



Quantitative dependence of methane emission on soil properties

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Abstract

To identify the key soil parameters influencing CH₄ emission from rice paddies, an outdoor pot experiment with a total of 18 paddy soils was conducted in Nanjing Agricultural University during the 2000 rice growing season. The seasonal average rate of CH₄ emission for all 18 soils was $6.42 \pm 2.70 \text{ mg m}^{-2} \text{ h}^{-1}$, with a range of 1.96 to $11.06 \text{ mg m}^{-2} \text{ h}^{-1}$. Correlation analysis indicated that the seasonal average of CH₄ emission was positively dependent on soil sand content and negatively on total N as well as NH₄⁺-N determined before rice transplanting. Copper content of soils had a significant negative impact on CH₄ emission. No clear relationship existed between CH₄ emission and soil carbon content. In addition, soil type cannot explain the variability in CH₄ emission. Soil parameters influencing CH₄ emission were different as rice growth and development proceeded. A further investigation suggested that the seasonal average rate of CH₄ emission could be quantitatively determined by a linear combination of soil NH₄⁺-N, available copper, the ratio of available to total sulphur, and the ratio of available to total iron. Moreover, the average rates of CH₄ emission in the vegetative, reproductive and ripening stages could be also respectively described by a linear combination of different soil variables.

Introduction

Atmospheric methane (CH₄) is recognized as one of the most important greenhouse gases. Rodhe (1990) reported that CH₄ has some 15–30 times greater infrared absorbing capability than CO₂ on a mass basis and may account for 15% of anticipated global warming. Worldwide, irrigated rice cultivation is thought to be a major source of atmospheric CH₄ (Schütz et al., 1991; Neue et al., 1994) and may contribute 10–30% of the total emitted into the atmospheric CH₄ pool (Cicerone and Oremland, 1988; Houghton et al., 1990). 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 CH₄ emissions (Bouwman, 1991). Since soil properties control CH₄ production/emission

in wetland ecosystems (Neue and Roger, 1993; Conrad, 1993) and up to now the soil factor has not been taken into account in the IPCC Guidelines because data on harvested area by major soil type are not available from the standard activity data sources (IPCC, 2000), clarifying the role of soil properties in CH₄ emission is of great importance to quantify emission inventories.

Efforts have been expended over the past two decades to identify the soil parameters controlling CH₄ emission from rice paddies. Yagi and Minami (1990) found that CH₄ 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 that from andosol soils. Observations from three upland soils in India by Parashar et al. (1991) indicated that CH₄ emissions were generally highest in sandy loam puddled soil, lower in sandy loam soil, and lowest in silty clay

loam soil. By comparing a variety of CH₄ emission data sets obtained over a 4-year period from three different soil types in Texas, the United States, Sass et al. (1994) reported a correlation existed between seasonal CH₄ emission and the percent sand in the soils. Moreover, laboratory incubation studies indicated that CH₄ production is dependent on soil sand fraction and soil organic carbon (Neue and Roger, 1993; Neue et al., 1994), soil organic carbon and organic nitrogen (Wassmann et al., 1998), and soil total inorganic electron donors and available organic carbon (Yao et al., 1999).

It has been well documented that rice plants play a crucial role in the processes of CH₄ production, oxidation and emission (Schütz et al., 1991), liberating organic substances into the rhizosphere by root exudation and plant biomass litter for methanogens (Holzapfel-Pschorn et al., 1986; Schütz et al., 1991), transporting CH₄ from the anoxic sediment into the atmosphere (Schütz et al., 1989; Nouchi, 1994) and the diffusion of atmospheric oxygen into the rhizosphere supporting CH₄ oxidation (Conrad and Rothfuss, 1991; Gerard and Chanton, 1993). Though incubation studies provided very useful information of CH₄ production associated with soil properties (Neue and Roger, 1993; Neue et al., 1994; Wassmann et al., 1998; Yao et al., 1999), we believe that soil parameters controlling CH₄ emission would be different when rice plants are involved. On the other hand, because CH₄ fluxes cannot be measured continuously in all paddy soils, a practical method is required to evaluate the role soil parameters play in CH₄ emission.

In this paper, we report results of CH₄ emission studies from various rice paddy soils in an outdoor pot experiment. The major objectives of this study were to identify the key soil parameters influencing CH₄ emission and to determine the integrative effect of soil parameters on CH₄ emission.

Material and methods

An outdoor pot cultivation experiment was conducted at Nanjing Agricultural University, Nanjing, Jiangsu province of China during the 2000 rice growing season. A total of 18 soils were involved. The soils are mainly representative of five paddy soil types in China, including hydromorphic, percologenic, submergenic, gleyed and degleyed paddy soils. Acreage percentages of these five types to the total paddies in China were 52.2, 18.9, 13.2, 8.5 and 3.5%, respectively (National

Soil Survey Office, 1998). During the winter season in 1999, soil samples were collected from approximately 0 to 20 cm depths of rice paddies in the region of latitude between 31°20'N and 33°20'N, longitude between 118°50'E and 120°10'E, Jiangsu province. Before rice transplanting, air-dried soil samples were used to determine the physico-chemical properties according to the Chinese Soil Society guidelines (Liu, 1996). An atomic absorption spectrometer was employed to determine the amounts of available and total iron, available and total copper, exchangeable and total manganese, and exchangeable and total magnesium. A wide variation in physico-chemical properties was observed among the soils (Table 1). The coefficient of variation (CV), a measure of relative variation, ranges from 28.1 to 158.4% for all checked properties except the pH value and the content of total iron.

