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Within field spatial variation in methane emissions from lowland rice in Myanmar

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Abstract

An assessment of within field spatial variations in grain yield and methane (CH₄) emission was conducted in lowland rice fields of Myanmar. Two successive rice fields (1st field and 2nd field) were divided into fertilized and non-fertilized parts and CH₄ measurements were conducted at the inlet, middle and outlet positions of each field. The results showed that CH₄ emissions at non-fertilized parts were higher than those at fertilized part in both rice fields. The average CH₄ emissions ranged from 8.7 to 26.6 mg m⁻² h⁻¹ in all positions in both rice fields. The spatial variation in CH₄ emission among the positions was high in both rice fields with the highest emissions in the outlet of the 1st field and the inlet of the 2nd field. The CH₄ emissions at these two positions showed 2 - 2.5 times higher than those at other positions in both rice fields. Stepwise regression analysis indicates that soil total carbon content is the primary factor for CH₄ emission. The average CH₄ emissions during rice growing season were 13.5 mg m⁻² h⁻¹ for the 1st field and 15.7 mg m⁻² h⁻¹ for the 2nd field. Spearman rank order correlation analysis showed that CH₄ emission was significantly and positively correlated with soil temperature, surface water depth and negatively correlated with soil redox potential. The result indicated that high within field spatial variation in CH₄ emissions required different site specific management practices to mitigate CH₄ emissions in lowland paddy rice soil.

Keywords: Fertilizer; Lowland rice; Methane emission; Soil properties; Spatial variation

1. Introduction

Rice is the most important crop in Myanmar. In terms of rice growing area and production, Myanmar ranks seventh in the world (FAO 2010). The total area of rice cultivation is 8.06 million ha, among which 68% represents lowland rice cultivation areas (FAO 2010). Most of the major lowland rice growing areas such as the Ayeyarwady, Yangon and Bago Divisions are naturally provided with fertile deltaic alluvial soil and abundant monsoon rainfall. Irrigated lowland rice is one of the major rice ecosystems in these regions, especially in semi-rainfed areas. Rice fields in Myanmar are connected as successive fields in lowland areas with a few centimeters of difference in elevation. Even though the importance of paddy rice in Myanmar, basic information of the paddy rice cultivation such as spatial variability of soil properties and yield and its related methane (CH₄) emission are still missing.

Spatial variation of CH₄ emission from rice fields is regulated by a variety of agronomic and environmental factors, as well as the complex interactions of the whole system involving the rice plants, soil and atmosphere (Jean and Pierre 2001; Wang and Li 2002). Studies have shown variations in CH₄ emission from continuously flooded rice soils in different locations with varying soil properties and climates (Kimura et al. 1991; Yang and Chang 2001; Kumar and Viyol 2009). Soil organic carbon (SOC) acts as a substrate for methanogens (Penning and Conrad 2007), thus it has significant correlation with CH₄ production (Wassmann et al. 1998). In toposequence rice fields, the observed high rates of CH₄ emission from middle and particularly bottom field positions were associated with their higher TN, TC and clay contents compared to the top field positions (Oo et al. 2013). Mitra et al. (2002) also observed that higher TN and TC stimulated CH₄ production from rice soil. Xiong et al. (2007) reported that clay soil produced much more CH₄ than loess soil during the flooding period. Soil properties vary highly even within a single field (Inman et al. 2005). Analysis of the spatial variability of CH₄

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emission with field is necessary to create inventory data for Myanmar.

It is well known that CH₄ emission from paddy rice fields is a net product of CH₄ production and oxidation. Methane emission from paddy rice fields during the growing season are significantly affected by water management, organic matter application, soil organic matter, C content, soil pH, pre-season water status and climate (Yan et al. 2005). Beside the soil environmental factors, CH₄ emissions from rice fields are also directly or indirectly affected by application of N and other nutrients (Schimel 2000). For example, at the plant or ecosystem level, ammonium-based fertilizers can stimulate rice plant growth, which may increase CH₄ emission by providing more methanogenic substrates and enhancing the efficiency of CH₄ transport to the atmosphere (Schimel 2000; Bodelier et al. 2000b; Zheng et al. 2006). Several field-scale studies have demonstrated that addition of N fertilizers increases CH₄ emissions in rice soils (Banik et al. 1996; Shang et al. 2011). In contrast, others have observed that CH₄ emissions were inhibited with N fertilizer (Xie et al. 2010; Dong et al. 2011). Application of phosphate (P) fertilizer may stimulate CH₄ uptake in the soil (Zang et al. 2011) and inhibits the acetoclastic methanogenic activity in the rice rhizosphere (Conrad et al. 2000) which leads to inhibition of CH₄ emission from rice soil. Application of potassium (K) fertilizer alleviates the soil reducing condition (Chen et al. 1997) and inhibits the CH₄ emission from rice field (Babu et al. 2006). However, there are also studies that report no effect on CH₄ emission due to K fertilizer (Wassmann et al. 1993). The application of P and K fertilizer inhibits CH₄ emission from soil may be due to their effect on plant ventilation and root exudates (Conrad and Klose 2005). In Myanmar, common practice of fertilizer application for paddy rice is urea and ammonium sulfate as a source of nitrogen, triple super phosphate as a source of phosphorus and muriate of potash as a source of potassium. The effect of N, P and K fertilizers on CH₄ emission from rice soil in Myanmar is uncertain.

Due to the interactive effects of soil, climatic and cultural factors, the uncertainty in estimating CH₄ emission from rice fields is high. The upscaling of emission rates is hampered by this uncertainty and the pronounced spatial and temporal variations (Sass et al. 2002). There is an urgent need to evaluate the interaction between CH₄ emission and rice production in a changing climate in order to estimate source strength (Neue et al. 1997) and provide a basis for future decisions regarding mitigation options. Extensive field measurement of CH₄ emission is necessary to develop a reliable regional and global CH₄ budget and identify effective mitigation measures, especially in area where no study on CH₄ emission is conducted yet, such as in Myanmar. In this experiment, one

year field experiment was conducted to understand within field spatial variation in CH₄ emission among the positions in the field related to water flow pattern and its related soil and soil environmental factors. The objective of this study was to assess the spatial variations in soil properties, plant performance and CH₄ emissions from different positions within a field in relation to water flow pattern and mineral fertilizers in lowland rice of Myanmar.

2. Materials and methods

2.1. Study site and experimental design

The field experiment was carried out from June to November, 2012 during the monsoon rice growing season in Dawmakwin Village, Kanyutkwin, Paga Division, (18°48'43" N, 96°43'57" E), Myanmar (Figure 1). The field had been under rice (*Oryza sativa* L.) and black gram (*Vigna mungo*) rotation for 25 years. The soil was classified as a fluvisol (alluvial soil) (FAO/UNESCO, Food and Agriculture Organization of the United Nations/United Nations Educational and Cultural Organization 1974), which contained large amount of silt (Table 1). The weather in the study area is tropical monsoon climate with an annual rainfall of 2545 mm, and minimum and maximum temperatures of 19.6°C and 32.2°C, respectively, in 2012 (Figure 2).

Two successive rice fields (hereafter referred to as the 1st field and 2nd field) covering a total of 0.5 ha were selected for this experiment (Figure 3). The 1st field received water directly from the channel with a single inlet and water drained via a single outlet to the 2nd field. The 2nd field received water from a single inlet from the above-lying 1st field and water drained via a single outlet to a lower-situated field. According to this water flow pattern, the field was divided into three positions: inlet, middle and outlet position.

