Spatial and Temporal Variations in Soil Parameters, Plant Growth and Environmental Impact of Paddy Rice Production in South East Asia

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DECLARATION OF ORIGINALITY

I hereby declare that this thesis and the work reported herein was composed by and originated entirely from me. Information derived from the published and unpublished work of others has been acknowledged in the text and references are given in the list of sources.

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Thank you

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Abstract

It is essential to know the spatial variability of soil factors and their influence on the variability of crop growth and yield, and greenhouse gas emission from lowland rice ecosystem for developing the site-specific management strategies of crop for sustainable rice production in Southeast Asia. For this purpose, two field experiments were conducted in Northwest Vietnam and lowland Myanmar. The research objectives were i) to assess the spatial variations in soil properties, crop yield and CH_4 emission related to field positions, ii) to assess the influence of mineral fertilizer on plant growth related CH_4 emission from paddy soils and iii) to conduct a quantitative analysis of the relation of grain yield and greenhouse gas emission to the economic benefit of the different positions in these study areas of Southeast Asia.

In 2011, field experiment was conducted in spring and summer rice seasons with two cascades of double-cropping paddy rice fields in Yen Chau district, Northwest Vietnam. The cascades were divided into fertilized and non-fertilized parts and all measurements were conducted at top, middle and bottom field of each part. Silt and clay content showed increasing trend towards the bottom field positions while higher sand content was observed in top field positions in both cascades. Total nitrogen and carbon contents showed higher in lower lying fields than that in the top field positions. Plant growth and yield component parameters showed higher in middle positions than that of other positions. Grain yields in the middle fields were higher than other field positions in both fertilized and unfertilized parts.

Variations in CH_4 emissions were also observed and the results showed that the rate and cumulative amount of CH_4 emissions in non-fertilized part were higher than that of fertilized one in both crop seasons. The spatial variation in CH_4 emissions among the positions was high in both cropping seasons with the highest in the bottom fields and the lowest in the top fields. The differences among field positions were influenced by clay content, TN and TC content which showed toposequence differences. Cumulative CH_4 emissions for spring rice ranged from 3.1 to 13.7 g CH_4 m^{-2} and that for summer rice from 4.3 to 23.5 g CH_4 m^{-2}. 61.7% were emitted during summer rice season and 38.1% from spring rice season.

In 2012, field experiment was conducted with two successive rice fields (1st field and 2nd field) in Kanyutkwin district, Pago Division, Myanmar. The fields were divided into fertilized and non-fertilized parts and all measurements were conducted at inlet, middle and outlet positions for both fields. Decreasing trend of sand content, soil total nitrogen and total carbon content were observed, while silt content tended to increase from 1st inlet to 2nd outlet position. Plant growth parameters showed better performance in all positions in the 1st field than in the 2nd field. High grain yield and yield components were observed in 1st inlet, 1st middle and 1st outlet positions in the 1st field. Farmer practice of fertilization increased grain yield over non-fertilized part, but it was not significant in all positions in the 1st field. In the 2nd field, although grain yield significantly increased in all positions due to fertilization, yield was still lower than that in the 1st field.

Considerable variations in CH_4 emissions were recorded among the positions, which were influenced by soil temperature, surface water pH, Eh, surface water depth, as well as the clay and TC content of soil. The CH_4 flux of the 1st outlet and 2nd inlet were 53.2 and 66.5 g CH_4 m^{-2}, respectively, and were 2 to 2.5 times higher than that of other positions. Seasonal cumulative CH_4 emissions for the 1st and 2nd fields were 33.6 and 39.3 g CH_4 m^{-2}, respectively. Fertilization reduced CH_4 emission in the 1st inlet (18.1%), 1st outlet (50.4%), 2nd inlet (15.9%) and 2nd outlet (13.4%). However, an increase in CH_4 emission due to fertilization occurred in the 1st middle (43.8%) and 2nd middle (7.7%) which might be related to different micro-elevation in the field.

Relationships among the grain yield, net income and greenhouse gas emission among the field positions were conducted using eco-balance analysis method. Rice production cost in Vietnam was comparably higher due to high cost of seeds, fertilizers and pesticides than that in Myanmar. Land preparation and labor costs were comparable in both study sites. High ranges of net incomes were observed among the positions of toposequence rice in Northwest Vietnam than that in Myanmar. Methane emission flux was higher in lowland, Myanmar than that in toposequence rice fields due to much more negative of soil redox status with high total C content of rice soil. High grain yields with low emission fluxes were achieved in fertilized and non-fertilized parts of middle positions in toposequence rice fields in Northwest Vietnam and mostly non-fertilized parts of all positions in the 1st field of lowland rice in Myanmar.

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List of Abbreviations

ANOVA : Analysis of Variance

C : Carbon

CH_4 : Methane

CO_2 : Carbon Dioxide

DAT : Days After Transplanting

EC : Electrical Conductivity

Eh : Redox Potential

K : Potassium

LSD : Least Significant Difference

N : Nitrogen

N_2O : Nitrous Oxide

NH_4 : Ammonium

NO_3 : Nitrate

P : Phosphorus

SOC : Soil Organic Carbon

TC : Total Carbon

TN : Total Nitr

Chapter 1

General Introduction

1 General Introduction

1.1 Rice in Southeast Asia

Rice is one of the most important staple foods for more than half of the world's population (IRRI, 2006) and influences the livelihoods and economies of several billion people. In 2010, approximately 154 million ha were harvested worldwide, among them 137 million ha (88 percent of the global rice harvested) were in Asia – of which 48 million ha (31 percent of the global rice harvested) were harvested in Southeast Asia alone (FAOSTAT, 2012). Approximately 45 percent of the rice area in Southeast Asia is irrigated, with the largest areas being found in Indonesia, Vietnam, Philippines, Thailand and Myanmar (Mutert and Fairhurst, 2002). In Southeast Asia, where agriculture is a major source of livelihood, approximately 115 million ha of land are devoted to the production of rice, maize, oil palm, natural rubber and coconut (ADB, 2009). Rice has been feeding the region's population for well over 4000 years and is the staple food of about 557 million people (Manzanilla et al., 2011). In 2007, the average annual consumption per capita was about 197 kg (FAOSTAT, 2012) and provided 49 percent of the calories and 39 percent of the protein in the diet (FAOSTAT, 2012). Throughout Southeast Asia today, rice is more than just food: it is the central subject of economic policy, a determinant of national objectives, and an important anchor in the maintenance of political stability.

1.2 Rice production in Vietnam

Vietnam is one of the centres of origin of rice cultivation and has become the second largest rice producer after Thailand in the Southeast Asia. Rice occupies 74 percent of Viet Nam's 5.7 million ha of arable land (IRRI, 2008). Rice production is dominated by small, irrigated farms based around the Mekong River Delta in the south (52 percent) and the Red River Delta in the north (18 percent). In Vietnam, 53% of the rice area is irrigated, 38% is rainfed, 5% is considered to be upland rice and 3% is flooded (Hatcho et al., 2010). In Northern Vietnam, 0.7 million ha are under paddy rice cultivation, of these 60% are located in hilly areas like toposequence of paddy rice terraces. Although the area of paddy rice remained relatively constant in Northern mountainous regions since 1995, the average rice productivity increased from 2.7 ton ha^{-1} to 4.6 ton ha^{-1} in 2009 (General Statistics Office of Vietnam, 2010).

1.2.1 Northern Mountainous Region of Vietnam

Vietnam`s topography is characterized by mountains with partly steep slopes, especially in the North-West with altitudes between 300 and 1000 m. This area occupies 95,434 km^2 and has a population of approximately 12 million people, including 30 ethnic minorities (Vien, 2003). In Yen Chau, 0.5 ha agricultural land was available per capita in 1980, which declined to 0.2 ha per capita in 1998 due to the population increased within these years by 300% (Wezel et al., 2002). Cultivated land per person in Northern Vietnam decreased strongly so that deforestation followed by slash and burn practices are not uncommon in order to expand the upland agricultural area (Dang et al., 2008). Because of the increasing land scarcity, the fallow periods become shorter and shorter whereas the cultivation period is extended (Wezel et al. 2002). This fact is reason enough for scientists to be engaged in the challenge to ensure food security without causing environmental damage at the same time (Ahn et al., 2005). The major challenge for the future is to find more sustainable ways of managing agro-resources in these vulnerable areas of Vietnam. In the study area, the upland crop-paddy rice system is connected and interdependent so that upstream land-use changes will also have impacts on downstream systems and their sustainability. Upstream erosion leads to sedimentation and siltation of downstream water bodies and paddy rice fields as well as to nutrient transportation within sediments and irrigation water. Therefore, soil erosion from upland is considered to have high impacts on the current productivity and sustainability of lowland paddy rice.

1.2.2 Linkage between upland and lowland

It is expected that upstream erosion leads to sedimentation and siltation of downstream water bodies and paddy fields as well as to nutrient transportation within sediments and irrigation water. Furthermore soil erosion is considered to have serious impacts on the current productivity and sustainability of the land. This is accelerated by high rainfall intensity during the rainy season and during field preparations. The weather in this area is tropical monsoon climate with an average annual precipitation of 1200 mm during rainy season from May to October. The consequence will be that soil and associated nutrients from upland erosion will settle in the paddy fields as the velocity of the water flow in the field is lower compared to the channel outside. Water will flow into the fields at the upper side and flows out at the lower side so that the distribution of the sediments is unequal throughout the rice fields. Sedimentation occurs according to different weight levels of certain soil particles: clay is lighter than silt and sand, and thus will be located in different parts of a rice field than the former two (Ahn et al., 2005). This fact may have an impact on nutrient distribution and on the texture in the field in the long-run. Furthermore, organic compounds present in the water also will influence soil fertility in paddies. These processes could have impacts on rice productivity and rice yields, depending on the distribution of the sediments within the fields. There have been studies about spatial variability of yield, crop growth performance and soil but still the knowledge about this impact in paddy fields is limited (Ahn et al., 2005).