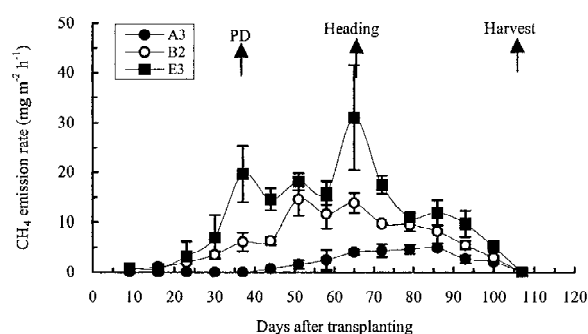
Pots made of pottery clay were 22 cm high with an inside diameter of 20 cm. The top edge of a pot has a groove for filling water to seal the rim of the gas-collecting chamber. Four kilograms of air-dried soil was placed in each pot, yielding an approximately 16 cm depth of soil. To reduce the potential unevenness of temperature distribution among pots, about 4/5 height of the pot was buried in soil. Three pots for each soil were employed as replicates.

A *japonica* cultivar, #9516, was planted in a seedling bed on May 30. Plants were transplanted on June 29 with eight seedlings for each pot. Panicle differentiation and heading occurred on August 2 and September 3, respectively. Plants were harvested on October 18. Nitrogen fertilization as urea was applied at the rates of 0.59, 0.15 and 0.15 g N per pot on June 29, July 17 and August 10, respectively. Phosphorus as KH₂PO₄ and potassium as K₂SO₄ were applied at the rates of 0.76 and 0.89 g per pot on June 29. No additional organic matter was incorporated to the soils in the experiment. Grain yield averages 30.7±2.9 g per pot, ranging from 27.1 to 35.0 g. During the growing season, all the pots were filled with passively dechlorinated tap water and remained flooded until 10 days before harvest.

Methane measurements were taken once a week between local time 08:30 and 10:30, by taking samples of the headspace gas in an open-bottom cylindrical chamber. The chamber was 100 cm high and wrapped with a layer of sponge and aluminum foil to minimize temperature changes during the period of sampling. While taking gas samples, the chamber was placed over the vegetation with the rim of the chamber fitted into the groove of the pot. Methane mixing ratios were

Table 1. Physico-chemical properties of air-dried paddy soil sample

Soil code	County /City	Village	Sub-class	Clay <0.002 mm (%)	Silt 0.002–0.05 mm (%)	Sand >0.05 mm (%)	pH	Organic carbon (g/kg)	Total nitrogen (g/kg)	Available nitrogen (mg/kg)	NH ₄ ⁺ -N (mg/kg)
A1	Jiangning	Jiefang	Percogenic	46.6	31.1	22.3	7.5	19.2	1.7	16.8	5.9
A2	Jiangning	Gaogang	Gleyed	37.1	53.7	9.2	7.5	15.5	1.6	4.0	2.5
A3	Jiangning	Jincun	Hydromorphic	49.1	41.4	9.5	6.7	19.4	1.9	114.0	63.3
B1	Yixing	Minglin	Hydromorphic	4.3	41.8	53.9	5.9	16.1	1.6	17.9	8.1
B2	Yixing	Yanghui	Percogenic	12.4	81.5	6.1	7.0	9.8	1.1	8.9	4.6
B3	Yixing	Lidu	Degleyed	37.5	55.1	7.4	6.4	17.9	2.0	43.3	29.7
C1	Baoying	Gongcheng	Percogenic	37.1	30.2	32.7	8.6	9.9	1.2	55.8	10.9
C2	Baoying	Zhangzhuang	Hydromorphic	56.6	37.2	6.3	8.3	18.2	1.8	19.2	12.3
C3	Baoying	Madu	Degleyed	59.8	36.6	3.5	8.0	27.1	2.9	136.0	51.0
C4	Baoying	Luchao	Degleyed	27.6	50.1	22.3	5.6	39.4	3.4	91.9	63.0
C5	Baoying	Daizhuang	Gleyed	32.1	39.0	28.9	7.5	18.0	2.0	110.5	32.8
D1	Yizheng	Beishang	Submergenic	43.1	36.0	21.0	7.1	8.6	1.1	10.2	6.0
D2	Yizheng	Qinfeng	Percogenic	31.7	54.7	13.6	7.9	10.5	1.0	8.0	5.3
D3	Yizheng	Huafeng	Hydromorphic	5.5	24.2	70.3	6.7	11.4	1.0	4.6	2.0
D4	Yizheng	Heyun	Percogenic	26.2	35.9	37.9	7.4	5.2	0.7	6.1	2.2
E1	Luhe	Jiebei	Gleyed	36.0	53.0	10.9	7.7	10.8	1.3	7.3	3.1
E2	Luhe	Changcheng	Hydromorphic	60.6	28.6	10.8	7.6	16.3	1.6	4.7	2.9
E3	Luhe	Daying	Hydromorphic	25.7	35.3	38.9	7.1	18.1	1.7	3.5	1.3
Minimum				4.3	24.2	3.5	5.6	5.2	0.7	3.5	1.3
Maximum				60.6	81.5	70.3	8.6	39.4	3.4	136.0	63.3
Mean				34.9	42.5	22.5	7.3	16.2	1.6	36.8	17.1
C.V.(%)				47.7	32.0	81.6	10.8	48.2	40.8	121.7	125.6