The experiment was laid out in a split-plot design with three replications for each field (Figure 3). All fields were divided into two parts to produce two strips to separate fertilized and non-fertilized parts. Two sets of factors included in this experiment were as follows: with (+F) and without (-F) fertilizer application as the main plot, and different positions as a subplot. The positions were the inlet, middle and outlet for the two fields, referred to as the 1st inlet, 1st middle, 1st outlet for the 1st field, and the 2nd inlet, 2nd middle and 2nd outlet for the 2nd field. The applied chemical fertilizers were Nitrogen (N) 50 kg ha⁻¹ (Ammonium sulfate), Phosphorus (P) 30 kg ha⁻¹ (Triple superphosphate) and Potassium (K) 20 kg ha⁻¹ (Muriate of potash) with two split applications according to the local recommendations by extension service. The first dressing was conducted at transplanting using 50% N, 100% P and 100% K of the total amount of fertilized applied. The second dressing contained the remaining 50% N which was applied at heading stage (60 days after transplanting).

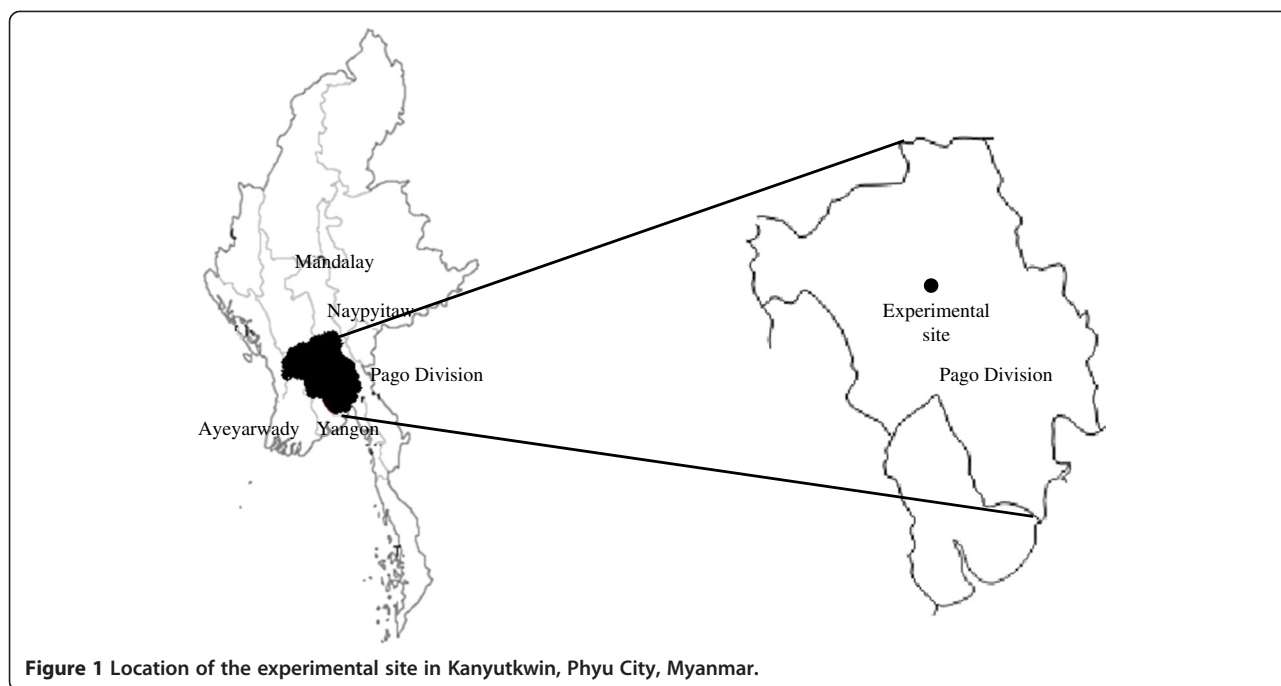


Figure 1 Location of the experimental site in Kanyutkwin, Phyu City, Myanmar.

The indica rice variety (*Oryza sativa* L. var. Sinthukha) was used in this experiment. Thirty-day-old seedlings were manually transplanted into the well-puddled fields. Rice seedlings were transplanted on June 29 and harvested on October 11, 2012. All management practices followed farmer practices. The fields were flooded 22 days before transplanting on June 7, 2011. The basal fertilizer was applied one day before transplanting. After transplanting, the fields were continuously flooded until 14 days before harvest because mid-season drainage was not successful due to continuous rainfall during that period.

2.2. Sample collection, soil parameters, and CH₄ analysis

Methane fluxes were measured in triplicate at 10-day intervals from 7 days after transplanting (DAT) until harvest throughout the rice growing seasons, using the closed chamber method (Lu et al. 1999) at each point. The air inside the chamber was mixed by a fan at the top of the

chamber. Gas samples were drawn from the chambers through a three-way stopcock using an airtight 50-ml syringe at 0, 15 and 30 minutes after closure. The air inside the chamber was thoroughly mixed by flushing the syringe three times before collecting the gas samples. The gas samples were then transferred to 10-ml vacuum glass vials with rubber stoppers and kept cool and dark until analysis. The temperature inside the chamber was recorded at the time of sampling using a micro-temperature thermometer (PC-9125, AS ONE Co., Tokyo, Japan). Methane concentrations in the collected gas samples were analyzed using a gas chromatograph equipped with a flame ionization detector (GC-8A, Shimadzu Corporation, Kyoto, Japan). The detector and column were operated at 180° and 80°C, respectively. Methane fluxes were calculated from the slope of a CH₄ concentration vs. time regression when their linear correlation coefficients were significant at the 0.05 level.

Table 1 Physico-chemical properties of the experimental soils at different positions within the field before transplanting of lowland paddy rice, 2012

		Sand (%)	Silt (%)	Clay (%)	TN (g kg ⁻¹)	TC (g kg ⁻¹)	Organic matter (%)	pH	EC (ms m ⁻¹)
1st field	Inlet	37.8 a	28.0 b	34.2 c	0.28 a	2.2 ab	5.1 a	6.0 bc	0.44 ab
	Middle	19.9 b	37.4 b	40.7 bc	0.32 a	2.0 b	5.3 a	6.4 a	0.41 b
	Outlet	10.8 c	44.5 ab	44.7 ab	0.33 a	2.7 a	5.5 a	6.2 ab	0.58 a
2nd field	Inlet	10.2 c	36.0 b	53.8 a	0.12 b	2.5 a	5.4 a	5.7 d	0.56 a
	Middle	8.3 c	48.7 a	39.0 bc	0.12 b	2.0 b	4.7 ab	5.7 d	0.39 b
	Outlet	9.7 c	52.0 a	38.4 bc	0.08 b	1.1 c	4.2 b	5.9 cd	0.32 b

Means with the same letter are not significant difference at 5% level by Fischer.