1.3 Rice in Myanmar

Rice (*Oryza sativa* L.) has been the major crop in terms of agricultural production and food consumption in Myanmar. Most of the agricultural land in Myanmar has been used for rice cultivation, although its share of gross sown area gradually decreased from over 60% in the early 20th century to about 40% today (Matsuda, 2009). Rice is grown under various farming systems all over the country, with rain-fed and irrigated paddy fields being found, as well as upland farming, which is sometimes part of a shifting cultivation system. As for its consumption, rice is one of the principal parts of the diet in most components of the country (Matsuda, 2009).

1.3.1 Lowland rice – Delta region, Myanmar

Total area under paddy rice cultivation is 8.06 million ha; of these 68 percent are lowland rice cultivation areas (FAO, 2010). The delta zone consists of the Ayeyarwaddy, Yangon, and Bago Divisions. These divisions are covered mostly by large flat areas, which correspond to two deltas formed by Ayeyarwaddy River and the Sittaung River (Matsuda, 2009). The annual rainfall ranges approximately from 1200 to 3200 mm (Matsuda, 2009). The region is relatively well reclaimed as agricultural land and wet rice cultivation, traditionally rain-fed in the monsoon or late-monsoon season, is dominant. Irrigated lowland rice is one of the major rice ecosystems in these regions especially in semi-rainfed lowland area. In the summer season, rice is presently grown as described below, and the cultivation of some kinds of pulses (e.g black gram) has recently increased (Okamoto, 2001).

In lowland area, rice fields are located on the gently sloping land with differences in elevation for a few centimeters in an undulating topography. The differences in position may lead to differentiation in soil properties and soil fertility status (Hseu and Chen, 2001; Tsubo et al., 2006) and therefore crop yield. There is lack of information about spatial variations in soil properties and their related crop yield in lowland paddy rice of Myanmar.

1.4 Spatial variation in soil properties and rice production

The paddy field size in Southeast Asia is mostly so small that the effect of sediments and nutrients associated with runoff and irrigation water on the crop yield within and between the fields were neglected. Instead within and between the fields basic, the blanket management recommendation which means the same in fertilizer and other practices for the whole watershed was done for rice production.

However, the differences of soil nutrients within even a small paddy field are larger than somebody would expect. According to several researchers, especially in Japan, the spatial variability of the soil properties in upland rice fields as well as in paddy rice fields is big (Moritsuka et al., 2004). This within field spatial variability gains more and more attention as the rice fields are increasingly merged together (Ahn et al., 2005) to a field size of more than 0.5 ha (Moritsuka et al., 2004) in order to decrease the rice production costs, to facilitate future mechanization (Ahn et al., 2005) and to handle the declining number of farmers (Moritsuka et al., 2004). For rice production a big spatial variation in rice growth performance as well as in soil fertility is not desired (Moritsuka et al., 2004).

Besides that economic issues concerning spatial variability, the environmental aspect is of same importance. Only if experts and extension agents have the knowledge about spatial variability of nutrients within the field they can give correct and precise site-specific recommendations for the application of fertilizer. We can distinguish between spatial variations of different factors like rooting depth, pest pressure or soil properties which later may cause the spatial variability of crop yield. Hence, for later management it is also very important to point out and to document how the rice crop responds to these spatial variability. There is a lot of information about spatial variability of yield available for upland crops as well as for lowland paddy fields (Wenzel et al., 2002, Moritsuka et al., 2004, Ahn et al., 2005). In this context many factors play an important role, for example soil properties such as pH, organic matter content and texture (Ahn et al., 2005). Researchers tried to find out more about the spatial variability of different soil properties depending on the soil type. As a result, it was reported that most of the exchangeable cations had a high spatial variation of over 30% in contrast to the pH with a variation of only 12% (Ahn et al., 2005). These results correspond with results of researchers who found out that the coefficient of variation of pH was only 6% and for exchangeable Mg up to 81%. This could be due to the fact that pH, organic matter and soil texture are more stable and less dynamic than exchangeable NH_4-N or NO_3-N (Ahn et al., 2005). These characteristics of soil properties are considered to play an important role in terms of influencing the yield and growth performance of rice (Ahn et al., 2005). Once reached the paddy fields by erosion, the sediments with their soil properties can distribute in a different manner throughout the rice field. Wenzel et al. (2002) found that the topsoil depth can be associated with more organic matter and higher K and pH values whereas a higher clay and N content results from a greater disposition of the field. All these soil parameters are not occurring separate and pH correlates to the organic matter, K, N, and CEC is found. The same trend could be observed for a high CEC which is positive related to pH, organic matter, N, P, K and clay content (Wenzel et al., 2002).

Much research was done about spatial soil variability and how it affects the yield and growth of soybean, maize and rice (Machado et al., 2000, Yamagishi et al., 2003, Ahn et al., 2005, Vieira et al., 2010). The results showed that the soybean yield was higher in parts with higher clay content in the soil. For maize other researchers found that the yield is very spatially variable but not necessarily because of the soil fertility. According to other studies, the grain yield is determined not only by a single factor but rather by a mixture of many factors together (Machado et al., 2000, Yamagishi et al., 2003, Vieira et al., 2010). In this context Machado et al. (2000) gave recommendations about the handling of fertilizer and irrigation for proper management. For grain yield management they suggest using the knowledge about these factors which do not change during a growing season, i.e. soil texture or elevation, as information basis for identifying the right fertilizer application and water management. Information about the unstable factors and their effects on the grain yield within a season, i.e. rainfall, disease, shall be added. With the help of a factor analysis, it was proven that grain and straw yield of rice are affected by factors related to soil fertility. These results are confirmed by another study in Spain where factors such pH and total N gave the information needed for 54% of the rice yield variation (Ahn et al., 2005). Data about the yield and the growth performance of rice are therefore very important because they enable a site-specific management

(Chung et al. 2013).

1.5 Different spatio-temporal scale in soil properties

Worldwide, rice production is found to be very heterogeneous as it is highly depending on climatic conditions, soil fertility, variety suitability, land and water management and fertilizer application (Bouman and Tuong, 2001; Fageria et al., 2003; Kyuma, 2004; Haefele and Wopereis, 2005). The assessment of the main factors influencing spatial variation in crop performance is highly depending on the spatio-temporal scale chosen (Liu et al., 2008; Haefele and Konboon, 2009; Lennartz et al., 2009).

At field level, for example, puddling is one of the main factors affecting the dynamic soil-water system by altering the plough pan and therefore hydraulic conductivity and anaerobic conditions and land preparation can play an important role on soil-water dynamics within the field (Singh et al., 2006; Lennartz et al., 2009).

At toposequence level, internal runoff and deposition pattern processes play significant role for spatial variation (Homma et al. 2003, Dercon et al., 2006). An increase of soil fertility, crop productivity and an increase of water availability due to higher soil organic carbon (C) and clay deposits were linked with fields situated at the lower slope positions of a terrace sequence (Homma et al., 2003; Tsubo et al., 2007; Boling et al., 2008; Ruth and Lennartz, 2008). These processes alter the soil chemistry of fields mainly at the foot slope position (Tachibana et al., 2001) especially clay composition was altered (Prakongkep et al., 2008).

At watershed level, the redistribution of nutrients through erosion-sedimentation processes in upland-lowland areas and its impact on soil fertility in lowland rice paddy fields need to be taken into account besides climate, the nature of parent material and landscape features (Mingzhou et al., 2007; Liu et al., 2008). Sediment could increase applied fertilizer use efficiency increasing cation exchange capacity, clay content and soil organic matter (Mingzhou et al., 2007). Therefore, beside internal runoff and soil deposition processes in rice paddies, it is important to understand the impact of external sediment contributions as an additional source of nutrient deposits regarding specific fertilizer recommendations for improving resource use and crop management. King et al., (2009) demonstrated the importance of C and N transport by irrigation and runoff water in a furrow irrigated fields. According to their study, irrigation water enriched with sediments and dissolved organic C resulted in a net increase in total C and N loads in irrigated fields. Sediment deposits represent reallocated C in the landscape and due to their large variability in irrigated fields furthermore play a significant role when discussing C sequestration in intensively irrigated agro-ecosystems (Poch et al., 2006).

1.6 Methane Emission from Paddy Fields

Methane is a potent greenhouse gas that has 25 times higher global warming potential than CO_2

(International Panel of Climate Change (IPCC), 2007). Methane is present at a concentration of about 1774 ± 18 ppb in the atmosphere and its concentration recently has increased by 7 ppb $year^{-1}$ (IPCC, 2007). Over 50% of the global annual CH_4 emission is of anthropogenic origin (IPCC, 2007). Rice fields are an important atmospheric CH_4 source, contributing about 5-19% of total global CH_4 emission to the atmosphere (IPCC 2007). The cultivation of paddy rice fields is the leading anthropogenic source of CH_4 (Jacobson, 2005), contributing about 10–20% of the total anthropogenic CH_4 emission with an annual global emission ranging from 50 to 100 Tg CH_4 $year^{-1}$ (Reiner and Milkha, 2000). Wetland rice fields are now the second largest anthropogenic source of atmospheric CH_4 (Chen & Prinn, 2006) and will continue to be a major source because increases in global rice production and planting area are required to feed an ever-rising human population, especially in Asian countries (Minamikawa et al., 2006). Thus, reduction of CH_4 emission from paddy rice fields represents one of the major options for mitigation of global warming.