Figure 1. Seasonal pattern of CH₄ emission from different soils.

obtained by gas chromatography (Shimadzu, GC 14-A) with a flame ionization detector. The emission was determined from the slope of the mixing ratio change in the five samples of 60 cm³ taken over a 20-min sampling period. Sample sets that did not yield a linear regression value of r^2 greater than 0.90 were rejected. Rates of CH₄ emission were determined from an average of three replicates. Chamber air temperature was recorded with each set of emission measurements.

Results and discussion

Variation in methane emission among soils

A wide variation in CH₄ emission was observed among the soils (Table 2). The average emission rate over the season was 6.42 mg m⁻² h⁻¹ for all 18 soils with a standard deviation of 2.70 mg m⁻² h⁻¹. The highest emission rate came from soil E3 with an average value of 11.06 mg m⁻² h⁻¹ and the lowest was from soil A3 with an average value of 1.96 mg m⁻² h⁻¹, approximately a 5.6-fold difference between the highest and the lowest. Based on the seasonal average, we counted the frequency distribution of CH₄ emission rates from a total of 54 pots (18 soils with triplicates). Among the 54 pots, 20% (11 out of 54) had emission rates less than 4 mg m⁻² h⁻¹, 50% (27 out of 54) between 4 and 8 mg m⁻² h⁻¹, and 30% (16 out of 54) higher than 8 mg m⁻² h⁻¹, respectively.

Figure 1 shows representative seasonal patterns of CH₄ emission from three soils typical of low, medium and high emission. As shown in Figure 1, CH₄

Table 1. contd.

Soil code	Total phosphorus (g/kg)	Available potassium (mg/kg)	Sulphur		Iron		Copper		Manganese		Magnesium	
			Available (mg/kg)	Total (g/kg)	Available (mg/kg)	Total (g/kg)	Available (mg/kg)	Total (g/kg)	Exchangeable (mg/kg)	Total (g/kg)	Exchangeable (mg/kg)	Total (g/kg)
A1	1.28	162	22.3	0.435	30.0	32	2.8	0.050	3.1	0.496	807.1	2.3
A2	1.46	96	14.7	0.334	55.8	28	5.3	0.043	16.8	0.413	652.6	2.2
A3	1.30	103	14.3	0.393	20.4	30	5.3	0.070	29.1	0.424	649.2	3.0
B1	1.36	49	14.1	0.479	57.9	16	1.9	0.025	11.1	0.135	43.1	1.3
B2	1.46	36	24.6	0.402	46.1	18	2.0	0.023	46.4	0.455	233.0	2.0
B3	1.16	119	11.1	0.358	24.7	27	2.3	0.033	44.3	0.345	533.3	2.2
C1	1.78	125	138.1	0.424	25.8	23	1.5	0.024	30.7	0.510	298.0	12.0
C2	2.51	131	92.5	0.372	29.9	31	2.5	0.037	8.6	0.729	423.4	11.0
C3	2.34	141	101.2	0.766	54.7	32	3.4	0.035	3.6	0.711	600.4	9.4
C4	1.50	126	121.0	1.203	23.9	25	3.7	0.031	25.1	0.271	746.8	4.3
C5	1.84	148	26.5	0.450	52.6	27	3.1	0.034	15.9	0.496	765.1	4.5
D1	1.58	283	9.5	0.389	235.0	27	4.6	0.035	44.6	0.649	565.8	4.0
D2	1.48	26	3.0	0.404	79.4	19	1.5	0.020	16.0	0.479	325.8	3.6
D3	1.16	56	6.3	0.389	49.4	22	1.0	0.026	50.6	0.486	340.1	3.4
D4	1.17	131	8.5	0.896	125.5	28	3.9	0.034	26.6	0.670	767.8	4.3
E1	0.86	119	16.0	0.310	50.4	24	2.9	0.030	17.1	0.350	724.4	2.8
E2	1.08	119	24.6	0.304	44.0	35	3.0	0.050	8.3	0.350	988.8	4.2
E3	1.75	70	43.1	0.489	632.0	30	2.4	0.024	48.8	0.611	696.6	4.6
Minimum	0.86	26	3.0	0.304	20.4	16	1.0	0.020	3.1	0.135	43.1	1.3
Maximum	2.51	283	138.1	1.203	632.0	35	5.3	0.070	50.6	0.729	988.8	12.0
Mean	1.50	113	38.4	0.489	91.0	26	3.0	0.035	24.8	0.477	564.5	4.5
C.V.(%)	28.1	51.3	111.9	47.8	158.4	19.8	42.3	35.5	65.3	33.0	42.8	68.5

emissions from the highest emission soil E3 increased rapidly, while that from the lowest emission soil A3 increased slowly during the early growing season. Two emission peaks occurring in the developmental stages of panicle differentiation and heading were observed from soil E3. As rice growth and development proceeds, CH₄ emission from soil A3 remained lower in comparison with that from the soils of B2 and E3. Emissions from soil E3 were considerable higher than those from soil B2 over the entire season. The comparable seasonal pattern of CH₄ emission (Figure 1) suggests that soils emit more CH₄ throughout the season when high emission rates occur in the early season.