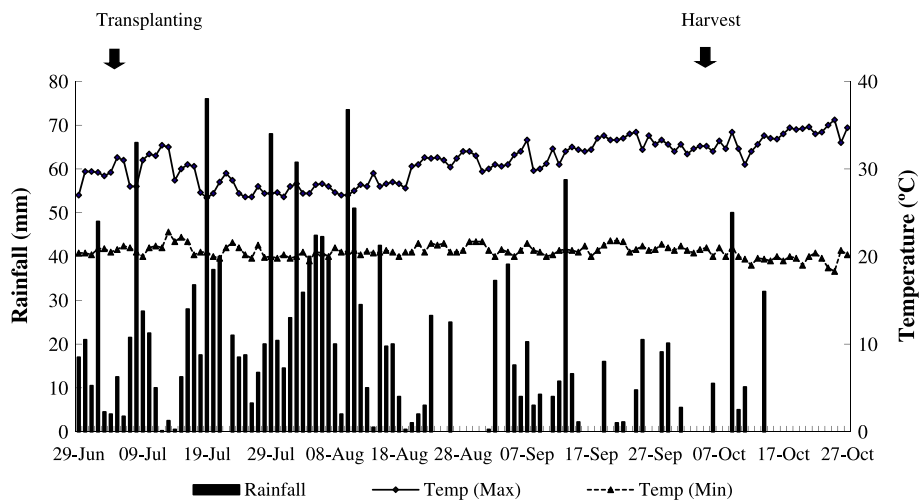


Figure 2 Daily rainfall distribution, maximum and minimum temperatures during monsoon rice growing season for 2012 at experimental site of Kanyutkwin, Phyu City, Myanmar.

Top-soil samples at a depth of 0–10 cm were taken before transplanting to analyze the physical and chemical properties of the soil. Soil particle analysis was performed using the pipette method (Gee and Bauder 1986), and soil organic matter contents were analyzed by the hydrogen peroxide method (Schultz et al. 1999). Total nitrogen

(TN) and total carbon (TC) contents were analyzed using an NC analyzer (Sumigraph NC-80; Sumika Chemical Analysis Service Co., Japan). The soil pH was measured in the supernatant suspension of a 1:2.5 soil: water mixture using a portable pH meter equipped with a combined electrode (glass:Ag/AgCl, Horiba, Japan). The electrical

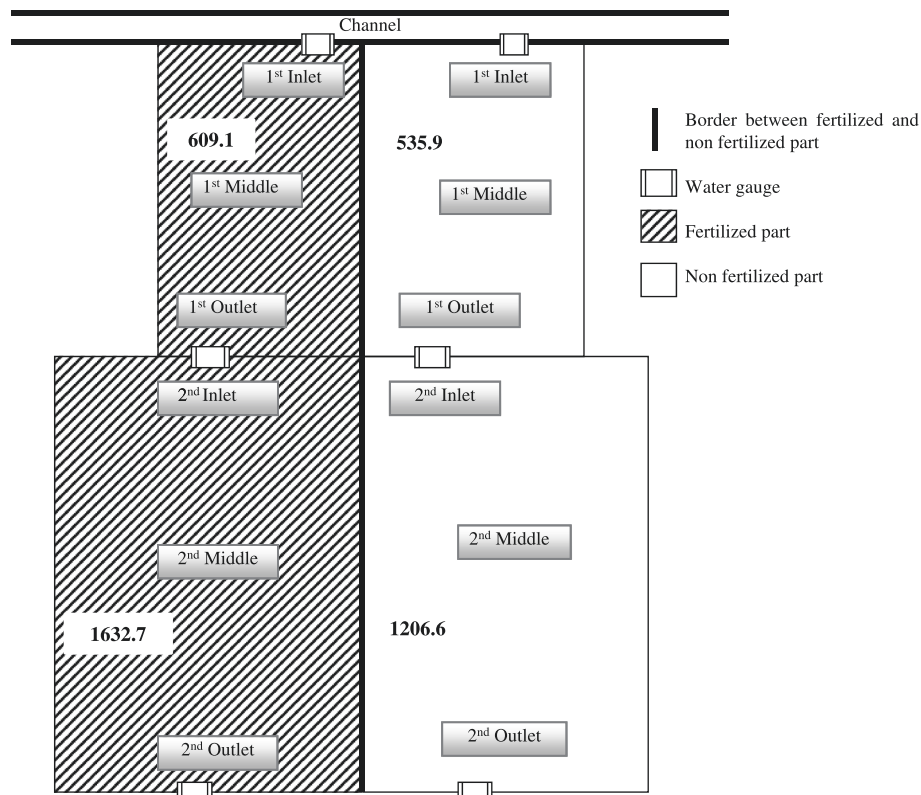


Figure 3 Schematic representation of experimental layout with two successive lowland rice fields, Kanyutkwin, Myanmar (Area – m²).

conductivity of the soil water was measured in the supernatant suspension of a 1:5 soil : water mixture using an EC meter (OM-51, Horiba, Japan).

Soil temperature at a depth of 10 cm was recorded at the time of gas sampling. Water depth was also recorded among the positions at 10-day intervals throughout the growing seasons. The pH of the surface water was measured using a portable pH meter (D-51T, Horiba, Japan) equipped with combined electrode (glass:Ag/AgCl). The redox potential was recorded using a battery-operated Eh meter (D-51T, Horiba, Japan) by inserting the platinum electrode into the soil under investigation to a root-zone depth of 5 cm throughout the growing season. Mean value of redox potential was shown in the result using the raw millivolt data, not used any correction factor. Plant height and tiller number were recorded as growth parameters, and grain yield was determined from a 1-m² sampling area at harvest and was expressed as unhulled rice at 14% moisture content. Aboveground straw weight was determined after drying the plant materials at 80°C for two days.

2.3. Statistical analysis of data

Statistical analysis was performed using the CropStat 7.2 statistical software program. The treatment mean comparison was tested at the 5% level of probability using the least significant difference (LSD) test by Fischer. Comparison of rate and cumulative CH₄ flux was performed separately for fertilizer and position effect. Stepwise multiple regression analysis was performed to determine relationship between soil properties and CH₄ emission. Spearman rank order correlation analysis was done using the Sigma-Plot 11.0 statistical software program.

3. Results

3.1. Soil environmental factors

Sand was the dominant type with 37% in the 1st inlet position (Table 1). Silt content showed an increasing trend from the 1st inlet to 2nd outlet positions. The highest clay content was observed in the 1st outlet and 2nd inlet followed by the 2nd middle and 1st middle positions. Soil TC content differed significantly ($p < 0.01$) among positions and ranged from 1.1 to 2.5 g kg⁻¹ soil in both experimental fields. The 1st outlet and 2nd inlet showed significantly ($p < 0.05$) higher TC content than that of other positions. Soil TN content and soil pH were higher in all positions (1st inlet, 1st middle and 1st outlet) of the 1st field compared to those of the 2nd field. High organic matter and EC were observed in all positions of the 1st field and 2nd outlet of the 2nd field.

Soil redox potential (Eh) was as low as -180 mV at one week after transplanting and remained at a low level throughout the growing season (Figure 4c and d). Soil Eh of the 1st outlet and 2nd inlet positions tended to