Continuously flooded paddy fields enhance anaerobic fermentation of C sources supplied by the rice plants and added organic matter, and results in CH_4 production. Methane emission is the net result of CH_4 production and oxidation in the soil and the transport of CH_4 gas from soil to the atmosphere. 60–90% of total CH_4 is emitted through rice plants (Holzapfel-Pschorn et al. 1986). Therefore, the magnitude of CH_4 emission from rice plants is regulated by complex and dynamic interactions among the plants, environment, and microorganisms (Kaushik and Baruah, 2008).

1.7 Spatial variation in methane emission

The measurements at various locations of the world show that there are large temporal variations of CH_4 fluxes and that the flux differs markedly with soil type and texture, application of organic matter and mineral fertilizer (Neue and Sass, 1994). The wide variations in CH_4 fluxes also indicate that the flux is critically dependent upon several factors including climate, characteristics of soils and paddy, and agricultural practices, particularly water regime (Neue and Sass, 1994). The parameters that affect CH_4 emissions vary widely both spatially and temporally. Multiple year data sets near the same location and under similar conditions can lead to substantial differences in seasonal CH_4 emission levels, making it difficult to establish a single number as the CH_4 emission level from a field, let alone at a regional or country level (Babu and Puttaiah, 2013). Thus, at the current level of understanding, a reported range in CH_4 emission levels for a country is more realistic than a single number as the CH_4 emission from the rice fields.

Spatial and temporal variation of CH_4 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).

The temporal and spatial variations of CH_4 production are related to rice root biomass, which might be seen as a function of cultivar and soil dependent property (Sass et al., 1990). Kanno et al. (1997)

have observed that CH_4 emission was more in gley soil than those from other soil types such as Andosol, upland soils, fine textured lowland soils, medium, and coarse-textured lowland soils and gravelly lowland soils. Wang et al. (1999) have concluded that soil temperature and CH_4 concentration in the soil solution are the two major factors controlling spatial variation in CH_4 emissions.

Soil texture and mineralogy through their effect on puddling can affect percolation rate and thereby net emission of CH_4 in waterlogged paddy soils. Yagi and Minami (1990) have found that CH_4 emission decreased in the sequence of peaty soils, alluvial soils, and Andosols. Yagi et al. 1997 have found that soil properties like total N, soil texture (clay and sand fractions mainly), CEC, available K and active Fe content have significant effect on CH_4 production potential of the top soil and subsoils.

Due to the interactive effects of soil, climatic and cultural factors, the uncertainty in estimating CH_4 emission from rice fields is increasing. The upscaling of flux rates is hampered by this uncertainty and the pronounced spatial and temporal variations (Van der Gon et al., 2000; Sass et al., 2002). There is an urgent need to evaluate the interaction between CH_4 emission and rice production in a changing climate and provide a basis for future decisions regarding mitigation options. More research is necessary to understand the temporal and spatial variation in CH_4 emission within paddy rice fields in order to develop a reliable regional and global CH_4 budget and identify effective mitigation measures.

1.8 Mitigation methane emission from rice field

Rice production, especially from flooded rice soils, is a large source of atmospheric CH_4, therefore a large contributor to global warming (FAO, 2004a). According to the IPCC (2007), estimates of the global emission rate from paddy fields (where CH_4 is predominant) are 60 Tg/year. Under anaerobic conditions of submerged soils of flooded rice fields, the CH_4 that is produced predominately escapes from the soil into the atmosphere via gas spaces that are found in the rice roots and stems, and the remainder of the CH_4 bubbles up from the soil and/or disperses slowly through the soil and overlying flood water.

Flood irrigation is an inexpensive method that practiced traditionally for paddy rice production. If the fields are completely even then it is possible to practice a reasonable irrigation for efficient use of water, but this is not always the case. Hence, there is a high risk of loss of water and nutrients to the subsoil and groundwater overflow due to heavy rain events. Furthermore, flooding techniques involve a high risk of CH_4 emissions. This is particularly evident in rice production, where the warm and waterlogged rice fields provide an optimal environment for CH_4 production. Rice production is responsible for 50 to 1000 million tonnes CH_4/year and is probably the largest of the human-induced sources of this greenhouse gas (FAO, 2007b). Research has shown that it is possible to reduce CH_4 emissions from rice production (FAO, 2007b). In 2006, Jondee et al. discussed how they changed the breeding programme for drought-prone rainfed lowland rice in order to increase tolerance to drought in Thailand. In addition, a study conducted in China, indicated that water management by flooding with mid-season drainage and frequent waterlogging without the use of organic amendments is an effective option for mitigating the combined climatic impacts from CH_4 and N_2O in paddy rice production (Zou et al., 2005).

Intermittent irrigation or alternate wetting and drying could reduce emissions from rice-fields, while the transfer and adoption of a rice integrated crop management approach (e.g. the Australian RiceCheck and ADW (IRRI)) would increase the efficiency of N fertilizer in rice production, thus reducing N_2O emissions (FAO, 2007c). Performing mid-season drainage and intermittent irrigation reduces the CH_4 levels by about 50 percent (FAO, undated).

On average after the rice is harvested and dehusked, rice straw and rice husk remain in the field and are commonly re-incorporated into the soil or burned, which causes CH_4 and soot to be released into the atmosphere. In paddy fields, rice straw is a reasonable type of organic matter return to the field as C input in terms of the C cycle. Many studies have reported that rice straw incorporation increases CH_4 emission from paddy rice soils (Yagi and Minami, 1990; Yang and Chang, 1997). In Japanese paddy fields, because of aerobic decomposition during the fallow period, the application of straw in the previous autumn or winter decreased CH_4 emission compared to just before transplanting (Goto et al., 2004; Matsumoto et al., 2002). Timing of rice straw incorporation is important to mitigate CH_4 emission from paddy rice soil.

1.9 Influence of nitrogen fertilizer on methane emission

Nitrogen fertilizers are commonly used in rice cultivation in order to achieve high grain yields. According to statistics from the Food and Agricultural Organization (FAO, 2012) of the United Nations, the world average rate of N fertilizers applied in rice production is 73 kg N ha^{-1}, with a range of 27-151 kg N ha^{-1} worldwide. There is an ongoing discussion regarding the possible effects of N application on CH_4 emission from rice fields. Application of N may directly or indirectly influence all of the processes determining CH_4 production, oxidation, and transport from the soil to atmosphere.

Nitrogen fertilizers stimulate crop growth and provide more C substrates (via organic root exudates and sloughed-off cells) to methanogens for CH_4 production (Aulakh et al., 2001; van der Gon et al., 2002; Inubushi et al., 2003). For example, several field scale studies have demonstrated that addition of N fertilizers increased CH_4 emissions in the rice soils (Banik et al., 1996; Shang et al., 2011). In their studies, stimulation of CH_4 emissions with N fertilizers was probably the result of stimulation of methanogens due to greater production of crop biomass by N fertilizers than control. In contrast, others have reported inhibition of CH_4 emissions with N fertilizer inputs in the rice soil (Xie et al., 2010; Dong et al., 2011). For example, Dong et al. (2011) reported that CH_4 emissions have decreased by 38-49% with addition of ammonia-based non sulfate fertilizer (150-250 kg N ha^{-1}) in the rice soils. In their study, N fertilizers stimulated activities of methanotrophs that resulted in greater CH_4 oxidation in N fertilizer than control treatment in the rice soils (Bodelier et al., 2000a, b). Application of ammonium sulfate fertilizers has shown to decrease CH_4 emission by inhibiting the activities of methanogens in the rice soils (Schutz et al., 1989; Cai et al., 1997). Sulfate acts as an electron acceptor under anaerobic conditions, which depresses CH_4 production through competition for electrons (Schutz etal. 1989; Scheid et al. 2003). Moreover, the product of sulfate reduction, hydrogen sulfide, may poison methanogenic bacteria and further depress CH_4 production (Minami, 1994). It is clear that the effect of N application on CH_4 emission is N-form dependent.

Till today, no single consensus exists on net impacts of N fertilizer on CH_4 emissions in the rice soils (Cai et al., 1997; Dong et al., 2011; Shang et al., 2011). Therefore, it is necessary to assess the effect of N fertilizer on plant growth related CH_4 emission from paddy rice soil for designing possible mitigation strategies in the rice soils.

1.10 Eco-balance analysis for rice production and environmental impact

Based on the consensus definition of “sustainable growth” (World Commission on Environment and Development 1987), analysis of production systems has been conducted to achieve the highest productivity with the least environmental loads. An analysis method such as the life cycle assessment (ISO 14000 Information Centre 2002) is a useful tool for this purpose. In agricultural systems, the relationship between productivity and environmental load must also be analyzed comprehensively and quantitatively to provide a criterion for farmers and policy makers to choose the most environmentally friendly management method.

In order to progress towards a sustainable future it is important to understand what sustainability means and how it can be measured (Wackernagel and Yount, 1998). Out of the various indicators that have arisen over the recent past which measure sustainable development, Ecological Footprint Analysis (EFA) is widely known. The Ecological Footprint (EF) is a resource and emission accounting tool introduced in the early ‘90s by Mathis Wackernagel and William Rees (1996) to track human demand on the biosphere‘s regenerative capacity (Wackernagel et al., 2002). One of its key features is that it is not just a stand-alone environmental indicator - it is also a useful measure of resource use. By tracking a wide range of human activities, the ecological footprint provides an aggregated indicator for some anthropogenic pressures that are more typically evaluated independently (CO_2 emissions, fisheries collapse, land-use change, deforestation, agricultural intensification, etc.). Therefore, by using the measure like the footprint, it becomes easier to understand the environmental consequences of the pressures humans place on the biosphere and its component ecosystems.

