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Spatial and Temporal Variations in Methane Fluxes from Irrigated Lowland Rice Fields

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An assessment of spatial and temporal variations in methane (CH_4) emission was conducted in three experimental fields (UQ, UY and UE) of the International Rice Research Institute Experimental Farm in Bay, Laguna, Philippines during the 2009 dry season. Aside from CH_4 fluxes, the following parameters were also determined: hot water-extractable C (HWEC), floodwater temperature (FWT), floodwater depth (FWD) and plant height. Field sampling was conducted using static chambers and CH_4 concentrations were analyzed using a gas chromatograph. The highest average emission rate was observed in field UQ, followed by UE and UY (651, 107 and 95 mg CH_4 m^{-2} d^{-1}, respectively). The UQ field also had the highest average HWEC (618 mg kg^{-1} compared with 496 for UY 496 and 482 for UE). Significant temporal variations in CH_4 emission, HWEC and FWT were observed within each field. Stepwise multiple regression analysis showed that HWEC, plant height, FWT and FWD accounted for 62% of the spatial and temporal variabilities in CH_4 fluxes. Soil HWEC showed the greatest contribution (R^2 = 0.46, *P*<0.0001), followed by plant height (R^2 = 0.11, *P*<0.0001), FWT (R^2=0.03, *P*<0.04) and FWD (partial R^2=0.02, *P*<0.07).

Key Words: flooded rice, hot water-extractable carbon, methane emission

Abbreviations: CH_4 – methane, CO_2 – carbon dioxide, DAT – days after transplanting, DOC – dissolved organic carbon, FID – flame ionization detector, GC – gas chromatograph, GHG – greenhouse gases, HWEC – hot water-extractable carbon, N_2O – nitrous oxide, OM – organic matter, SOC – soil organic carbon

INTRODUCTION

Methane (CH_4) is a potent greenhouse gas that has 25 times more global warming potential (GWP) than CO_2 (Solomon et al. 2007), contributing 15% to enhanced global warming (Jain et al. 2004). The concentration of CH_4 in the atmosphere has been increasing in the last 200 yr and has reached 1.77 ppm by volume in 2005, which is more than double that of its pre-industrial value (Solomon et al. 2007). Methane is the end product of the anaerobic decomposition of organic matter (Liesack et al. 2000) produced by strictly anaerobic bacteria (methanogens) in a very reduced (redox potential: <-150 mV) environment (Wang et al. 1993). Irrigated rice accounts for more than 75% of global rice production (IRRI 1993) and these rice fields are the major source of CH_4 gas (Minami and Neue 1994; Neue and Sass 1994), contributing about 18% of 596 Tg global CH_4 flux (Denman et al. 2007). Thus, several studies were conducted to mitigate CH_4 emissions in rice fields through soil and water management (Ko et al. 2002; Harada et al. 2007; Ahmad et al. 2009; Ishibashi et al. 2009).

Methane emission from rice fields is controlled by several factors, although this is determined mainly by organic inputs and water regime (Yan et al. 2005). Because of the interactive effects of soil, climatic and cultural factors, the uncertainty of estimating CH_4 emission from rice fields is increasing. Upscaling of flux rates is hampered by this uncertainty and by pronounced spatial and temporal variations (Sass et al. 2002; Van Bodegom et al. 2000). With increasing global temperature and with the intensification of rice production to meet the food demand of a growing population, the factors that control CH_4 emissions are predicted to change drastically in the future (Wassmann

and Aulakh 2000). There is an urgent need to evaluate the interaction between CH_4 emission and rice production in a changing climate to estimate source strength (Neue et al. 1997) and provide a basis for future decisions regarding mitigation options. The increasing uncertainties of diurnal, temporal and spatial variation (Neue 1993) should be narrowed down to be able to come up with a reliable global CH_4 budget and identify effective mitigation measures.