To further identify variations in CH₄ emission among these soils, average rate of CH₄ emission from each soil was calculated for the vegetative, reproductive and ripening developmental stages. The vegetative stage refers to the period before panicle differentiation; the reproductive stage, from panicle differentiation to heading; and the ripening period, from heading to maturity (Yoshida, 1981). Results

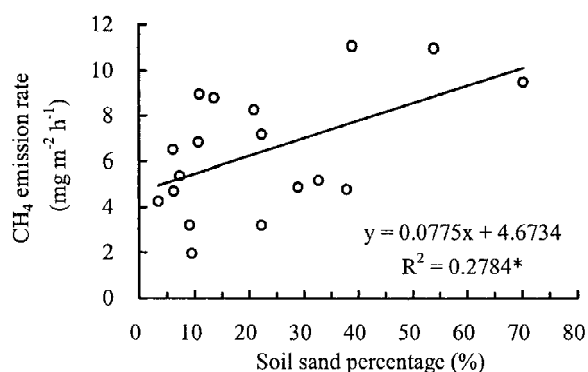
from calculations indicated that the variation in CH₄ emission among soils was also significant in each rice developmental period. The average emission rates for the vegetative, reproductive and ripening stage ranged from 0.03 to 8.38 mg m⁻² h⁻¹, from 2.60 to 19.83 mg m⁻² h⁻¹, and from 3.08 to 9.48 mg m⁻² h⁻¹, respectively (Table 2). It is also noteworthy that the variation in the emission was high for all developmental stages. The average emission rates for the vegetative, reproductive and ripening stage were respectively 2.63, 10.99 and 6.04 mg m⁻² h⁻¹ (Table 2), suggesting that more attention should be focused on the reproductive stage to control and reduce CH₄ emissions.

Soil parameters influencing CH₄ emission

Field measurements by Sass et al. (1994) and Cai et al. (1998) showed that soils with high sand content result in higher CH₄ emission than more clay- or silt-rich soils. A very similar result was also obtained in this study (Figure 2). However, the value of *R*² suggested that the soil sand content could only explain

Table 2. Methane emissions from irrigated rice cultivation in various paddy soils

Soil code	Entire growing season		Vegetative period		Reproductive period		Ripening period	
	Average	SD	Average	SD	Average	SD	Average	SD
	(mg m ⁻² h ⁻¹)	(mg m ⁻² h ⁻¹)	(mg m ⁻² h ⁻¹)	(mg m ⁻² h ⁻¹)	(mg m ⁻² h ⁻¹)	(mg m ⁻² h ⁻¹)	(mg m ⁻² h ⁻¹)	(mg m ⁻² h ⁻¹)
A1	7.18	1.57	2.48	0.19	13.92	3.26	6.59	1.78
A2	3.20	0.65	0.53	0.09	4.18	1.08	4.64	0.85
A3	1.96	0.42	0.03	0.03	2.60	0.52	3.12	0.48
B1	10.97	0.66	8.34	1.48	17.23	2.32	9.26	1.08
B2	6.50	0.57	2.72	0.42	12.23	1.92	6.00	0.26
B3	5.37	1.13	0.56	0.20	8.98	3.88	6.47	0.83
C1	5.18	0.76	2.85	0.36	12.11	1.95	3.08	0.92
C2	4.69	0.62	1.57	0.39	9.74	0.76	3.19	0.97
C3	4.25	1.40	0.60	0.27	9.24	4.04	3.47	0.59
C4	3.20	1.11	0.77	0.36	5.57	3.45	3.66	0.72
C5	4.88	0.52	0.40	0.18	6.89	1.30	5.56	1.04
D1	8.26	0.85	0.97	0.21	14.73	3.93	7.62	0.74
D2	8.79	0.29	8.38	0.24	12.87	0.68	6.40	0.21
D3	9.49	0.60	6.99	0.67	15.28	1.82	7.65	2.47
D4	4.78	2.15	0.39	0.22	5.51	1.42	5.77	2.4
E1	8.96	1.41	2.52	0.52	16.21	3.73	9.48	1.27
E2	6.83	0.35	0.90	0.10	10.69	1.37	7.59	1.57
E3	11.06	0.89	6.28	1.21	19.83	2.79	9.18	0.95
Average	6.42		2.63		10.99		6.04	
SD	2.70		2.85		4.81		2.17	

Figure 2. Correlation of seasonal average rate of CH₄ emission against soil sand percentage.

some 27.8% of CH₄ emission variability among the soils, indicating that the sand fraction may be not a dominant parameter.

Previous incubation studies (Neue et al., 1994; Wassmann et al., 1998; Yao et al., 1999) indicated that CH₄ production was positively correlated with soil organic carbon and scientists used this soil parameter as a key criterion to estimate CH₄ emission from

rice paddies (Bachelet and Neue, 1993; Cao et al., 1995). However, our measurements did not show any indication that CH₄ emissions increase with increasing soil organic carbon. On the contrary, relatively lower CH₄ emissions were observed from the soils with a high organic carbon content (Figure 3a). A further analysis indicated that CH₄ emission from soils of group C (collected in Baoying County) was negatively correlated with soil organic carbon (Figure 3b), while the emission from soils of group D (collected in Yizheng City) was positively correlated with soil organic carbon (Figure 3c). We did not find any other soil parameters that could significantly correlate CH₄ emission for these two soil groups. No significant correlation of seasonal average emission with soil organic carbon was found for the soils of group A, B and E.