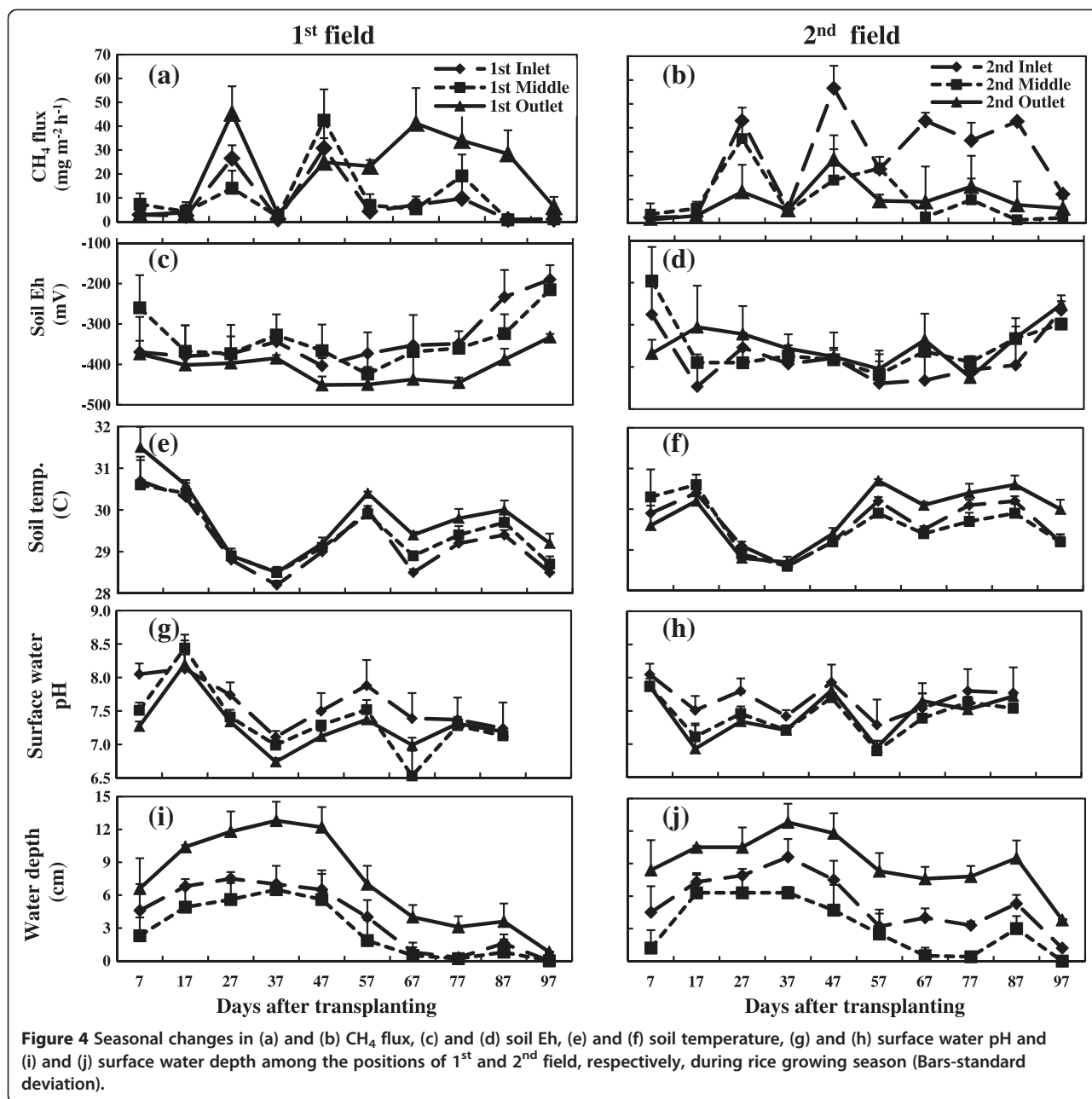
decrease faster and was lower than that of other positions, especially from 47 DAT to the end of the growing period. Soil temperature ranged from 28 to 32°C (Figure 4e and f). It was higher at the beginning and then decreased to the lowest value at 37 DAT due to continuous rain and cloudy conditions. The soil temperature then increased gradually and remained less variable until the end of the growing period. Among the positions, the 1st outlet, 2nd inlet and 2nd outlet positions exhibited a higher soil temperature than that of other positions, especially during the middle and late growing periods. Surface water pH ranged between 6.5 and 8.5 throughout the growing season (Figure 4g and h). Significant ($p < 0.05$) differences in surface water depth among positions were observed throughout the growing season (Figure 4i and j). The 1st and 2nd outlets exhibited the highest water depths, followed by the 1st and 2nd inlets, and the lowest depth was found for both middle positions.

3.2. Influence of position on seasonal variation in CH₄ emission

Methane emission from all positions in both fields generally showed two peaks during the rice growing season (Figure 4a and b). The first peak was found at 27 DAT (tillering stage), which was followed by a sudden drop at 37 DAT. The second peak occurred at 47 DAT (maximum tillering stage) for the 1st inlet, 1st middle, 2nd middle and 2nd outlet positions, which then decreased towards the end of the growing period. The 1st outlet also showed an emission peak at 47 DAT and maintained a high emission to the end of the growing period. The 2nd inlet showed a maximum peak at 67 and 87 DAT (booting and flowering stages), and exhibited a high emission in the late growing period.

Methane emission showed significant ($p < 0.01$) differences among positions in both rice fields (Table 2). The average rate and cumulative CH₄ emission during the rice growing season exhibited the following order of magnitude: 2nd inlet > 1st outlet > 2nd middle > 1st middle > 2nd outlet > 1st inlet. The highest average CH₄ emission was 21.3 and 26.6 mg CH₄ m⁻² h⁻¹ in the 1st outlet of the 1st field and 2nd inlet of the 2nd field, respectively, and the lowest value of 8.7 mg CH₄ m⁻² h⁻¹ was recorded for the 1st inlet position of the 1st field. The 1st outlet and 2nd inlet were 2 to 2.5 times significantly higher than that of other positions in both rice fields. The average CH₄ emission rate of all positions in the 1st field was 13.5 mg CH₄ m⁻² h⁻¹, which did not differ statistically from that of the 2nd field (15.7 mg CH₄ m⁻² h⁻¹).

Seasonal variation in CH₄ emission from fertilized and non-fertilized parts showed similar trends and patterns throughout the growing season (Figure 5). The average rate and cumulative CH₄ emission from fertilized parts was significantly ($p < 0.05$) lower than that from non-



fertilized parts in both rice fields (Table 2). Average CH₄ emissions for non-fertilized and fertilized parts were 15.5 and 11.4 mg CH₄ m⁻² h⁻¹ in the 1st field and 16.8 and 11.8 mg CH₄ m⁻² h⁻¹ in the 2nd field, respectively.

3.3. Plant growth and crop yield

There were significant ($p < 0.05$) differences in tiller number and plant height among the positions only in the 2nd field (Table 2). All positions in the 1st field showed a higher tiller number and plant height compared to that of any position in the 2nd field. Significant ($p < 0.05$) differences in straw and grain yield were

observed among the positions in both rice field. Higher rice straw and grain yields were found for all positions in the 1st field, while the lowest grain yield was observed in the 2nd outlet position. Fertilized parts showed significant ($p < 0.05$) higher tiller number, straw and grain yield in both rice fields while plant height was observed only significant ($p < 0.05$) in the 2nd field due to fertilization.