The amount and pattern of CH_4 emission can be controlled by soil, climatic and cultural factors. Studies have shown variations in CH_4 emission from continuously flooded rice soils in different locations with varying soil properties and climates (Kimura et al. 1991; Adhya et al. 1994; Minami and Neue 1994; Inubushi et al. 1997; Yang and Chang 1998; Yao et al. 1999; Yang and Chang 2001; Gogoi et al. 2008; Kumar and Viyol 2009). Soil organic carbon (SOC) acts as a substrate for methanogens (Penning and Conrad 2007), thus it has significant correlation with CH_4 production (Wassmann et al. 1998). It has a different fraction and easily degradable fraction affects the rate of CH_4 production (Yao et al. 1999). Hot water-extractable carbon (HWEC) consists of a labile carbon which is easily decomposable or readily mineralizable (Schulz and Körschens 1998; Chodak et al. 2003) and serves as an indicator of the decomposable SOC pool (Schulz et al. 2011). Dissolved organic carbon (DOC), which is also a component of HWEC, increases with plant growth and has a positive correlation with CH_4 emission (Lu et al. 2000b). Since this labile fraction of organic matter can respond rapidly to changes in carbon supply (Zhang et al. 2006), application of rice straw contributes higher amount of CH_4 emission in flooded soils (Wang et al. 1992; Wattanable et al. 1995; Yagi 1997; Rath et al. 1999; Bossio et al. 1999; Naser et al. 2007). Generally, peaks of CH_4 emission appear once at the early tillering stage and at the flowering or reproductive stage (Yang and Chang 1999). The early-season peak appears in soil with high inherent and added organic matter (OM) or where rice straw has been incorporated (Neue et al. 1997; Wassmann et al. 2000), whereas peaks at the reproductive stage are due to the supply of plant-borne C through root exudates and decaying tissues (Neue et al. 1997).

Most studies reported on large-scale spatial variation comparing sites which are far away from each other and with very different soil properties and climate. However, the variations in CH_4 emission across nearby fields in relation to change in soil, water and plant properties have not been investigated thoroughly. Therefore, this study aimed to assess the spatial and temporal variations in CH_4 emission rates from three nearby irrigated lowland rice fields at the International Rice Research Institute (IRRI) Farm and to quantify the simultaneous effects of soil labile C, floodwater temperature, floodwater depth and plant growth on the observed CH_4 fluxes.

MATERIALS AND METHODS

Site Description and Crop Management

This study was conducted at the IRRI Experimental Farm in Bay, Laguna, Philippines during the 2009 dry season under irrigated conditions. Gas samplings were done within the experimental sites identified herein as UQ (latitude: 14° 08' 33.88" N, longitude: 121° 15' 57.96" E, 21 m asl), UY (latitude: 14° 08' 27.63" N, longitude: 121° 15' 55.15" E, 21 m asl) and UE (latitude: 14° 08' 49.26" N, longitude: 121° 15' 58.26" E, 21 m asl) fields, about 1 km away from each other. The soil was classified as Aquandic Epiaquoll (Dobermann et al. 2000). The soil properties (0–15 cm depth) of the study sites are shown in Table 1. Field UQ had the highest clay and carbon content but the lowest available K (Ammonium Acetate extraction) and P (Olsen P). Most of the soil properties of UY and UE were similar, except for the higher P content in the former.

Rice seedlings (*Oryza sativa* L. cv. Angelica) were transplanted on 9 Jan 2010, 31 Dec 2008 and 15 Jan 2009 in the UQ, UY and UE fields, respectively, with a plant spacing of 20 cm x 20 cm, giving a plant density of 25 hills m^{-2}. Rice straw harvested from the previous crop was incorporated into the soil on 31, 13 and 20 Oct 2008 in UQ, UY and UE, respectively. Thus, the time intervals from straw incorporation to transplanting were 70, 79 and 87 d for UQ, UY and UE, respectively. The UY field had the highest straw yield of 7 t ha^{-1}; followed by UE, 6.0 t ha^{-1} and UQ, 5.8 t ha^{-1}. Urea, single super phosphate (SSP) and muriate of potash (MOP) were applied at the rate of 120-30-30 kg NPK ha^{-1}. SSP and MOP were applied during land preparation as basal, while urea was applied in three splits: 14 DAT, at maximum tillering and at panicle initiation (total amount, 120 kg N ha^{-1}).