Limitation of EFA as an indicator of sustainability is that it does not include measures of social well being. It has also been pointed out (see Van den Bergh and Verbruggen, 1999; Lenzen and Murray, 2003) that since Ecological Footprints do not track land use practice it is possible to achieve a smaller Ecological Footprint through more intensive measures like industrialized agriculture. The biggest limitation of the EFA is that it leaves out many components of ecological demand on nature (Lenzen and Murray, 2003). For instance, while calculating Ecological Footprints only CO_2 emissions from energy are considered, other green house gases which have a more damaging effect per unit volume and emissions from other sources like dairy farming, industrial processes, coal seams, waste and bio-productive land are not taken into account.

The Carbon Footprint introduced in the scientific and public arena, is a measure of the total amount of GHG emissions that are directly and indirectly caused by an activity or are accumulated over the life stages of a product. The strengths and benefits of Carbon Footprint is the ability to allocate responsibility for production-related GHG emissions to consuming entities or activities. It should also be mentioned that, by tracking a wider set of GHG (if compared with the Ecological Footprint), the Carbon Footprint allows for a more comprehensive assessment of human contribution to GHG emissions that cause climate change, though additional research would then be needed to assess the link between our activities and climate change. With fewer assumptions than Ecological Footprint approach it leads to (likely) lower uncertainty (i.e., error bars) in estimates of Carbon Footprint for nations, products etc. The weaknesses of Carbon Footprint are: deriving a maximum 'allowable' amount of GHG emissions (a "Carbon Footprint threshold") would be needed once a 'sustainability threshold' for global warming has been agreed; and currently, no uncertainty studies are available. More problems same as EFA, it does not include the social and environmental driving forces.

An evaluation method is required that can provide decision criteria and insights into how environmental impacts and production can be balanced. Kimura and Hatano (2007) have proposed an evaluation method that compares the environmental load to the productivity to analyze the relationship between them. The analysis of the relation between production and environmental load has been defined as "eco-balance" (Kimura and Hatano 2007). The eco-balance approach allows an analysis of the trade-off relationship between production and environmental impact for various impacts. In Kimura and Hatano's (2007) study, historical changes in N flows of a municipality from 1912 to 2002 were analyzed to evaluate the relationship between production and environmental pollution. The eco-balance analysis explored the direction of change and provided detailed analysis of the change in subsystems in an effort to analyze the driving forces behind changes in production and environmental loads.

1.11 Objective of this study

1.11.1 Goal and objectives

The goal of this study was to understand redistribution and deposition patterns of sediment rich materials within and between the fields through irrigation and runoff water and its impact on rice productivity, net income and greenhouse gas emissions in the lowland cultivated rice fields in Southeast Asia. For this purpose, the two study sites were chosen based on their different rice ecosystems; one typical mountainous intensive double cropping paddy rice in Northwest Vietnam and another typical traditional practice in lowland area, Myanmar.

1.11.2 Hypotheses

The main hypotheses addressed in this thesis are:

1. High spatial variations exists in soil properties, crop yield and CH_4 emission among the positions
2. Mineral fertilizers reduce CH_4 emission from paddy rice soil in both experimental sites
3. Using eco-balance analysis, incentives to choose management methods with lower environmental load can be created

The specific objectives were to:

1. To assess the spatial variations in soil properties, crop yield and CH_4 emission related to field positions
2. To assess the farmer practice of fertilization on growth and yield of lowland rice
3. To assess the influence of mineral fertilizer on plant growth related CH_4 emission from paddy rice soil
4. To conduct a quantitative analysis of the relation of grain yield and GHG emission to the economic benefit of the different positions
5. To conduct comparison between Vietnam and Myanmar site in term of grain yield, CH_4 emission and economic benefit from paddy rice production

Chapter 2

Toposequential variation in soil properties and crop yield from paddy rice cascade in Northwest Vietnam

2 Toposequential variation in soil properties and crop yield from paddy rice cascade in Northwest Vietnam

2.1 Introduction

In Northern mountainous region of Vietnam, an important agro-ecosystem is a composite swidden agriculture which integrates annual food crops, such as maize, cassava and upland rice, and fallow in the uplands and permanent wet rice fields in valley bottoms of the catchment (Lam et al., 2005) to form a single household resource system (Rambo, 1998). More recently, traditional agriculture methods involving fallows are more and more replaced by market oriented land use annual mono-cropping systems that have a low soil cover during their establishment phase (eg. maize), inducing severe erosion on steep slopes. Such land use alterations have dramatic environmental effects (Wezel et al., 2002) and high precipitation will lead to accelerate soil degradation due to erosion of the steep slopes used for agriculture.

Soil erosion is considered to have serious impacts on the current productivity and sustainability of the land. Upstream erosion will lead to sedimentation and siltation of downstream water bodies and paddy fields as well as nutrient transportation within sediments and irrigation water. During erosion events, nutrients are removed and attached to eroded sediments, reallocated in the watershed (Dung et al., 2008; Pansak et al., 2008). Sediment rich water will flow into the paddy fields at the upper side and flow out at the lower side so that the distribution of the sediments is unequal throughout the rice fields. The deposited sediments create patterns of spatial variability in soil fertility of downstream watershed (Gao et al., 2007; Mingzhou et al., 2007) and will influence the crop productivity of the terrace rice fields.

Rice fields are located on the gently sloping land which differs in elevation for a few meters in an undulating topography. These differences in toposequence position may lead to differentiation in soil properties and hydrological conditions (Hseu and Chen, 2001; Tsubo et al., 2006) and therefore crop yield. Topography directly affects soil-forming processes through erosion and deposition, and variation has been observed in soil texture (Yamauchi, 1992), nitrogen, phosphorus and potassium content (Moormann et al., 1977; Eshett et al., 1989; Posner and Crawford, 1992; Yamauchi, 1992) among the toposequence positions. Furthermore, organic compounds present in the water also will influence soil fertility in paddy rice fields. However, redistribution of nutrients through erosion-sedimentation processes in upland-lowland areas and its impact on soil fertility in the lowland are too often neglected (Mochizuki et al., 2006; Rüth and Lennartz, 2008).

In general, large field to field variations in soil fertility and rice growth along the toposequence are not desirable for rice production. For developing the site-specific fertilizer management strategies of crop, it is essential to know the spatial variability of soil factors and to assess their influence on the variability of crop growth and yield. Assessing spatial variation among the toposequence field positions is necessary for identifying and quantifying the limiting factors for rice growth, and addressing the spatial variability of rice yield. There have been studies about spatial variability of yield, crop growth performance and soil although the knowledge about sediment inducing spatial variation in soil properties and crop yield among the toposequence position due to upland soil erosion is still limited.

Thus, the objectives of this study were (1) to assess the sediment inducing toposequential variability of soil properties and crop yield at cascade level and (2) to distinguish between the inherent spatial variability in soil fertility induced by sediment deposits and soil fertility influenced by farmers' fertilization practices.

2.2 Materials and method

The field experiments were carried out from February until November 2011, during two rice cropping seasons in the Chieng Khoi commune (350 m.a.s.l., 21º 7′60″N, 105º40′0″E), Yen Chau district, Northwest Vietnam. The studied area is located in the tropical monsoon area with very hot and rainy summers with 858 mm (May-October, 2011) and cool and dry winters with 201 mm rainfall (November-April, 2011) (Fig. 2.1). The annual precipitation was 1059 mm in 2011. Open channel irrigation system and a lake reservoir allow for two rice cropping seasons a year; spring crop from February to June and summer crop from July to November.

Two rice cascades (Cascade 1 and 2) were selected for this experiment. The length and altitude differences were 83 m and 7 m for cascade 1 and 87 m and 5 m for cascade 2, respectively. Both cascades contained 5-6 successive paddy fields, covering a total area of 0.8 ha. The uppermost field of cascades received water directly from the irrigation channel. All other fields received water from a single inlet from above lying field and drain via single outlet to the lower situated field. At the beginning of the first crop season, sediments entering the rice fields are mainly provided through irrigation system. The irrigation water had an average concentration of 2 mg l^{-1} organic C and 1.5 mg l^{-1} total N when no rain occurred (Schmitter et al. 2010). During rainy season, additional sediments from upland are delivered to some of the rice fields besides the irrigation system.

The experiment was laid out in a split plot design with three replications at each site. All fields in both cascades were divided into two parts resulting in two strips per cascade. Two sets of factors included in this experiment were as follows: different toposequence positions (top, middle and bottom) as the main plot and with (+F) and without (-F) fertilizer application as the subplot. The soil type was Gleysols (silty loam in the different horizons) (UNESCO, 1974). The applied chemical fertilizers were 213 kg N ha^{-1}, 150 kg P ha^{-1} and 93 kg K ha^{-1} per rice season with split applications according to the local recommendations by extension service. The first dressing, at transplanting, contained 56% N, 100% P and 34% K of the total amount of fertilizer applied in the form of NPK and urea. Second and third dressings contained 22% N and 33% K of the total amount of fertilizer in the form of urea and Kali (K_2SO_4– 40% K_2O) which were applied at active tillering and heading stage.

The sticky rice variety (*Oryza sativa*, Var. Nep 87) was used in both cropping season for both cascades. Seedlings of 18 days old were transplanted in the well-puddle fields. Rice seedlings were transplanted on February 28 and harvested on June 30, 2011 for the spring rice and the corresponding dates for the summer rice are July 28 and November 7, 2011, respectively. After harvesting the spring rice, all the fresh crop residues leftover were incorporated into the soil by plowing and harrowing. All management practices were followed by farmer practices in both cropping seasons. Previous to this experiment, all fields were used similarly for continuous double-cropping paddy rice for several years.