It may be postulated that the methanogenic carbon substrates come mainly from rice plants via root exudation and biomass litter, added organic matter and soil organic carbon. Nevertheless, soil organic carbon represents the main component of humus that is more recalcitrant. On the standard method of soil organic carbon analysis, organic debris is removed from soil before soil organic carbon analysis. Though the

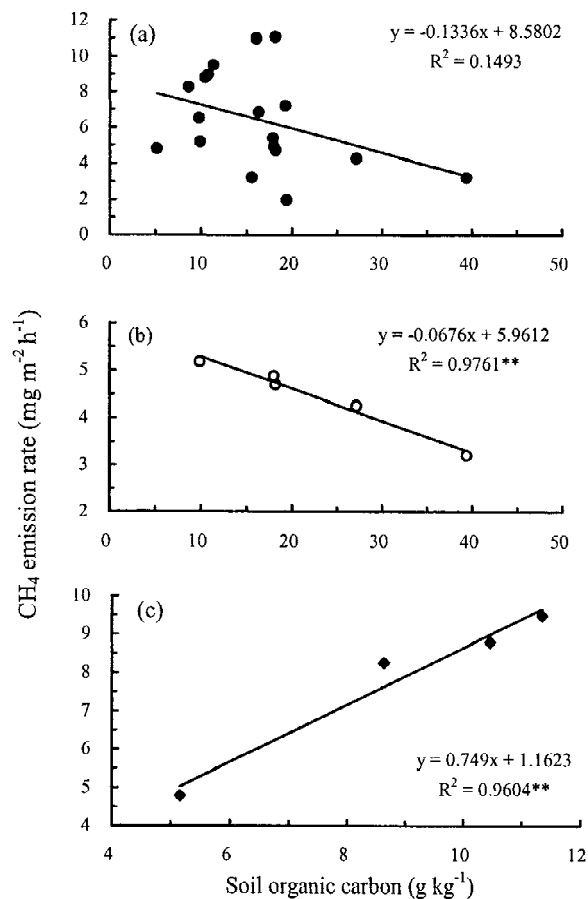


Figure 3. Correlation of seasonal average rate of CH_4 emission against soil organic carbon. (a) Measurements from all 18 soils, (b) measurements from soils collected in Baoying, and (c) measurements from soils sampled in Yizheng.

organic debris would also supply substrates for CH_4 production, the contribution of soil organic carbon including the organic debris, in contrast to the carbon source from rice plants, to the CH_4 emission would be very small in the presence of a rice crop. Whether the soil organic carbon can be regarded as a main input remains a question in estimating CH_4 emissions from rice cultivation.

Methane production from incubation studies was found to be positively correlated soil total N (Wassmann et al., 1998; Yao et al., 1999). A plot of seasonal average CH_4 emission against soil total N, however, yielded a weak negative correlation ($r^2 = -0.2053$, $P < 0.10$) in this study (Figure 4). Note that the uncertainties in CH_4 emission are obvious for the soils with total N content lower than 2 g kg^{-1} , though comparable low CH_4 emissions were observed

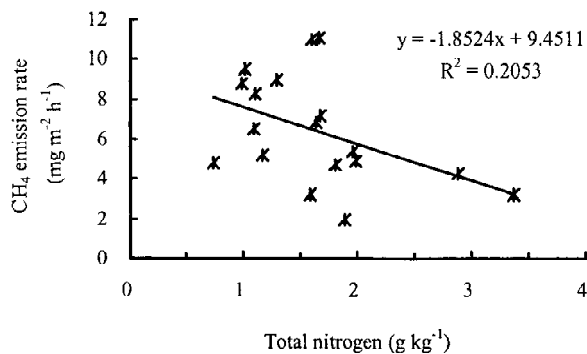


Figure 4. Correlation of seasonal average rate of CH_4 emission against soil total nitrogen.

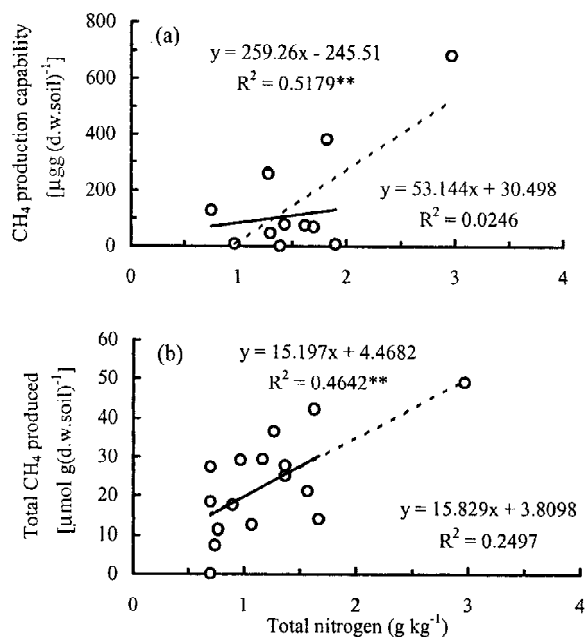


Figure 5. Correlation of CH_4 production against soil total nitrogen. (a) Data sets adopted from Wassmann et al. (1998), and (b) data sets adopted from Yao et al. (1999). Dash lines were derived from all the data sets. Solid lines were derived for the soils with total nitrogen content of lower than 2 g kg^{-1} . See text for details.