Gas Chambers Set up in the Field

Methane emissions were measured using the 'closed chamber' technique. The gas chambers were made of transparent acrylic glass plates with metal frame; the dimensions were 60 x 60 x 122.5 cm. Each chamber was equipped with a battery-powered fan to ensure thorough mixing of air inside the chamber, a thermometer to measure the inside temperature during gas sampling and a rubber septum fixed in the chamber wall to collect the gas. During measurement, the chambers were temporarily fitted on a metal base that was submerged in the soil and floodwater. The chamber that covered nine rice hills had a closed head space when placed in the field. Three replicate gas chambers spaced at 10 m distance were set up in each field.

Gas Sampling and Analysis of Methane Gas

Gas sampling was conducted once a week at 1400 h for 3 consecutive days, i.e., 1 d for each field. Air samples were taken from the chamber head space by using a

Table 1. Physicochemical characteristics of soils used in the three experimental sites.

Soil Property	UQ	UY	UE
pH	6.2	6.2	6.1
CEC (meq 100 g^{-1})	30.45	29.75	31.30
Silt (%)	44	45	38
Clay (%)	38.5	32.0	32.0
Sand (%)	17.5	23.0	30.0
Total N (%)	0.14	0.13	0.12
Total C (%)	1.45	1.35	1.29
Available K (meq 100 g^{-1})	1.00	1.46	1.65
Available P (mg kg^{-1})	22.5	62.5	29.5
Bulk density (g cm^{-3})	1.15	1.16	1.07

UQ (latitude: 14° 08' 33.88" N, longitude: 121° 15' 57.96" E, 21 m asl), UY (latitude: 14° 08' 27.63" N, longitude: 121° 15' 55.15" E, 21 m asl) and UE (latitude: 14° 08' 49.26" N, longitude: 121° 15' 58.26" E, 21 m asl)

plastic 50-mL syringe. Four gas samples were taken at 10-min intervals for 30 min. The concentration of CH_4 in the samples was measured using a gas chromatograph (Shimadzu GC-14B, Shimadzu Corporation, Kyoto, Japan) with a flame ionization detector (FID). The carrier gas was nitrogen (N_2) with a flow rate of 14 mL min^{-1}. The column was packed with Porapak Q, and column temperature was maintained at 60 °C. A gas chromatograph (GC)-computer interface was used to quantify the peak area. The temporal increase of CH_4 concentration (ppm min^{-1}) was determined from the slope of the regression curve of CH_4 concentration against time (0, 10, 20 and 30 min). CH_4 emission, expressed as mg CH_4 m^{-2} d^{-1}, was calculated using the following equation (IAEA 1992):

$$CH_4 \text{ emission } (\text{mg m}^{-2}\text{ d}^{-1}) = \frac{\text{Slope (ppm min}^{-1}) \times 453 \times 16 \times 60 \times 24}{22.4 \times ((273+T)/273) \times 0.36 \times 1000}$$

where 453 is the volume of the gas chamber in liters (L), 16 is the molecular weight of CH_4, 60 is min h^{-1}, 24 is h d^{-1}, 22.4 is the volume of 1 mole of gas in L at standard temperature and pressure, 273 is the standard temperature in °K, T is the temperature inside the chamber in °C, 0.36 is the area occupied by the chamber in m^2, and 1000 is µg mg^{-1}.

