells, gasifies in the root cortex, and then is mostly released through the micropores in the leaf sheathes into the atmosphere (Nouchi 1994).

Root exudation has been found to stimulate methane production in rice paddies and methane emission (Raimbault *et al*. 1977) in laboratory experiments with 3-week old rice plants. A variety of studies indicate that root exudation is affected by weather, soil water stress and soil microorganisms as well as mineral nutrition (Hale *et al*. 1971; Hale & Moore 1979; Trolldenier 1981). It was reported as early as 1959 that the exudates from tomato roots were lower in quantity due to decreased photosynthesis by reducing light intensity (Rovira 1959). By varying planting date during the same season, Sass *et al*. (1991) reported that a 1% increase in accumulative solar radiation is accompanied by a 1% increase in rice grain yield and a 1.1% increase in methane emission.

To clarify the mechanism of methane transport through rice plants, Nouchi (1994) examined methane formation in flooded soil and emission through rice plants in pot culture (soil and hydroponics culture) experiments. The author found that methane transport in rice plants depended mainly on plant morphology. The emission rate from rice plants with nine tillers was larger than that from those with three tillers. In an Italian rice paddy, plots having one-third plant density of the control plot emitted about 25% less methane (Schütz *et al*. 1989a).

All of these studies suggest that the process of methane emission from rice paddies may be mainly modulated by rice plant growth and that environmental factors affecting rice growth may influence methane production and emission. When photosynthesis and the partitioning of photosynthate are affected by solar radiation or soil nutrition, for example, the substrates derived from rice plant may change either in quantity or in quality. It can be expected that the amount of root exudates from the rice plant grown under normal conditions would be higher than that under an abnormal condition, such as insufficient solar radiation or limited nutrition. With respect to the channels of methane emission, it can be recognized that the more plants or the more biomass, the more emission channels are available in a given species. For the same reason, plant biomass is an accumulation of daily net photosynthate which is affected by various factors. In contrast with the effect of soil texture on methane emission, rice net photosynthetic production may be characterized as a dynamic factor of modulating methane emission, which would be important for modelling methane emission at a process level.

5 Summary and conclusions

In this paper, we presented a series of comparative data of soils, rice grain yield and methane emissions from experiments conducted at Beaumont, Texas during the years 1991–95. On the basis of previous research on soil texture and methane emission, a soil index, SI, was proposed to characterize the relative effect of soil texture on emissions and is quantitatively linked by soil sand percentage. For individual cultivars grown in different years or planted at different dates during the same growth season, methane emission was found to increase with rice grain yield. However, measurements from 10 cultivars in 1993 did not show significant differences in grain yield between high and lower emission cultivars in comparison with their emissions. Similar to the soil index, a variety index, VI, was defined to identify the intervarietal difference in methane emission and is associated with the amount of methane emission per unit grain yield.

Assuming that soil index, variety index and rice grain yield are independent of each other and that only plant-mediated methane emission occurs in the absence of any other organic inputs, seasonal methane emission is hypothesized to be a multiple function of soil index, variety index and grain yield, which is quantitatively described by $E\ (g\ m^{-2}) = 0.048 \times SI \times VI \times GY$. Constant 0.048 is derived from the investigation of 10 cultivars planted in 1993 and GY represents rice grain yield ($g\ m^{-2}$). Computed emissions applying this relationship are well matched with observed data. The comparison of computed with observed seasonal methane emission over an 80-day period using a total of 32 data sets yields a correlation coefficient r^2 of 0.800 with a slope of 0.956 and an intercept of 0.02.

On a carbon to carbon basis, the ratio of seasonal methane emission to net primary productivity was calculated over the 5-year period, producing an average value of 2.8% with the range from 1.2% to 5.4%. This wide range was also found to be soil and variety dependent and can be quantitatively explained by $C[CH_4]/C[NPP]\ (\%) = 3.21 \times SI \times VI + 0.12$ ($n = 32, r^2 = 0.738$). Under the condition of 30% soil sand, this ratio is $\approx$ 3% for the majority of cultivars studied.

Proven useful in interpretation of field measurements over a five-year period conducted in Texas, the relationship of methane emission with soil sand percentage, rice cultivar and grain yield may have value to assess methane emissions from flooded rice paddy soils in general. Since the relationship was derived from experiments in Texas, a further validation and modification may be required to extrapolate it to a wider scale.

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