3.4. Influence of soil properties and soil environmental factors and plant growth on CH₄ emission

To determine the controlling factors of CH₄ emission, soil properties from Table 1 were used in the stepwise

Table 2 Influence of fertilizer and positions on rate and cumulative CH₄ flux, plant growth and yield of lowland rice

		CH ₄ flux rate (mg m ⁻² h ⁻¹)	CH ₄ flux Cumulative (g m ⁻²)	Tiller number	Plant height (cm)	Grain (g m ⁻²)	Straw (g m ⁻²)		
1 st field	Treatment	-F	15.5 a	38.7 a	9.0 b	106.9 a	501.9 a	608.8 b	
		+F	11.4 a	28.5 a	9.9 a	111.2 a	528.2 b	631.1 a	
	Position	Inlet	8.7 b	21.7 b	9.0 a	111.5 a	532.7 a	636.0 a	
		Middle	10.4 b	26.0 b	9.7 a	106.5 a	507.8 b	598.5 b	
2 nd field	Treatment	-F	16.8 b	41.9 b	8.0 b	101.5 b	424.9 b	544.1 b	
		+F	11.8 a	29.5 a	8.9 a	113.6 a	493.0 a	580.7 a	
	Position	Inlet	26.6 a	66.4 a	8.9 a	105.3 a	475.2 a	576.3 a	
		Middle	10.8 b	27.0 b	7.8 ab	98.4 b	462.7 ab	532.3 b	
			Outlet	9.8 b	24.5 b	7.7 b	104.8 a	449.0 b	534.8 b

-F and +F stand for non-fertilized and fertilized part, respectively. Means with the same letter are not significant difference at 5% level by Fischer.

multiple regression. According to analysis result, five soil characteristics; organic matter content, soil EC, clay, sand and TC content were found to greatly affect ($p < 0.05$) and account for 97% of the variance in CH₄ emission in the 1st field. The equation for the stepwise multiple regression is: CH₄ emission = 65.929 + (4.517 * OM (%)) + (41.686 * EC) - (0.401 * Clay (%)) - (0.476 * silt (%)) - (12.079 * pH) + (2.265 * TC (g kg⁻¹)). In the 2nd field, only two soil characteristics; clay and TC content were found to greatly affect

($p < 0.001$) and account for 76% of the temporal variability in the CH₄ emission. The equation for the stepwise multiple regression is: CH₄ emission = -11.381 + (0.425 * clay (%)) + (6.196 * TC (g kg⁻¹)).

Surface water pH was significantly correlated with CH₄ emission for both rice fields (Table 3). Surface water depth showed a significant and positive correlation with CH₄ emission in the 1st field, but there was no significant correlation for the 2nd field. Significant negative

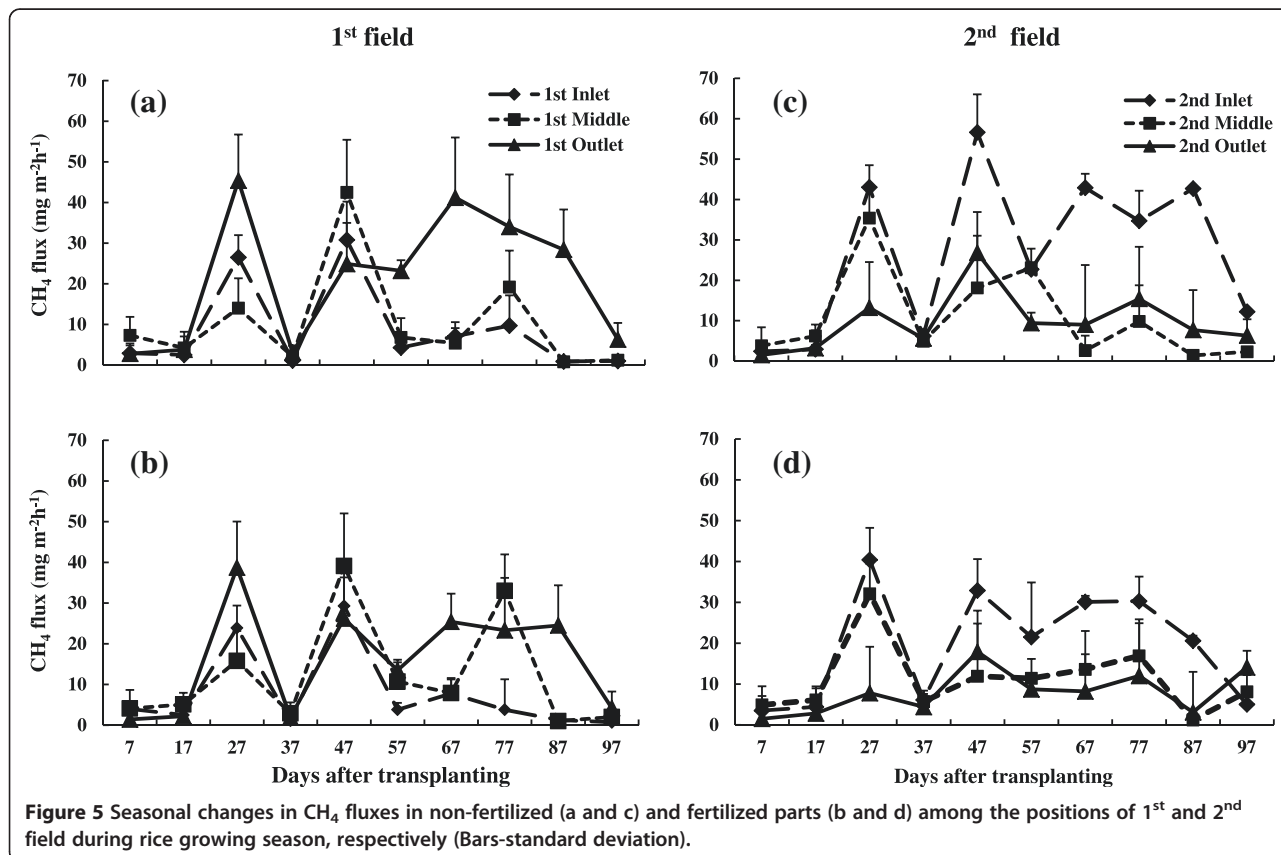


Table 3 Spearman rank order correlation between CH₄ emission rate and soil and plant parameters of lowland rice

	Soil temp.	Surface water pH	Water depth	Soil Eh	TN	TC	Grain	Straw
1 st field	0.51*	0.74*	0.54*	-0.67**	0.34 ^{ns}	0.55*	0.04 ^{ns}	0.03 ^{ns}
2 nd field	0.29 ^{ns}	0.89**	0.04 ^{ns}	-0.56**	0.45 ^{ns}	0.57*	0.12 ^{ns}	0.24 ^{ns}

** , * and ns stand for significant at 1%, 5% and non significant, respectively.

correlations between CH₄ emission rate and soil Eh were observed in both rice fields. Soil temperature was significantly and positively related with CH₄ emission only in the 1st field. The CH₄ emission rate was positively correlated with TC content in both rice fields. No correlation was observed between CH₄ emission and TN, or plant growth and yield parameters, for either of the rice fields.

4. Discussion

4.1. Average CH₄ emission

Methane emissions showed two peaks in both rice fields, while the trend of the position differed between the fields (Figure 4a and b). The first emission peak was observed at 27 DAT (active tillering stage), which might be associated with microbial decomposition of native organic matter under high temperature (Holzapfel et al. 1986). Higher CH₄ emission at the tillering stage was generally due to lower rhizospheric CH₄ oxidation and more effective transport mediated by rice plants (Suryavanshi et al. 2012). Li et al. (2011) also suggested that this was caused by fermentation of easily degradable soil organic matter and flood conditions for methanogenesis in the soil after transplanting.

The sudden drop of CH₄ emission at 37 DAT was probably due to low soil temperature and continuous rainfall during this period (Figure 2). The temperature did not drop as low as to inhibit methanogen activity, but it affected the diffusion of CH₄ from the water to the air concentrations according to Henry's law (Carroll 1991). More gas can be dissolved as entrapped bubbles at low temperature and leads to decrease in the apparent emission. The rain also did not directly influence the methanogen activity, but due to the associated change in the air pressure. Gaseous CH₄ pool in the water can be released as bubbles if air pressure drops (Tokida et al. 2012). The static closed chamber techniques often failed to catch sudden changes in emissions and thus, all points showed low emission at 37 DAT.