Measurement of Hot Water-Extractable Carbon

Soil core samples (0–15 cm depth) were collected around the chamber after every gas sampling, using 5-cm-diameter PVC pipes. A total of 20 soil core samples were collected around each chamber. Ten collected soil cores were combined in one plastic bag and thoroughly mixed. Thus, two composite soil samples were obtained around each chamber at each sampling time for soil analysis. External debris were removed from the soil samples in each bag and the soil mixed before analysis. Thirty grams of fresh soil sample with 100 mL deionized-distilled water were transferred into a 250 mL flat-bottomed boiling flask. These soil samples were heated under reflux at 100 °C and cooled to room temperature. After cooling at room temperature, the boiled samples were centrifuged for about 10 min to get an extract free from the soil particles. Hot water-extractable carbon (HWEC) was analyzed with an OI 1020A TOC analyzer following procedures described by Tirol-Padre et al. (2007) and Chodak et al. (2003). HWEC was expressed as mg C kg^{-1} dry soil using the following formula:

HWEC (mg C kg^{-1} soil) = ppm C x [vol extractant (mL) + soil moisture (mL)]/soil dry wt (g)

Plant height was monitored at weekly interval on every gas sampling date. Rice hills within the area covered by chambers were selected for the measurement. The average value was made from three replicate chambers. The tip of the longest leaf of the hill was considered as the end point of the rice plant. Water and air temperatures were recorded on every gas sampling date, while floodwater level was monitored every day throughout the growing season.

Data Analysis

Tests of fixed effect of site and days after transplanting (DAT) on CH_4 emission rates and HWEC were done using the SAS mixed procedure. Stepwise multiple regression analysis was done to quantify the simultaneous effects of HWEC, floodwater temperature, floodwater depth and plant height on CH_4 emissions. All analyses were done using SAS V9.1 (SAS Institute 2003).

RESULTS AND DISCUSSION

Spatial and Temporal Variations in CH_4 Emission

Spatial and temporal variations in CH_4 emission were apparent from the tests of fixed effects using the SAS mixed procedure. The effects of site (spatial), DAT (temporal) and site x DAT on CH_4 emissions were highly significant (Table 2). The average CH_4 emission rate was much higher in UQ (651 mg m^{-2} d^{-1}) than in UY (95 mg m^{-2} d^{-1}) and UE (107 mg m^{-2} d^{-1}) throughout the crop cycle. Similarly, cumulative CH_4 emission was also higher in UQ (36 g m^{-2}) than in UY (6 g m^{-2}) and UE (7 g m^{-2}).

Temporal variations in CH_4 emission rates were significant in each field. Methane emission rates from the three fields showed increasing trends with rice growth and these peaked at the flowering stage (Fig. 1), confirming previous findings (Neue and Sass 1994; Adhya et al. 1994; Singh et al. 1998; Yang and Chang 1999). Since the same rice variety was grown in all the three fields, the plant heights among the fields were not significantly different and showed similar trend (Fig. 2a),

Table 2. Tests of fixed effects of sites and days after transplanting (DAT) on CH_4 emission rates and hot water-extractable carbon (HWEC).

Effect	DF	F Value	Pr>F
CH_4 Emission			
Site	2	1484.1	<0.0001
DAT	8	32.7	<0.0001
Site x DAT	16	14.4	<0.0001
HWEC			
Site	2	137.4	<0.0001
DAT	8	17.2	<0.0001
Site x DAT	15	14.47	<0.0001

HWEC – Hot water-extractable carbon

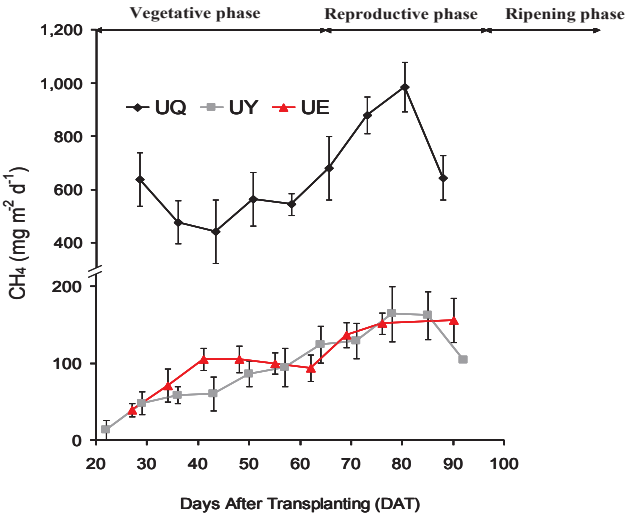

Fig. 1. Methane emission pattern at different stages of rice growth in three experimental sites (UQ, UY and UE) of the International Rice Research Institute (IRRI); vertical bars indicate the standard deviation of means (n = 3).