Top soil samples at 0-5 cm depth were taken before transplanting and after harvest for sand, silt, clay, TN and total carbon TC content. Soil particle analysis was done by pipette method (Gee and Bauder, 1986). Total N and TC contents were analyzed by using a 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). Electrical conductivity of the soil water was measured in the supernatant suspension of a 1:5 soil: water mixture using EC meter (OM-51, Horiba, Japan). Water samples were collected at 10 days interval for NH_4 concentration analysis. The analysis was done by using ion selective pack test for NH_4, simplified chemical analysis (Kyoritsu Chemical-Check Lab., Corp).

Seven samples hills were collected from each plot for collection of data on plant characters and yield components. Grain yield was determined from 1 m^2 sampling area at harvest and was expressed as rough (unhulled) rice at 14% moisture content. All the data were evaluated by ANOVA by using CropStat 7.2 statistical software. Treatment means were compared by LSD at p=0.05 according to Fisher test.

2.3 Results

2.3.1 Soil properties

Soil physical properties varied significantly among the field positions in both rice cascades (Table 2.1). Sand was the dominant particle type in the top fields containing 54.0% and 58.9% in cascade 1 and 2, respectively. The middle and bottom fields showed higher silt content in both cascades; 51.9 and 49.7% in cascade 1 and 43.4 and 37.3% in cascade 2, respectively. In cascade 1, clay content was significantly (p<0.01) higher in middle field but there were no statistical differences in clay content between top and bottom field. Significantly (p<0.01) higher clay content was found in the middle and bottom fields of cascade 2 than in the top field.

Soil TN and TC contents were significantly (p<0.01) different among the field positions (Table 2.1). In cascade 1 and 2, the average values of TN from different field positions were 0.25 g kg^{-1} and 0.24 g kg^{-1} in the top soil layer, respectively. TC content for cascade 1 and 2 were 4.8 g kg^{-1} and 3.9 g kg^{-1}, respectively. When comparing different toposequence positions, TN content was significantly (p<0.01) higher in the middle field with 0.32 and 0.29 g kg^{-1}, followed by the bottom field with 0.29 and 0.26 g kg^{-1} and the lowest was observed in the top field with 0.17 and 0.18 g kg^{-1} in cascade 1 and 2, respectively. In both rice cascades, similar trend like TN was also found for TC content. The highest TC content was observed in the middle fields followed by bottom field and the lowest was in the top field. There were no significant differences in TN and TC content of the soil taken before transplanting and after harvest (data not shown). Soil pH ranged from 8.0 to 8.4 in both rice cascades and significant (p<0.05) higher soil pH was found in bottom fields than the others (Table 2.1). Electrical conductivity (EC) value was found significantly higher in top field than bottom fields in both rice cascades (Table 2.1).

2.3.2 NH_4 concentration in surface water

Seasonal variations in NH_4 concentrations were observed among the field positions in both cascades in spring rice (Fig. 2.2a & 2.2b) and also in summer rice (Fig. 2.2c & 2.2d). In spring rice, the concentration of NH_4 in surface water ranged from 0.2 to 0.85 mg L^{-1} for cascade 1 and 0.2 to 0.68 mg L^{-1} for cascade 2 with the highest peaks at 27 DAT. Seasonal NH_4 concentrations for top, middle and bottom fields in average of both cascades were 2.7, 3.5 and 3.1 mg L^{-1}, respectively. In summer rice, the concentrations of NH_4 in flood water were observed in the range of 0.2 to 0.84 mg L^{-1} in cascade 1 and 0.2 to 0.8 mg L^{-1} in cascade 2 with the highest peaks occurred between 17 and 27 DAT during rice growing season. Top, middle and bottom fields contained average NH_4 concentration in surface water of 2.8, 3.5 and 3.1 mg L-1, respectively, for both rice cascades.

2.3.3 No. of effective tillers

Significant differences (p<0.05) in effective tiller per hill were observed among the different toposequence positions in both cascades (Table 2.3 and Fig. 2.3). In spring rice, for the effect of field position on average of both cascades, number of effective tillers per hill was found the highest in the middle field than the other fields. The lowest number of effective tillers was observed at top field in cascade 1 and at bottom field in cascade 2. The fertilized part produced more effective tillers than unfertilized part in both rice cascades.

In summer rice, the middle field also showed the highest number of effective tillers in average of both cascades followed by bottom field and the lowest was found at top field. Application of fertilizer produced significantly ($p<0.05$) higher number of effective tillers than unfertilized part in both cascades (Table 2.3 and Fig. 2.3).

2.3.4 Yield component parameters

In spring rice, fertilizer treatment did not show any significant variation with respect to panicle length and filled grain proportion in cascade 1 and 2 (Table 2.2 and 2.3). The overall mean values were higher in fertilized part than unfertilized part. Regarding the effect of different toposequence positions, significant ($p<0.05$) differences in panicle length were observed with the longest in the top field followed by the middle and the lowest was observed in the bottom field in both cascades (Table 2.2). Middle field showed the highest filled grain proportion followed by the bottom field and the lowest was found in the top field in both cascades.

In summer rice season, fertilizer application did not show any significant variation in respect of filled grain proportion but showed significant ($p<0.05$) differences in panicle length in both cascades (Table 2.3). Among the field positions, middle field showed significantly higher value in panicle length and filled grain proportion than other fields in both cascades (Table 2.2). The variation in panicle length and filled grain proportion was influenced by interaction of fertilizer and field position only in cascade 2 of spring rice. In summer rice, only panicle length was significantly ($p<0.05$) influenced by fertilized and field position in both cascades.

In both rice seasons, significant ($p<0.05$) differences in grains per panicle and 1000 grain weight were observed due to fertilizer and different toposequence positions (Table 2.3). Fertilization increased grains per panicle and 1000 grain weight than unfertilized part in both rice seasons (Table 2.2). In spring rice, the middle field showed the highest value of grains per panicle and 1000 grain weight in both cascades. The variation in grain per panicle was also influenced by fertilizer and field position in cascade 2 and 1000 grain weight in cascade 1. In summer rice, the highest values of grains per panicle and 1000 grain weight were also observed in middle field followed by the bottom field and the lowest was found at the top field in both cascades. There were no interaction effect of fertilizer and field position on grain per panicle and 1000 grain weight in summer rice in both cascades.

2.3.5 Spatial variability in grain yield

The grain yield of rice differently responded to the different toposequence positions of the fields and to the different fertilizer treatments (Fig. 2.4 and Table 2.3). Grain yield was also influenced by interaction of fertilizer and field position in both rice cascades except in summer rice of cascade 1 (Table 2.3). In spring rice, a significant ($p<0.05$) difference of grain yield was observed between the fertilizer treatments in both rice cascades with fertilizer application showing a higher value of grain yield (+F: 644.3 g m^{-2}) than unfertilized plot (–F: 483.3 m^{-2}) in the average of cascade 1 and 2. In summer rice, significantly ($p<0.05$) higher grain yield was observed in fertilized part (+F: 599.8) than unfertilized part (-F: 480.8) in the average of both cascades.

Significant ($p<0.05$) yield differences were observed among the toposequence positions in both cascades of spring rice (Table 2.3) and the highest yields were observed in the middle field in both cascades. The middle field produced the highest grain yield of 644.8 g m^{-2} followed by the first field; 518.2 g m^{-2} and the lowest value 512.1 g m^{-2} was found in the last field during spring rice season. The obtained grain yields for spring rice in cascade 1 and 2 were significantly ($p<0.01$) and positively related with TN content in the soil by a simple linear regression model (Fig. 2.5). Grain yields were also found to be negatively related ($p<0.05$) with sand content in cascade 2 but not related in cascade 1 (Fig. 2.6). Observed grain yields in spring rice season were significantly ($p<0.05$) related with silt content only in cascade 2 (Fig. 2.7). In spring rice, grain yields were significantly (p<0.05, r=0.812) correlated with NH_4 concentration in surface water in both rice cascades.

In summer rice, the highest value 559.2 g m^{-2} of grain yield was also observed in middle field followed by the bottom field; 517.7 g m^{-2} and the last was in the top field; 400.2 g m^{-2} in average of both cascades. The obtained grain yields for summer rice in both cascades were significantly ($p<0.01$) and positively related with TN content (Fig. 2.5) and negatively ($p<0.01$) related with sand fraction by a simple linear regression model (Fig. 2.6). Observed grain yields in summer rice season were significantly ($p<0.01$) related with silt content in both cascades (Fig. 2.7). According to spearman rank order correlation analysis, grain yields were significantly (p<0.05, r=0.88) related with average concentration of NH_4 in surface water for both rice cascades in summer rice.

2.4 Discussion

2.4.1 Influence of toposequence position on soil properties

There were substantial differences in soil texture among the different toposequence positions (Table 2.1). The downward movement of finer nutrient rich soil material along with irrigation and runoff water from upland were deposited to the lower lying fields of the cascades (Schmitter et al. 2010). Therefore, silt and clay contents were higher in the middle and bottom fields than top field. The increasing trend in clay content from top to bottom along the toposequence was also observed by Eshett et al. (1989) in Nigeria and Posner and Crawford (1992) in Senegal and Boling et al. (2008) in Thailand and Indonesia.