The second emission peak occurred at maximum tillering (47 DAT) and the late growing period. This could be attributed to high soil temperature and decomposition of soil organic matter and decaying plant residues from shed leaves and root turnover. Methane emissions during late growing periods might have been associated with the higher availability of root exudates or decaying plant residues for methanogenic bacteria in the rice rhizosphere, and the highly reduced conditions in this rhizosphere (Mitra et al. 2005).

The seasonal average CH₄ emission rate ranged from 8.7 to 26.6 mg CH₄ m⁻² h⁻¹ over the rice growing season (Table 2). This is higher than the IPCC (1996) default value of CH₄ emission; 8.3 mg CH₄ m⁻² h⁻¹ from irrigated rice fields for Myanmar. Lowland-upland rotation usually results in low CH₄ emissions; such as 1.4 mg CH₄ m⁻² h⁻¹ averaging over the rice growing season in rice-wheat rotation (Zou et al. 2004) or an average CH₄ emission during rice growing season of 3.4 mg CH₄ m⁻² h⁻¹ after upland crops such as mustard, chickpea or blackgram (Adhya et al. 2000). The range of cumulative seasonal CH₄ emissions in this study was 21.2 to 66.4 g CH₄ m⁻² (Table 2). This is comparatively higher than that reported for toposequence rice fields cultivating double-cropping paddy rice in Northwest Vietnam, which ranged from 7.4 g m⁻² to 37.2 g CH₄ m⁻² (Oo et al. 2013). The rather higher emissions might be due to the difference in elevation between the fields, while in our study a difference of only a few centimeters existed between the fields with poor drainage, continuous flooding and high soil temperature throughout the growing season. Differences in CH₄ emissions between two locations were also shown by Zhang et al. (2009), who reported high spatial variability in CH₄ emissions from rice fields in the Taihu Lake region of China, and demonstrated higher annual CH₄ emissions on the plains compared to the hilly regions.

The fields in our study were located in a lowland area with poor field drainage conditions. The installation of drainage pipes or other techniques to improve drainage are seldom found in Myanmar and almost all paddy fields in Myanmar are under similar situation with the current field condition. In addition, the fields were continuously flooded throughout the rice growing season. Mid-season drainage could not be conducted due to frequent rainfall (Figure 2). The soil Eh was kept low (Figure 4a and b), and the high temperature favored high CH₄ emission. Since a wide area of paddy fields in Myanmar are under similar condition as our field, the current CH₄ emission from Myanmar may be highly underestimated.

4.2 Influence of mineral fertilizer on CH₄ emission

Many paddy rice fields in Myanmar rely on mineral fertilizers to increase crop yields (FAO 2010). Nitrogen fertilizers stimulate crop growth and provide more C substrates via organic root exudates and sloughed-off cells to methanogens for CH₄ production (van der Gon et al. 2002; Inubushi et al. 2003). Addition of N fertilizer increased CH₄ emissions in rice soil due to the stimulation of methanogens by

greater production of crop biomass under N fertilization (Banik et al. 1996) and Shang et al. 2011). In contrast, N fertilizer has also stimulated the activities of methanotrophs that resulted in greater CH₄ oxidation (Bodelier et al. 2000a, b). Methane emission rate from ammonium sulfate treatment was the lowest, followed by ammonium chloride treatment, and then urea treatment (Kimura 1992). Another study reported that CH₄ emission was 30–50% lower following application of ammonium sulfate compared to urea-treated rice plots (Cai et al. 1997). For P and K fertilizers, reduction of CH₄ was found in several studies (Rao et al. 1986, Adhya et al. 1998, Babu et al. 2006), while also no effect was also found (Wassmann et al. 1993). In this study, the results showed that application of ammonium sulfate as N source, triple superphosphate as P source and potassium sulfate as K source inhibited the rate and cumulative CH₄ emissions from rice soils by 26.5 and 29.8% in the 1st field and 2nd field respectively when compared with non-fertilized treatment (Figure 5 and Table 2). A similar result was reported by Datta et al. (2013) and Yang et al. (2010). Sulfate-containing fertilizers are known to decrease CH₄ emission as a result of competition between sulfate-reducing bacteria and methanogens for hydrogen and acetate substrates (Hori et al. 1990, Schütz et al. 1989). Significant reduction in CH₄ emission due to fertilization could be either due to ammonium sulfate, or due to P and K fertilizers in this study.

4.3. Influence of different positions and soil environmental factors on CH₄ emission

Many studies have reported that soil properties of paddy rice have a strong influence on CH₄ emission from rice fields (Mitra et al. 2005; Oo et al. 2013). This experiment showed that the soil variability affects significantly the CH₄ emissions not only among different fields, but also within a field (Figure 4a and b). Spatial variability of CH₄ emissions among toposequence positions was related to transportation and deposition of organic-rich sediment materials within toposequence rice fields in Viet Nam (Oo et al. 2013). In the current study, the observed high rates of CH₄ emission from the 1st outlet and 2nd inlet positions were associated with a high clay, TC and organic matter content (Tables 1 and 3). Schmitter et al. (2010) reported that the increase of SOC was related to an increase of clay and silt fractions which point to transportation of organic rich sediment material by the irrigation channel. In the current study, it showed clearly that most of the sediments deposited in the 1st field (Table 1). As a result, sand showed decreasing trend with the highest content in 1st inlet, silt showed increasing trend with the highest in 2nd outlet and the highest clay was observed in 1st outlet and 2nd inlet positions. Since irrigation water velocity was low, the condition between 1st outlet and 2nd inlet was similar.

Both positions showed high clay, TC, soil EC, organic matter content and low sand content (Table 1).

Higher clay and TC contents favor methanogenic activities (Mitra et al. 2002; Xiong et al. 2007; Gaihre et al. 2011) as also confirmed by the positively correlation of TC content and CH₄ emission in this study (Table 3). Higher TC content stimulated CH₄ production in rice soil (Mitra et al. 2002, Oo et al. 2013). Another reason for the high rates of CH₄ emission from the 1st outlet and 2nd inlet might be the lower Eh values due to a high water depth in these positions (Figure 4i and j), which were negatively correlated with CH₄ emission in this study (Table 3). Soil with a high clay and TC content exhibits negative Eh values within two weeks after submergence, and thereafter becomes more negative than soil with a lower C content (Xiong et al. 2007). A more rapid decrease in Eh after flooding and subsequent stability due to the high C content in the outlet of the 1st field and inlet of the 2nd field might explain the greater CH₄ production. Stepwise multiple regression analysis was used to identify key factors regulating CH₄ emission from soils and the results showed that a series of soil factors could affect CH₄ emission from both rice fields. However, there was only one common factor; TC content regulating CH₄ emission from both rice soils. The positive relationship of CH₄ emission with TC content has been widely reported (Mitra et al. 2002, Xiong et al. 2007, Gaihre et al. 2011, Oo et al. 2013). Although clay content appears in both regression equations for the two fields, clay content is not the primary factor for controlling CH₄ emission due to the opposite values in equations in this study.