indicating plant growth in this study is only responsible for temporal variation in CH_4 emission. UQ had a high emission rate at early tillering stage (28 DAT), which decreased toward 42 DAT and increased again toward flowering; on the other hand, UY and UE had low emission rates at the early stages and increased toward flowering. There was a shorter time interval between residue incorporation and transplanting in UQ than in UY and UE. Thus, the higher CH_4 emission rate in UQ at the early vegetative stage (28 DAT) manifested the anaerobic decomposition of incorporated residues. Methane emission during early tillering stage in the UQ field followed the same trend as HWEC which peaked during the early and later plant growth stages (Fig. 2b). The HWEC represents the easily decomposable and readily mineralizable portion of carbon (Schulz and Körschens 1998; Chodak et al. 2003), and is the substrate for methanogens (Wang et al. 1995). It was shown in earlier reports that the easily decomposable part of carbon has a positive correlation with CH_4 emission (Wassmann et al. 1998; Kumar and Viyol 2009). Another source of HWEC could be the carbon from root exudates, which also increases with plant growth until flowering and CH_4 emission and thus follows the same trend (Aulakh et al. 2001).

The higher CH_4 emission in the early stage is generally caused by soil OM and the added organic amendments. Lu et al. (2000a) partitioned the active soil organic carbon (SOC) into two pools, i.e., fast pool and slow pool; the decomposition of the fast pool is responsible for the CH_4 production at the initial phase while the decomposition of the slow pool contributes to the latter phase of CH_4 production. The latter season peak, however, has been attributed to the supply of plant-borne C through root exudates and decaying tissues (Neue et al. 1997). Higher CH_4 emission at flowering stage is also associated with the well-developed aerenchyma tissue, which serves as a medium for CH_4 transport (Adhya et al. 1994). The conductance of the rice plant for CH_4 transport increased with plant growth, and this was found to be higher when there is high root volume during the reproductive stage (Yao et al. 2000). At the same stage, there is a decrease in the oxidation of CH_4 in the rhizosphere (Adhya et al. 1994). In the present study, we observed higher HWEC during the flowering stage (Fig. 2a). Since the plant root secretes OM, increased root volume with plant growth increases the dissolved organic carbon (DOC) in the root zone and reaches the maximum value between flowering and maturity (Lu et al. 2000b). This rhizodeposition is the main source of CH_4 emission from rice fields (Kimura et al. 2004; Aulakh et al. 2001). The decreasing trend in CH_4 emission during maturity stage was attributed to the decreasing DOC with reduced root exudates (Zhan et al. 2010) and to the decreasing transport capacity of the aerenchyma tissues.

Spatial and Temporal Variations in HWEC

The soil HWEC concentrations also showed highly significant variations within and across the three fields. Tests of fixed effects also showed highly significant site, DAT, and site x DAT effects on HWEC concentrations (Table 2). Temporal variations in HWEC were observed during the rice-growing period in each of the fields (Fig. 2b). HWEC was high during early tillering in UQ, following the same trend as that of CH_4 emission. The high concentration of HWEC at the early stage of plant growth may be caused by the decomposition of rice straw residues, which also resulted in higher CH_4 emission. A significant increase in HWEC was observed in UQ from 42 DAT toward the flowering stage. In UY, a peak of soil HWEC concentration was also observed at the early stage of plant growth, but this did not reflect on CH_4 emission rate. From 36 DAT onward, HWEC did not exhibit much change in UY. There was no peak in HWEC at the early