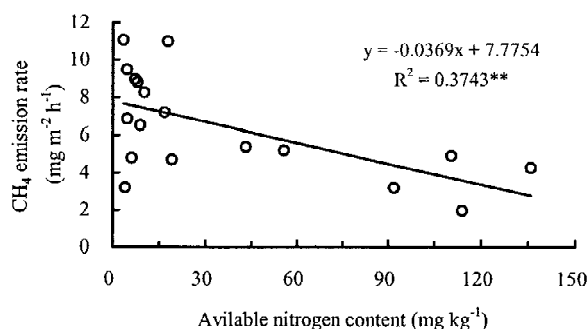


Figure 6. Correlation of CH_4 emission with soil available nitrogen content determined before transplanting.

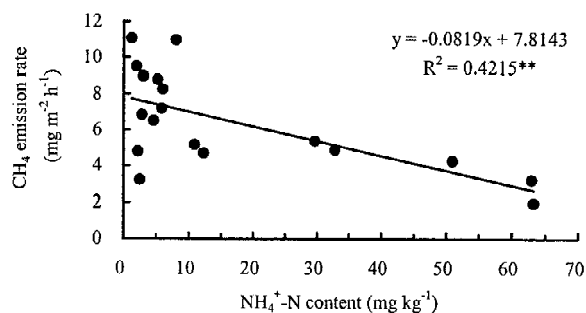


Figure 7. Correlation of CH₄ emission with soil NH₄⁺-N content determined before transplanting.

from soils with a high content of total N (Figure 4). We cited the data sets of CH₄ production and soil total N from Wassmann et al. (1998) and Yao et al. (1999) and plotted the production against the total N with the same unit for soil total N as used in Figure 4. It is apparent that the CH₄ production was not dependent on soil total N ($r^2 = 0.0246$, Figure 5a) or positively correlated with soil total N at a weak probability level ($r^2 = 0.2497$, $P < 0.10$, Figure 5b) for the soils with total N content of lower than 2 g kg⁻¹. Correlation shown in Figures 4 and 5 indicated that the effect of total N on CH₄ emission differs from that on CH₄ production, especially for the soils with a high content of total N.

When seasonal average CH₄ emissions were plotted against soil available N (Figure 6) and soil NH₄⁺-N (Figure 7), respectively, a linear negative correlation was obtained. It must be noticed that large uncertainties in CH₄ emission existed for soils with low available N or NH₄⁺-N. This result suggests that soils with a high content of available N or NH₄⁺-N result in lower CH₄ emission, while soils with a low content of available N or NH₄⁺-N may not yield higher CH₄ emission. Xu et al. (2000) made simultaneous measurements of NH₄⁺-N concentration in floodwater and CH₄ emission from a greenhouse pot experiment over a rice-growing season in Belgium. They found a wide random variation in CH₄ emission, ranging from a negligible amount to a value of 75 μg per kilogram air-dried soil per hour ($n = 28$), occurred when the NH₄⁺-N concentration was lower than 1.25 mg per liter. On the other hand, the CH₄ emission was almost undetectable for the NH₄⁺-N concentrations between 1.25 and 3 mg per liter ($n = 20$). It was therefore thought that CH₄ oxidation might be associated with NH₄⁺ turnover in the surface layer soil (Xu et al., 2000).

Over an entire growing season, average rates of CH₄ emission were negatively correlated with soil available copper (Figure 8a). A negative exponential correlation of CH₄ emission against soil available copper was found to be statistically significant for the vegetative stage (Figure 8b) and reproductive stage (Figure 8c), whereas there was no significant relationship between these two parameters during the ripening stage (Figure 8d).

The negative correlation of available copper and CH₄ emission in the vegetative stage and reproductive stage (Figure 8b and c) was much stronger than during the ripening stage (Figure 8d) at which time the soil had been flooded for about 2 months. This result suggests that the effect of soil available copper on CH₄ emission may be associated with soil biochemical processes. Possible interpretation might be that a higher concentration of available copper may chelate more root exudation and yield a carbon-copper compound, which then reduces the availability of methanogenic substrates. Data sets from a similar outdoor pot experiment with 10 paddy soils during 2001 rice growing season (this group unpublished data) showed that soluble organic carbon of the soils was negatively correlated with the soil available copper, which provided an indirect evidence for the interpretation. More detailed investigation would be required to mechanically understand the effect of soil available copper on methanogenic substrates.

In contrast with the correlations in Figures 6 and 7, correlations in Figure 8 are more reasonable since the concentration of available copper is evenly distributed among the soils within a range from 1.0 to 5.3 mg kg⁻¹. These data suggest that available copper in soils might be a good indicator in addressing the effect of soil parameters on CH₄ emission.