TN and TC content also varied among the different toposequence positions (Table 2.1). The first field in the cascade had lower TN and TC content with higher sand fraction than the lower fields. Increase in soil TN and TC were related to the different toposequence positions, which were influenced by the distance from the irrigation channel and possibility of material transportation between fields due to runoff water from the upper fields. Tsubo et al. (2007) also reported the downward movement of finer nutrient in soil in rainfed rice terraces. Increase in TN and TC in the middle and bottom fields were related to increase in clay and silt fraction in these fields. The results of analysis of NH_4 concentration in surface water showed that the middle and bottom fields of both rice cascades were higher in concentration than top fields (Fig. 2.2). This indicates transportation of organic rich sediment material from the irrigation channel (Poch et al., 2006). In irrigated rice fields, irrigation water has been identified as a considerable source of additional particulate N and organic C to be transported into irrigated fields depending on its origin (King et al., 2009). Besides irrigation water, runoff water from the surrounding steep slopes could be identified as an additional pathway of sediment delivery into the paddy fields influencing strongly the soil organic carbon content and textural changes of the paddy soil (Schmitter et al., 2010).

2.4.2 Influence of management and toposequence position on yield and yield component parameters

Cascade irrigation water can lead to an enrichment or depletion of soil fertility, which can explain the spatial variability patterns in landscape level (Schmitter et al. 2010). This study showed that the number of effective tillers was related to higher content of TN in both cascades (Fig. 2.3). Furthermore, both cascades showed generally higher number of effective tillers in the fertilized fields than in the unfertilized ones. This corresponds to the findings of Salahuddin et al. (2009) in Mymensingh, Bangladesh. They reported that the number of effective tillers increased with increasing N levels in soil. Significant higher grains per panicle, proportion of filled grain and 1000 grain weight were observed in the middle field which might be related to higher silt and clay content, TN and TC content and NH_4 concentration in surface water of the middle field in both rice seasons. Only the panicle length was the highest in the first field in spring rice.

The spatial variation in grain yield observed in both cascades showed a clear difference depending on the different topsequence positions within each season (Fig. 2.4). In both rice cascades, the grain yield increased along the cascade with increasing distance from the irrigation channel, which resembled the distribution of soil particles, and TN and TC content within the cascade. Schmitter et al. (2011) stated that the increase in grain yield towards the bottom fields of toposequence was related to an increase in soil organic C and decrease in sand content in Chieng Khoi area. Rice performance increased when finer nutrient rich sediments were deposited (Schmitter et al. 2011). In this experiment, the higher grain yield in middle fields were significantly related with the higher NH_4 concentration in surface water in both rice seasons. Mochizuki et al. (2006) also pointed out that the incorporation of SOC enriched sediments in lowland rice paddy fields had positive effect on grain yield. For both rice seasons, the TN and TC content and sand fraction significantly affected the obtained rice yields with higher yield at the lower situated rice fields containing higher silt, clay, TN and TC content.

2.4.3 Seasonal differences

In both cascades, among the toposequence positions, the highest yield was observed in the middle fertilized fields in spring and summer rice seasons (Fig. 2.4). Grains per panicle, effective tillers, proportion of filled grain and 1000 grain weight were also highest in the middle field. Grain yield was higher at bottom field than top field position in fertilized part of both cascades and unfertilized part of cascade 2 in spring rice. However, that was not the case at cascade 1 of unfertilized part in spring rice. This might be due to flood damage in the fields lower on the toposequence of cascade 1 which was located next to the river. Schmitter et al. (2010) pointed out that cascade 1 was affected by flooding during typhoons and discussed that flooding events in relation to sediment deposits altered the linear trend of soil fertility changes along a cascade.

In summer rice, higher grain yield was observed in bottom field than top field position in all parts of both cascades. The increase in grain yield in the bottom fields in both rice seasons might be related to an increase in TN and TC content and a decrease in sand content. Schmitter et al. (2011) reported that the grain yield increase along the cascade with increasing distance from irrigation channel resembled the soil fertility pattern observed in the top soil (i.e., an increase in SOC and decrease in sand content in this watershed area). A similar spatial variability of grain yield has been reported by Homma et al. (2003), Rüth and Lennartz (2008) and Haefele and Konboon (2009) who observed increasing grain yields due to deposition of nutrient rich fine sediments at the end of a toposequence.

2.4.4 Influence of fertilization

The effect of sedimentation can be seen clearly in the unfertilized part where the middle field produced the highest grain yields than other fields in both crop seasons (Fig. 2.4). Application of the recommended amount of fertilizers increased yields over unfertilized plots but fertilizer management did not mitigate spatial variation trend that middle field also produced the highest yield in both spring and summer rice. Mochizuki et al. (2006) reported that combining chemical fertilizer with the incorporation of the sediment soil into the paddy soil increased the grain yield significantly, while without fertilizer the sediments had no effect on yield. This result was in contrast to the findings of our research, where fertilized plots produced higher yield, but still showed the effect of toposequence positions. The study by

Schmitter et al. (2011) showed that on average, the fertilized fields yielded continuously more than the fields without fertilizer in Chieng Khoi area. In unfertilized part, there was a significant difference in grain yield among toposequence positions which showed the significant influence of sediment deposition from the upland to the lowland rice fields. Grain yield increased in lower lying fields when finer nutrient rich sediments were deposited depending on quality and quantity of the sediments and the deposition pathways.

2.5 Conclusion

This study showed clearly that the spatial variations in soil properties and crop production in the cascades could be linked to sediment deposition onto the top soil. The downward movement and deposition of sediment along the toposequence positions created spatial variability patterns and influenced the crop productivity. Although recommended types of fertilizer management practice increase grain yield over unfertilized parts, toposequence specific management practice such as the same amount of fertilization in all toposequence positions should not be practiced in this watershed area. The results highlighted that spatial variations in soil properties and crop yields required field specific and field adapted management practices for each position rather than toposequence specific management practice for sustainable land use in this watershed area.

Table 2.1 Physico-chemical properties of the experimental soils among the field positions before transplanting of spring rice, 2011 (Mean ± standard deviation)

Field position	Sand (%)	Silt (%)	Clay (%)	TN (g kg^{-1})	TC (g kg^{-1})	pH	EC (msm^{-1})
Cascade 1							
Top	54.0	32.6	13.4	0.17	3.2	8.1	24.2
Middle	23.3	51.9	24.8	0.32	5.6	8.0	25.3
Bottom	31.9	49.7	18.5	0.29	5.3	8.3	21.7
$LSD_{(0.05)}$	8.5	8.4	4.6	0.05	1.0	0.1	3.5
Cascade 2							
Top	58.9	34.1	7.0	0.18	2.5	8.0	25.3
Middle	25.5	43.4	31.2	0.29	4.4	8.2	23.4
Bottom	40.3	37.3	22.4	0.26	4.8	8.4	17.6
$LSD_{(0.05)}$	12.5	4.1	8.6	0.04	0.8	0.1	3.7

Table 2.2 Effect of fertilizer and toposequence position on yield components of spring and summer rice (Mean ± standard deviation)

	Spring rice				Summer rice			
	Panicle length (cm)	**Grains panicle^{-1}**	**Filled grain%**	**1000-grain wt (g)**	**Panicle length (cm)**	**Grains panicle^{-1}**	**Filled grain%**	**1000-grain wt (g)**
Cascade 1								
Treatment -F	21.7	136.1	78.9	24.1	18.9	80.5	76.2	24.2
+F	22.5	154.4	80.6	25.0	20.3	101.0	77.6	25.4
$Lsd_{(0.05)}$	1.2	13.2	4.5	0.8	0.6	12.1	6.7	1.0
Position								
Top	23.3	167.0	76.5	22.4	19.3	77.9	76.2	23.6
Middle	21.5	185.8	82.7	25.3	20.4	101.8	77.9	25.8
Bottom	20.1	95.9	80.0	24.0	19.9	92.4	77.4	24.9
$Lsd_{(0.05)}$	1.4	13.2	5.5	1.12	0.8	14.0	12.1	0.1
Cascade 2								
Treatment -F	21.5	132.1	72.4	24.2	19.2	86.0	72.8	24.0
+F	22.1	153.7	76.8	25.3	20.4	90.9	76.8	25.5
$Lsd_{(0.05)}$	0.8	16.1	4.7	0.8	0.7	10.8	6.0	0.2
Position								
Top	23.3	129.3	68.3	25.5	19.9	85.5	67.1	24.0
Middle	22.3	189.3	80.6	25.7	20.4	107.7	77.7	25.6
Bottom	19.7	110.0	74.9	22.3	19.1	95.6	73.3	25.1
$Lsd_{(0.05)}$	0.9	19.8	5.8	1.0	0.8	13.2	12.1	0.2

Table 2.3 Results of the ANOVA test for growth and yield components of rice during spring and summer rice growing period in 2011