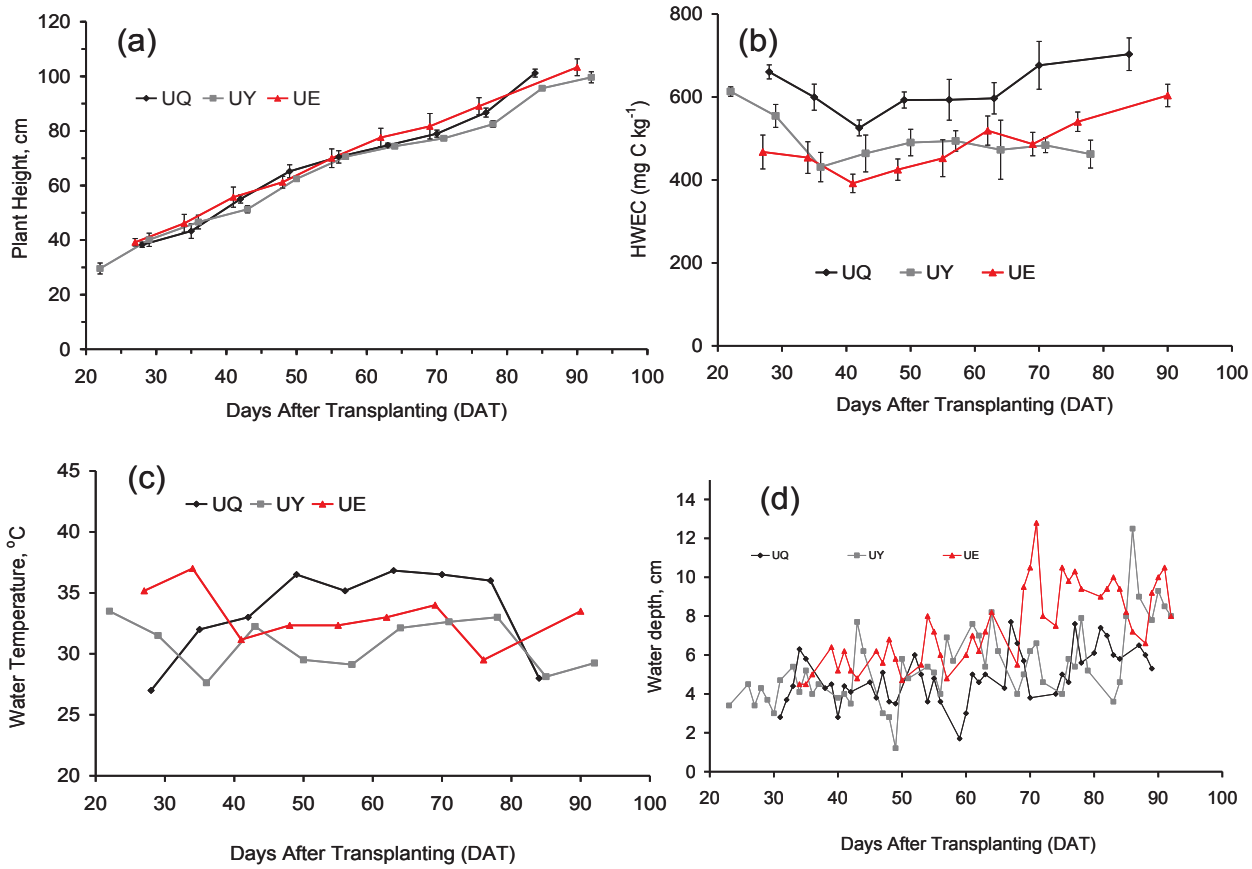

Fig. 2. Temporal changes in (a) plant height, (b) hot water-extractable carbon (HWEC), (c) water temperature and (d) water depth at three experimental sites (UQ, UY and UE); vertical bars in (a) and (b) indicate the standard deviation of means (n = 3).

growth stage in UE, where time interval between straw incorporation and transplanting was longest among the three fields. The amount of HWEC at 27 and 31 DAT was not significantly different from each other in UE. However, a significant increase in HWEC was observed toward the flowering stage. As with CH_4 emission, the concentration of HWEC in the UQ field was also higher than those of UY and UE.