Table 3 gives the Pearson correlation coefficients of CH₄ emission in Table 2 against various soil physico-chemical properties in Table 1. The correlation coefficients indicate that soil available N and NH₄⁺-N as well as soil sand percentage affect CH₄ emissions for all the three developmental stages, while other soil parameters influencing CH₄ emission were different as rice growth and development proceeds. For the vegetative stage, CH₄ emission was negatively correlated with soil available and total copper, total iron, exchangeable magnesium and available potassium, respectively, suggesting that the processes of CH₄ production in the soils may relate to these elements. A negative correlation of CH₄ emission with soil clay percentage was also observed for this stage.

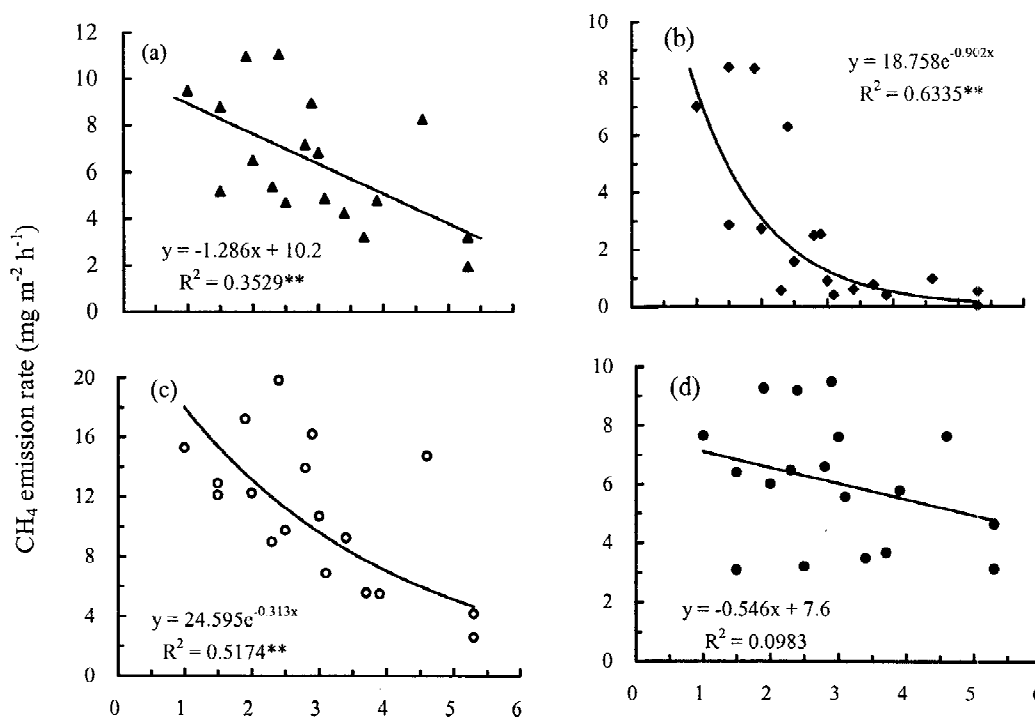


Figure 8. Correlation of soil available copper content determined before transplanting with average rate of CH₄ emission in an entire growing season (a), vegetative stage (b), reproductive stage (c), and in ripening stage (d).

Unlike the case in the vegetative stage, CH₄ emission in the reproductive stage did not significantly correlate with soil total iron, exchangeable magnesium and available potassium, while the influence of soil available iron, available and total copper on CH₄ emission was found to be statistically significant (Table 3). For the ripening stage, CH₄ emission was negatively correlated with soil total phosphorus, available sulphur and total magnesium, respectively.

When the CH₄ emission in Table 2 was examined with the corresponding soil type in Table 1, we found that a wide variation in CH₄ emission existed among soils of A3, B1, C2, D3, E2 and E3. These soils, however, were classified as the same type of hydromorphic. This result suggested that CH₄ emission was not dependent on soil type.

Although CH₄ emissions have been connected with rice biomass production (Sass et al., 1990; Huang et al., 1997a, b), CH₄ emissions from various soils in this study were not found to be associated with rice biomass production. Since the dependence of CH₄ emission on rice biomass production was only documented for the similar soils and cultivational practice (Sass et al., 1990; Huang et al., 1997a, b), it is not surprising that CH₄ emission is determined

by physico-chemical properties rather than by rice biomass production when various soils were involved.

Integrative effect of soil parameters on CH₄ emission

In order to determine the integrative effect of soil parameters on CH₄ emission, we applied a stepwise regression method for each item of the CH₄ emissions (Table 2) against soil properties (Table 1) and some derived variables from Table 1. The derived variables include the ratios of soil available to total sulphur, available to total iron, available to total copper, exchangeable to total manganese, and exchangeable to total magnesium. Result of the stepwise regression is shown in Table 4.