	Effective tiller no.	Panicle length	Grain panicle^{-1}	Filled grain %	1000 grain weight	Grain yield
Cascade 1						
Spring						
Fertilizer (F)	**	ns	*	ns	*	*
Field position(FP)	**	**	**	ns	**	**
F x FP	*	ns	ns	*	*	*
Summer						
Fertilizer (F)	*	**	**	ns	**	**
Field position(FP)	*	*	*	*	**	**
F x FP	ns	*	ns	ns	ns	ns
Cascade 2						
Spring						
Fertilizer (F)	*	ns	*	ns	*	*
Field position(FP)	**	**	**	**	**	**
F x FP	**	**	*	ns	ns	*
Summer						
Fertilizer (F)	*	**	*	ns	*	**
Field position(FP)	**	*	**	*	**	**
F x FP	*	*	ns	ns	ns	*

ns., not significant

** and * indicate significant at 0.01 and 0.05 levels, respectively

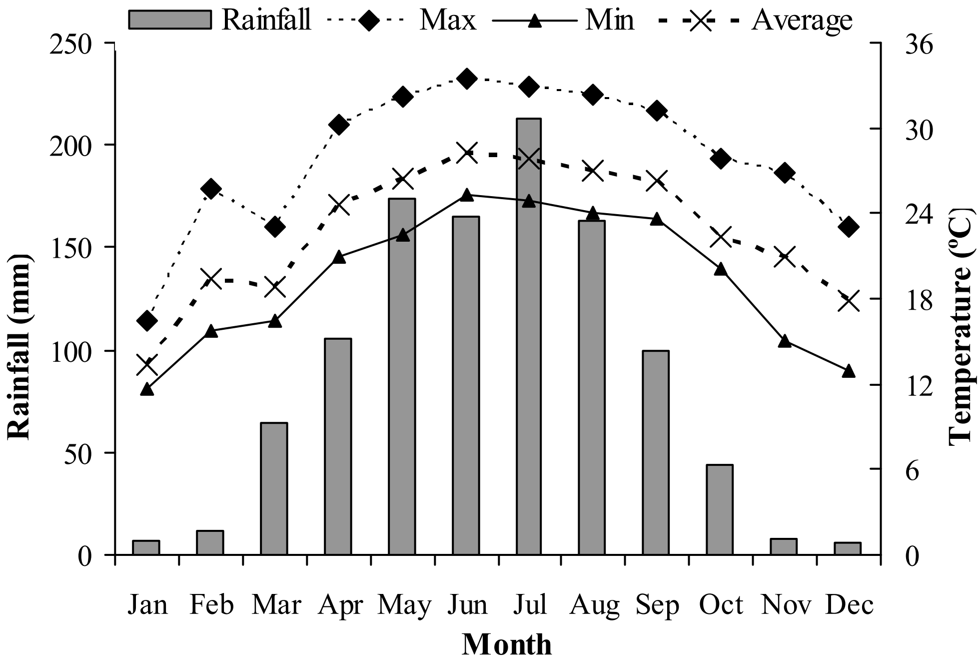


Fig 2.1 Monthly average rainfall and temperature of Yen Chau city recorded during the year 2011

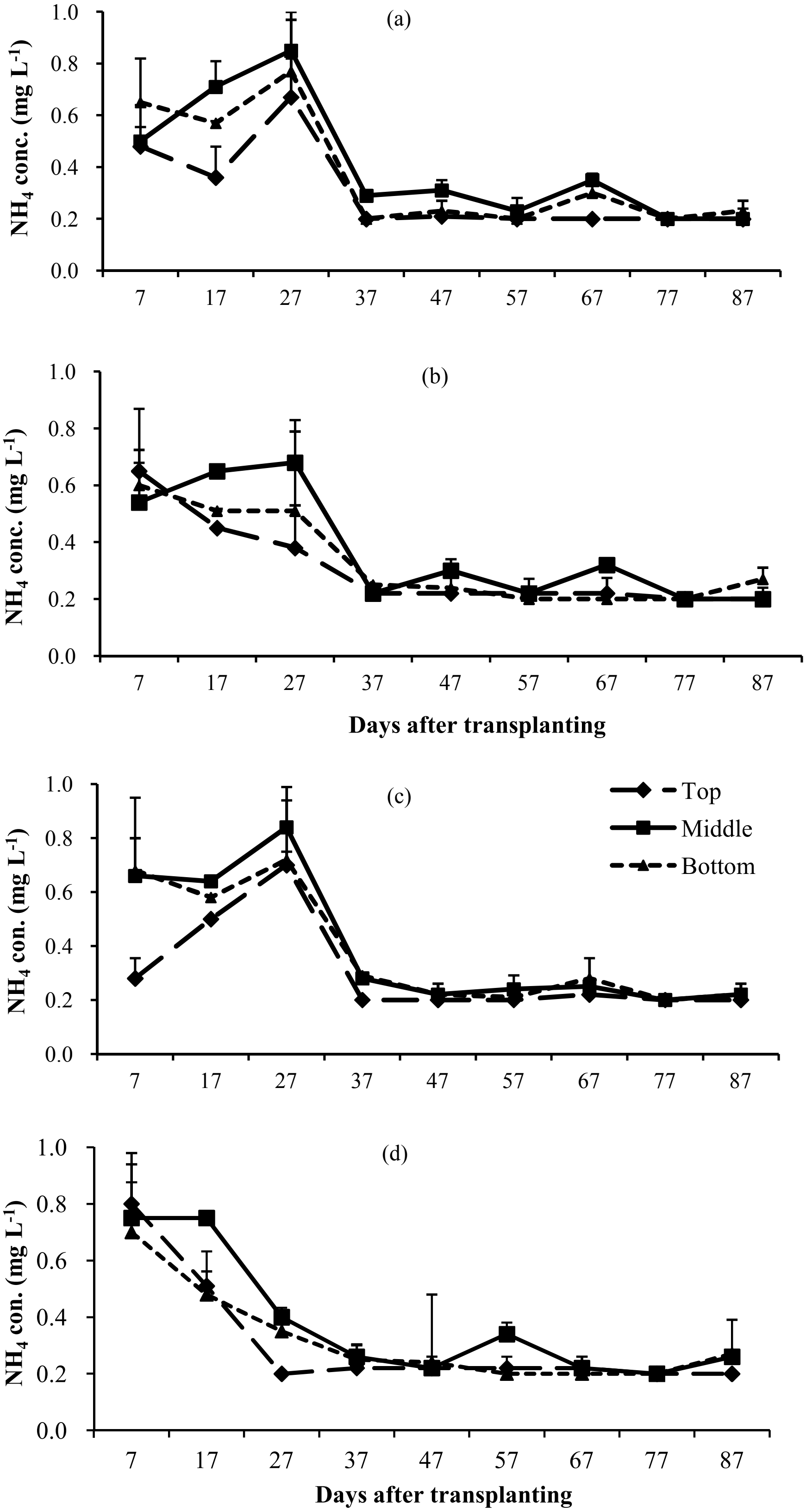
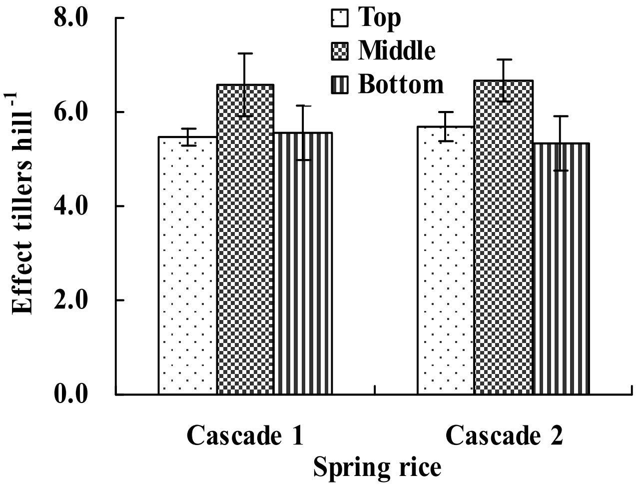


Fig 2.2 Seasonal variations in NH_4 concentration of surface water; (a & c -cascade 1) and (b & d – cascade 2) among the positions of toposequence rice field (bar –standard deviation)



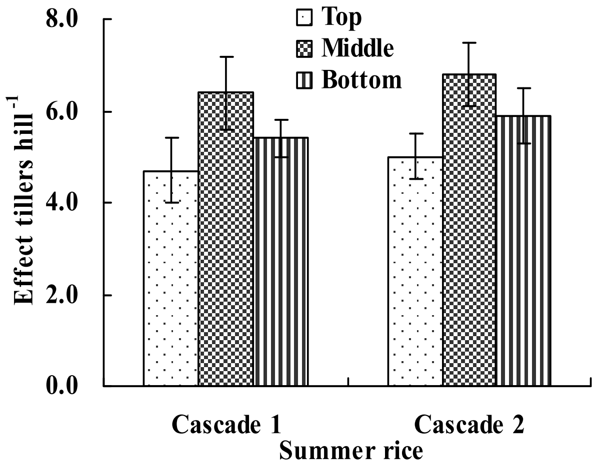


Fig 2.3 No. of effective tillers at different field position of cascade 1 and 2 in spring and summer rice seasons (Error bar indicates standard deviation)