Air and Floodwater Temperature and Floodwater Level

Air temperature slightly varied within the 27–42 °C range (data not shown) and floodwater temperature ranged from 27 to 37 °C (Fig. 2c) during the growth period. The calculations for CH_4 emissions have taken into account the changes in air temperature inside the chamber as given in the section on materials and methods. All the fields were continuously flooded until final drainage at maturity stage. The floodwater level ranged from 1.2 cm to 12.5 cm (Fig. 2d).

Stepwise Multiple Regression Analysis

Multiple regression analysis was done to quantify the simultaneous influences of HWEC, floodwater temperature, floodwater level and plant height on CH_4 emission rates. The combined effects of these parameters could account for 62% of the variability in CH_4 emission rates. The analysis also showed that HWEC influenced CH_4 emission rates most with a partial R^2 of 0.46 (Table 3). Thus, HWEC could explain 46% of the spatial and temporal variability in CH_4 emission rates. Floodwater temperature, floodwater depth and plant height contributed 2.6%, 1.9% and 10.9%, respectively, to the variability in the observed emission rates.

Multiple regression analysis showed that HWEC had the greatest contribution (R^2= 0.46, Pr <0.0001) to the variability in CH_4 emission relative to the other factors (Table 3). Higher clay and total organic carbon content (Table 1) also favored methanogenic activities. However, these were not included in the stepwise multiple regression analysis as these parameters are not so susceptible to temporal changes. The higher CH_4 emission in UQ compared with that in UY and UE may also be due to the lower soil P content in the former compared with the latter two fields. The observation on phosphorus and methane emission was similar with the

Table 3. Summary of stepwise multiple regression analysis for methane emissions.

Step	Variable	Partial R^2	Model R^2	Pr > F
1	HWEC	0.4623	0.4623	<.0001
2	Floodwater temperature	0.0265	0.4888	0.0399
3	Floodwater depth	0.0194	0.5082	0.0741
4	Plant height	0.1095	0.6177	<.0001

HWEC – Hot water extractable carbon

findings of Lu et al. (1999), Adhya et al. (1999) and Conrad et al. (2000) where lower phosphorus content tends to increase methane emissions. Low P level depressed shoot growth but increased root growth along with the development of root aerenchyma, leading to enhanced root exudation, and thus higher methane emission (Lu et al. 1999).

A slightly higher (2–3 °C) water temperature was observed in UQ than in UE and UY between 40 and 70 DAT (Fig. 2c). As with chemical and enzymatic reactions, temperature also affects the rate of microbiological reactions (Conrad 2002). With adequate water and OM source for food, the activities of methanogens are greatly influenced by temperature. Devevre and Horwath (2000) found a strong positive correlation between temperature and CH_4 emission and that higher CH_4 emissions are obtained in soil temperatures ranging from 30 to 35 °C (Minami and Neue 1994).

The contribution of floodwater depth was not significant in the present study (R^2= 0.019, Pr< 0.07). This finding seems to contradict previous studies that have singled out the key role of water management on CH_4 emission. Single drainage at mid-season reduces CH_4 emission significantly (Wassmann et al. 2000; Conrad 2002). However, these studies have imposed flooded vs. nonflooded conditions in the fields, whereas the present study compared different water levels. Since we maintained the field continuously flooded, the small variation in depth may not have affected CH_4 emissions to a large extent.

CONCLUSION

Results showed that considerable spatial variations in CH_4 emissions could be observed, even across nearby fields and these are influenced by soil properties highly susceptible to temporal variations (e.g., soil labile C). In this study, variations in HWEC contributed most to variability in CH_4 emission rates, suggesting that these could be a suitable indicator for predicting CH_4 emission rates, especially in environmental studies involving modifications in residue management practices. Small variations in floodwater depth would not contribute much to the variability of CH_4 emission rates when fields are kept continuously flooded and remain in reduced condition. Since CH_4 emissions increase with plant growth, mitigation options such as drying of the field during later stages (i.e., close to the flowering stage) could result in a greater reduction in CH_4 emissions.

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