Analysis of the stepwise regression indicated that a linear combination of four variables can explain more than 81% of the variability in seasonal average of CH₄ emission, including soil NH₄⁺-N, available copper, the ratio of available to total sulphur and the ratio of available to total iron (Table 4). Coefficients that estimated for the variables of soil NH₄⁺-N, available copper and the ratio of available to total sulphur are negative (Table 4), suggesting that soils with high concentration of these elements would result in lower CH₄

Table 3. Pearson correlation coefficients of CH₄ emission against soil physico-chemical properties

	Developmental stage			
	Entire growing season	Vegetative	Reproductive	Ripening
Clay	-0.4837*	-0.6169**	-0.3512	-0.4340 ^b
Silt	-0.1214	-0.0371	-0.1383	-0.0168
Sand	0.5276*	0.5859*	0.4199 ^b	0.4049 ^b
pH	-0.1030	-0.1287	0.0284	-0.2674
Organic carbon	-0.3863	-0.2484	-0.3102	-0.3767
Total nitrogen	-0.4488 ^b	-0.3592	-0.3527	-0.4154 ^b
Ratio of C/N	0.1086	0.3799	0.1081	-0.0229
Available nitrogen	-0.6112**	-0.4396 ^b	-0.5301*	-0.6210**
NH ₄ ⁺ -N	-0.6486**	-0.4487 ^b	-0.5978**	-0.6042**
Total phosphorus	-0.2536	-0.1084	-0.0910	-0.5467*
Available potassium	-0.2434	-0.6198**	-0.1382	-0.1358
Available sulphur	-0.3750	-0.2131	-0.1371	-0.6189**
Total sulphur	-0.3245	-0.1977	-0.3352	-0.3304
Available copper	-0.5939**	-0.6962**	-0.6314**	-0.3136
Total copper	-0.5472*	-0.5829*	-0.5516*	-0.3277
Available iron	0.4958*	0.2925	0.4961*	0.4439 ^b
Total iron	-0.4026 ^b	-0.6276**	-0.3238	-0.2589
Exchangeable manganese	0.2224	0.1466	0.2197	0.2164
Total manganese	-0.1430	-0.2296	-0.0327	-0.3126
Exchangeable magnesium	-0.3276	-0.6174**	-0.3461	-0.0252
Total magnesium	-0.2861	-0.1813	-0.0750	-0.5835*

^b, *, ** Significant at probability levels of 0.1, 0.05 and 0.01%, respectively.

Table 4. Results of stepwise regression of CH₄ emissions with the soil properties

Methane emission rate (mg m ⁻² h ⁻¹)	Variables	Estimated coefficient	P-value (2 Tail)	R ²
Entire growing season	Constant	10.4783	0.0000	0.8114
	NH ₄ ⁺ -N	-0.0358	0.0640	(P = 0.0001)
	Available copper	-1.1665	0.0017	
	Ratio of available to total sulphur (%)	-0.1003	0.0284	
	Ratio of available to total iron (%)	2.2588	0.0078	
Vegetative stage	Constant	6.0837	0.0000	0.8812
	Available potassium	-0.0109	0.0755	(P = 0.0000)
	Available iron	-0.0991	0.0000	
	Ratio of available to total copper (%)	-0.0503	0.0016	
	Ratio of available to total iron (%)	32.5036	0.0000	
Reproductive stage	Constant	16.1614	0.0000	0.6647
	Available copper	-2.3500	0.0010	(P = 0.0003)
	Ratio of available to total iron (%)	5.1579	0.0036	
Ripening stage	Constant	10.1985	0.0000	0.8521
	Available sulphur	-0.0285	0.0005	(P = 0.0001)
	Total manganese	-6.1394	0.0051	
	Available copper	-0.8626	0.0028	
	Available potassium	0.0140	0.0214	
	Ratio of available to total iron (%)	2.3910	0.0008	

emission on a seasonal average. On the other hand, a high ratio of available to total iron would enhance CH₄ emission.

The average rate of CH₄ emission in the vegetative stage can be well determined by a linear combination of four variables ($R^2 = 0.8812$, $P = 0.0000$), including soil available potassium, available iron, the ratio of available to total copper, and the ratio of available to total iron (Table 4). Two variables of available copper and the ratio of available to total iron were identified ($R^2 = 0.6647$, $P = 0.0003$) for the reproductive stage (Table 4). The average rate of CH₄ emission during the ripening stage was quantitatively determined by a linear combination of five variables ($R^2 = 0.8521$, $P = 0.0001$). These variables include soil available sulphur, available copper, available potassium, total manganese, and the ratio of available to total iron (Table 4).

As shown in Table 3, CH₄ emission is affected by various soil parameters. It is unlikely to expect that the variability in CH₄ emission from various soils could be explained by a single soil parameter (Table 4). Further improvement in the accuracy of estimating CH₄ emission from rice paddies would be possible if a more reliable soil-specific scaling factor, as shown in this study, could be derived from considerable measurements.

Conclusions

Methane emission was greatly dependent on soil properties rather than on soil type. Soil parameters influencing CH₄ emission were different as rice growth and development proceeds. Key soil parameters affecting CH₄ emission over an entire growing season included N status, concentration of available copper and sand percentage when the emission was correlated against a single soil parameter. Rice grown in soils with a high concentration of either available N or NH₄⁺-N resulted in lower CH₄ emission than nitrogen-poor soils. Methane emission was negatively correlated with soil available copper. High CH₄ emission was generally occurred in sand-rich soils. No clear relationship existed between soil carbon content and CH₄ emission. When soil parameters were integrally taken into account, seasonal average rate of CH₄ emission could be quantitatively described by a linear combination of four soil-related variables, including NH₄⁺-N, available copper, the ratio of available to total sulphur and the ratio of available to total iron.

More than 81% of the variability in seasonal average of CH₄ emission can be explained by this linear combination. A further conclusion is that soil parameters determined from rice-free incubation experiment were not representative of those obtained from rice-planted experiment.

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