In this study, seasonal variation in CH₄ emission was influenced by soil environmental factors such as soil Eh, surface water pH, soil temperature and surface water depth (Figure 4c-j). The soil redox potential declined after flooding and fluctuated between – 150 and – 450 mV in both fields throughout the growing season (Figure 4c and d). Negative correlations between CH₄ emissions and soil Eh existed in both rice fields (Table 3). Yagi and Minami 1990 reported that the critical values of soil Eh for initiation of Eh from -100 to -200 mV. The Eh range in this study was considerable more negative than the critical value and the low Eh easily led to higher methane production. Although positive correlation between soil temperature and CH₄ emission was observed only in 1st field (Table 3), the temperature range in this experiment fall within the optimum temperature for methanogens ranged from 25 to 37°C (Schütz et al. 1990). There were significant correlation between CH₄ emissions and surface water pH in both 1st and 2nd fields. High standing water pH might favor CH₄ emission in this study. Significant correlation between CH₄ emission and surface water depth was observed only in the 1st field but not the case in the 2nd field

(Table 3). Under flooded condition, negative redox status was already established (Figure 4c and d) and variation in surface water depth during growing season might not have affected on big differences of soil redox status (Figure 4i and j). Gaihre et al. 2011 reported that the contribution of floodwater depth was not significant in their study because they maintained the field continuously flooded, the small variation in depth might not have affected CH₄ emissions to a large extent. High spatial variation in CH₄ emission within the rice field in this experiment was mainly due to variation in TC content and soil environmental factors among the positions. Our analysis was focused on the effect of farmer management practice on within field spatial variation in CH₄ emission and we highlighted that there were high variations in CH₄ emissions among the positions and its influencing factors from paddy rice soil. Pandey et al. (2014) also showed one year field experiment to examine whether different organic amendments in combination with the safe alternate wetting and drying has the potential to suppress on greenhouse gas emissions from rice paddies. To develop effective mitigation strategies, further work is needed to investigate small and large scale spatial variations in CH₄ emission from rice soil for different locations in lowland area of Myanmar.

5. Conclusion

High spatial variations in grain yield and CH₄ emissions among the positions were found in two successive rice fields. The positions near the channel showed better soil fertility status as well as better growth performance in this study. The outlet of the 1st field and inlet of the 2nd field showed highest CH₄ emissions. The data strongly indicated that high CH₄ emissions were due to high TC content with low redox potential in these positions. Within field spatial variation in CH₄ emission was related with soil TC content, and soil environmental factors which showed differences among the positions in both rice fields according to water flow pattern. Application of mineral fertilizers reduced CH₄ emissions from paddy rice soil as compared to non-fertilized parts in both rice fields. Current mineral fertilizers management practice such ammonium based N fertilizer, triple superphosphate and muriate of potash is an effective way to reduce CH₄ emission from lowland rice fields but site specific management practices should be adopted for different positions to increase grain yield and mitigate CH₄ emission from lowland rice in Myanmar.

Competing interests

The authors declare that they have no competing interests. The authors alone are responsible for the content and writing of the paper.

Authors' contributions

AZO and SDBK conceived, designed and performed the experiments described in this work and wrote the manuscript. AZO and KTW analyzed

the data. SDBK supervised the work and analyzed the results. All authors read and approved the final manuscript.

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References

- Adhya TK, Mishra SR, Rath AK, Bharati K, Mohanty SR, Ramakrishnan B, Rao VR, Sethunathan N (2000) Methane efflux from rice-based cropping systems under humid tropical conditions of eastern India. *Agric Ecosys Environ* 79:85–90
- Adhya TK, Pattanaik P, Satpathy SN, Kumarswamy S, Sethunathan N (1998) Influence of phosphorus application on methane emission and production in flooded paddy soils. *Soil Biol Biochem* 30(2):177–181
- Babu YJ, Nayak DR, Adhya TK (2006) Potassium application reduces methane emission from flooded field planted to rice. *Biol Fert Soil* 42(6):532–541
- Banik A, Sen M, Sen SP (1996) Effects of inorganic fertilizers and micronutrients on CH₄ production from wetland rice (*Oryza sativa* L). *Biol Fert Soils* 21:391–322
- Bodelier PLE, Hahn AP, Arth IR, Frenzel P (2000a) Effects of ammonium-based fertilization on microbial processes involved in methane emissions from soils planted with rice. *Biogeochem* 51:225–257
- Bodelier PLE, Roslev P, Henckel T, Frenzel P (2000b) Stimulation by ammonium-based fertilizers of methane oxidation in soil around rice roots. *Nature* 403:421–424
- Cai Z, Xing G, Yan X, Xu H, Tsuruta H, Yagi K, Minami K (1997) Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilizers and water management. *Plant Soil* 196:7–14
- Carroll JJ (1991) "What is Henry's Law?". *Chem Eng Progress* 87(9):48–52
- Chen J, Xuan J, Du C, Xie J (1997) Effect of potassium nutrition of rice on rhizosphere redox status. *Plant Soil* 188:131–137
- Conrad R, Klose M (2005) Effect of potassium phosphate fertilization on production and emission of methane and its 13C-stable isotope composition in rice microcosms. *Soil Biol Biochem* 37:2099–2108
- Conrad R, Klose M, Claus P (2000) Phosphate inhibits acetotrophic methanogenesis on rice roots. *Appl Environ Microbiol* 66:828–831
- Datta A, Santra SC, Adhya TK (2013) Effect of inorganic fertilizers (N, P, K) on methane emission from tropical rice field of India. *Atmos Environ* 66:113–120
- Dong HB, Yao ZS, Zheng XH (2011) Effect of ammonium-based, non-sulfate fertilizers on CH₄ emissions from a paddy field with a typical Chinese water management regime. *Atmos Environ* 45:1095–1101
- FAO (2010) Selected indicators of food and agricultural development in the Asia-Pacific region, 1999–2009. RAP publication, Viale delle Terme di Caracalla, 00153 Rome, Italy
- FAO/UNESCO, Food and Agriculture Organization of the United Nations/United Nations Educational and Cultural Organization (1974) FAO-UNESCO Soil map of the world, 1:5,000,000 Vol I. Legend. UNESCO, Paris
- Gaihre YK, Tirol-Padre A, Wassmann R, Aquino E, Pangga VG, Sta Cruz PC (2011) Spatial and temporal variations in methane fluxes from irrigated lowland rice fields. *Phillip Agric Scientist* 94(4):335–342
- Gee GW, Bauder JW (1986) Particle-size Analysis. In: Klute A (ed) *Methods of soil analysis*. Part 1. 2nd ed. Agron Monogr 9: 383–411. ASA and SSSA, Madison, WI
- Holzappel PA, Conrad R, Seiler W (1986) Effects of vegetation on the emission of methane from submerged paddy soil. *Plant Soil* 92:223–233
- Hori K, Inubushi K, Matsumoto S, Wada H (1990) Competition for acetic acid between CH₄ formation and sulfate reduction in paddy soil. *Soil Sci Plant Nutr* 61:572–578
- IPCC (1996) *Guidelines for National Greenhouse Gas Inventories*. Cambridge University Press, Cambridge
- Inman DJ, Khosla R, Westfall DG (2005) Nitrogen uptake across site-specific management zones in irrigated corn production systems. *Agron J* 97:169–176
- Inubushi K, Cheng WG, Aonuma S, Hoque MM, Kobayashi K, Miura S, Kim HY, Okada M (2003) Effects of free-air CO₂ enrichment (FACE) on CH₄ emission from a rice paddy field. *Global Change Biol* 9:1458–1464
- Jean LM, Pierre R (2001) Production, oxidation, emission and consumption of methane by soils: a review. *Eur J Soil Biol* 37:25–50, doi:10.1016/S1164-5563(01)01067-6
- Kimura M (1992) Methane emission from paddy soils in Japan and Thailand. In: Batjes NH, Bridges EM (eds) *World Inventory of Soil Emission Potentials*: WISE Report 2. ISRIC, Wageningen, pp 43–79

- Kimura M, Miura Y, Watanabe A, Katoh T, Haraguchi H (1991) Methane emission from paddy field (Part 1) Effect of fertilization, growth stage and midsummer drainage: pot experiment. *Environ Sci* 4:265–271
- Kumar JIN, Viyol S (2009) Short term diurnal and temporal measurement of methane emission in relation to organic carbon, phosphate and sulphate content of two rice fields of central Gujarat, India. *J Environ Biol* 30:241–246
- Li D, Liu M, Cheng Y, Wang D, Qin J, Jiao J, Li H, Hu F (2011) Methane emissions from double-rice cropping system under conventional and no tillage in Southeast China. *Soil Till Res* 113:77–81
- Lu Y, Wassmann R, Neue HU, Huang C (1999) Impact of phosphorus supply on root exudation, aerenchyma formation and CH₄ emission of rice plants. *Biogeochem* 47:203–218
- Mitra S, Aulakh MS, Wassmann R, Olk DC (2005) Triggering of methane production in rice soils by root exudates: effects of soil properties and crop management. *Soil Sci Soc Am J* 69:563–570
- Mitra S, Wassmann R, Jain MC, Pathak H (2002) Properties of rice soils affecting CH₄ production potential: 1. Temporal patterns and diagnostic procedures. *Nutr Cycl Agroecosyst* 64:169–182
- Neue U, Wassmann R, Kludze HK, Bujun W, Lantin RS (1997) Factors and processes controlling methane emissions from rice fields. *Nutr Cycl Agroecosyst* 49:111–117
- Oo AZ, Nguyen L, Win KT, Cadisch G, Bellingrath-Kimura SD (2013) Toposequential variation in methane emissions from double-cropping paddy rice in Northwest Vietnam. *Geoderma* 209–210:41–49
- Pandey A, Main VT, Vu DQ, Bui TPL (2014) Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in Vietnam. *Agric Ecosys Environ* 196:137–146
- Penning H, Conrad R (2007) Quantification of carbon flow from stable isotope fractionation in rice field soils with different organic matter content. *Org Geochem* 38:2058–2069, doi: 10.1016/j.orggeochem.2007.08.004
- Rao VR, Rao JLN, Adhya TK (1986) Heterotrophic nitrogen fixation (C₂H₂ reduction) as influenced by phosphorous application in paddy soil. *Plant Soil* 92:125–132
- Sass RL, Fisher FM Jr, Andrews JA (2002) Spatial variability in CH₄ emissions from a Texas rice field with some general implications. *Global Biogeochem Cy* 16(1):15–1–15–7, doi:10.1029/2000GB001355
- Schimel J (2000) Global change: rice, microbes and methane. *Nature* 403:375–377
- Schmitter P, Dercon G, Hilger T, Thi Le Ha T, HuuThanh N, Lam N, Due Vien T, Cadisch G (2010) Sediment induced soil spatial variation in paddy fields of Northwest Vietnam. *Geoderma* 155:298–307
- Schultz MK, Biegalski SR, Inn KGW, Yu L, Burnett WC, Thomas LJW, Smith GE (1999) Optimizing the removal of carbon phases in soils and sediments for sequential chemical extractions by coulometry. *J Environ Monitor* 1:183–190
- Schütz H, Hozapfel-Pschorn A, Conrad R, Renuenberg H, Seiler W (1989) A three-year continuous record on the influences of day time, season and fertilizer treatment on CH₄ emission rates from an Italian rice paddy. *J Geophys Res* 194:16405–16416
- Schütz H, Seiler W, Conrad R (1990) Influence of soil temperature on methane emission from rice paddy fields. *Biogeochem* 11:77–95
- Shang QY, Yang XX, Gao CM (2011) Net annual global warming potential and greenhouse gas intensity in Chinese double rice-cropping systems: a 3-year field measurement in long-term fertilizer experiments. *Global Change Biol* 17:2196–2210
- Suryavanshi P, Singh YV, Prasanna R, Bhatia A, Shivay YS (2012) Pattern of methane emission and water productivity under different methods of rice crop establishment. *Paddy Water Environ*. doi: 10.1007/s10333-012-0323-5
- Tokida T, Cheng W, Adachi M, Matsunami T, Nakamura H, Okada M, Hasegawa T (2012) The contribution of entrapped gas bubbles to the soil methane pool and their role in methane emission from rice paddy soil in free-air (CO₂) enrichment and soil warming experiments. *Plant Soil*. doi:10.1007/s11104-012-1356-7
- van der Gon H, Kropff MJ, van Breemen N, Wassmann R, Lantin RS, Aduna E, Corton TM, Van Laar HH (2002) Optimizing grain yields reduces CH₄ emissions from rice paddy fields. *Proc Natl Acad Sci U S A* 99:12021–12024
- Wang MX, Li J (2002) CH₄ emission and oxidation in Chinese rice paddies. *Nutr Cycl Agroecosyst* 64:43–55
- Wassmann R, Neue HU, Bueno C, Lantin RS, Alberto MCR, Buendia LV, Bronson H, Papen H, Rennenberg H (1998) Methane production capacities of different rice soils derived from inherent and exogenous substrates. *Plant Soil* 203:227–237
- Wassmann R, Wang MX, Shanguan XJ, Xie XL, Shen RX, Papen H, Rennenberg H, Seiler W (1993) First records of a field experiment on fertilizer effects on methane emission from rice fields in Hunan Province (PR China). *Geophys Res Lett* 20:2071–2074
- Xie B, Zheng X, Zhou Z, Gu J, Zhu B, Chen X, Shi Y, Wang Y, Zhao Z, Liu C, Yao Z, Zhu J (2010) Effects of nitrogen fertilizer on CH₄ emission from rice fields: multi-site field observations. *Plant Soil* 326:393–401
- Xiong ZQ, Xing GX, Zhu ZL (2007) Nitrous oxide and methane emissions as affected by water, soil and nitrogen. *Pedosphere* 17(2):146–155
- Yagi K, Minami K (1990) Effects of organic matter application on methane emission from some Japanese paddy fields. *Soil Sci Plant Nutr* 36:599–610
- Yan X, Yagi K, Akiyama H, Akimoto H (2005) Statistical analysis of major variables controlling methane emission from rice fields. *Global Change Biol* 11:1131–1141
- Yang SS, Chang HL (2001) Methane emission from paddy fields in Taiwan. *Biol Fertil Soils* 33:157–165
- Yang X, Shang X, Wu P, Liu J, Shen Q, Guo S, Xiong Z (2010) Methane emissions from double rice agriculture under long-term fertilizing systems in Hunan, China. *Agric Ecosys Environ* 137:308–316
- Zang Y, Wang YY, Su SL, Li CS (2011) Quantifying methane emissions from rice paddies in Northeast China by integrating remote sensing mapping with a biogeochemical model. *Biogeosciences* 8(5):1225–1235
- Zhang L, Yu D, Shi X, Weindorf D, Zhao L, Ding W, Wang H, Pan J, Li C (2009) Quantifying methane emissions from rice fields in the Taihu Lake region, China by coupling a detailed soil database with biogeochemical model. *Biogeosciences* 6:739–749
- Zheng X, Zhou Z, Wang Y, Zhu J, Wang Y, Yue J, Shi Y, Kobayashi K, Inbushi K, Huang Y, Han S, Xu Z, Xie B, Butterbach-Bahl K, Yang L (2006) Nitrogen-regulated effects of free-air CO₂ enrichment on methane emissions from paddy rice fields. *Global Change Biol* 12:1717–1732
- Zou J, Huang Y, Zong L, Zheng X, Wang Y (2004) Carbon dioxide, methane and nitrous oxide emissions from a rice-wheat rotation as affected by crop residue incorporation and temperature. *Adv Atmos Sci* 21(5):691–698

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