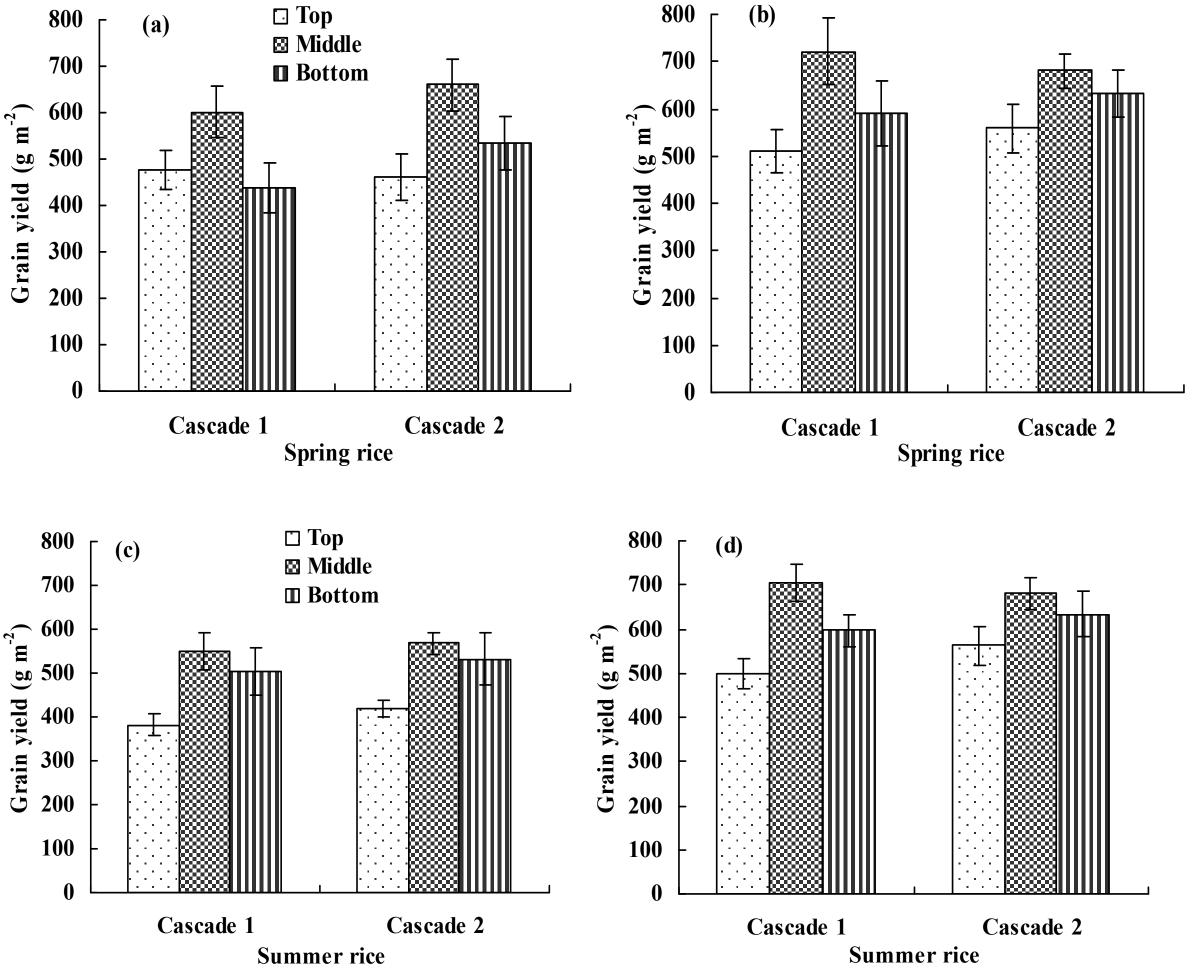


Fig 2.4 Grain yield in non-fertilized (a & c) and fertilized plots (b & d) at different toposequence positions of cascade 1 and 2 in spring and summer rice seasons (Error bar indicates standard deviation)

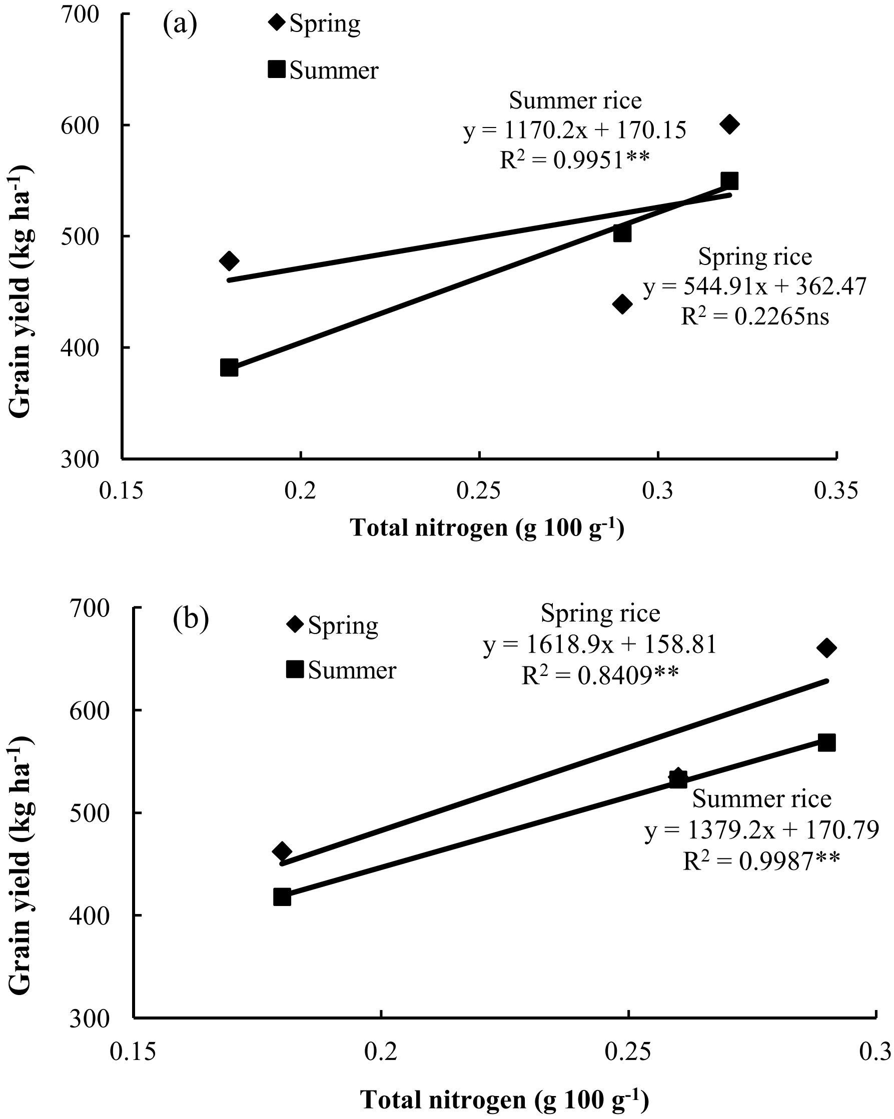


Fig 2.5 Relationship between grain yield and total nitrogen content of soil (a) Cascade 1 and (b) Cascade 2

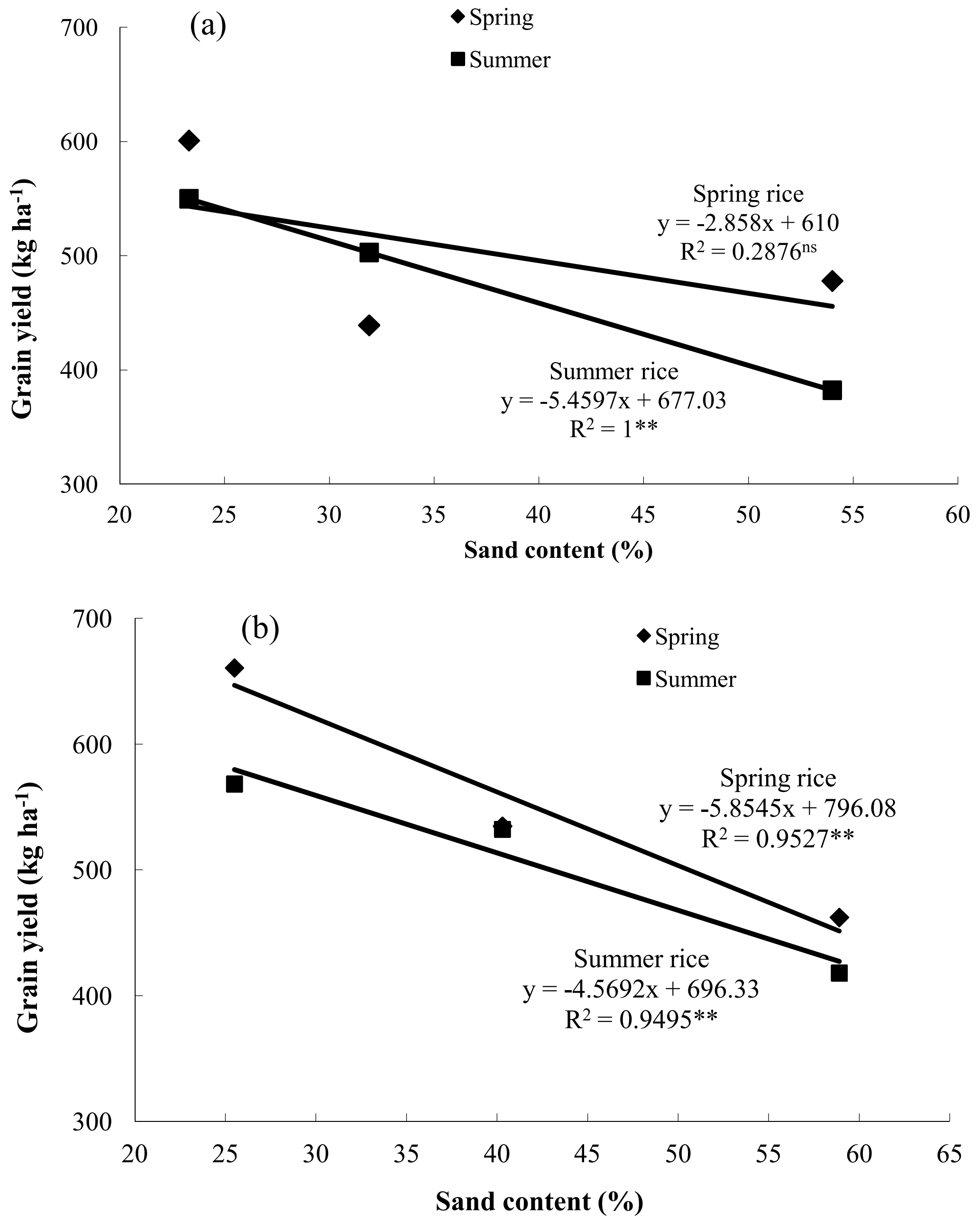


Fig 2.6 Relationship between grain yield and sand content (a) Cascade 1 and (b) Cascade 2

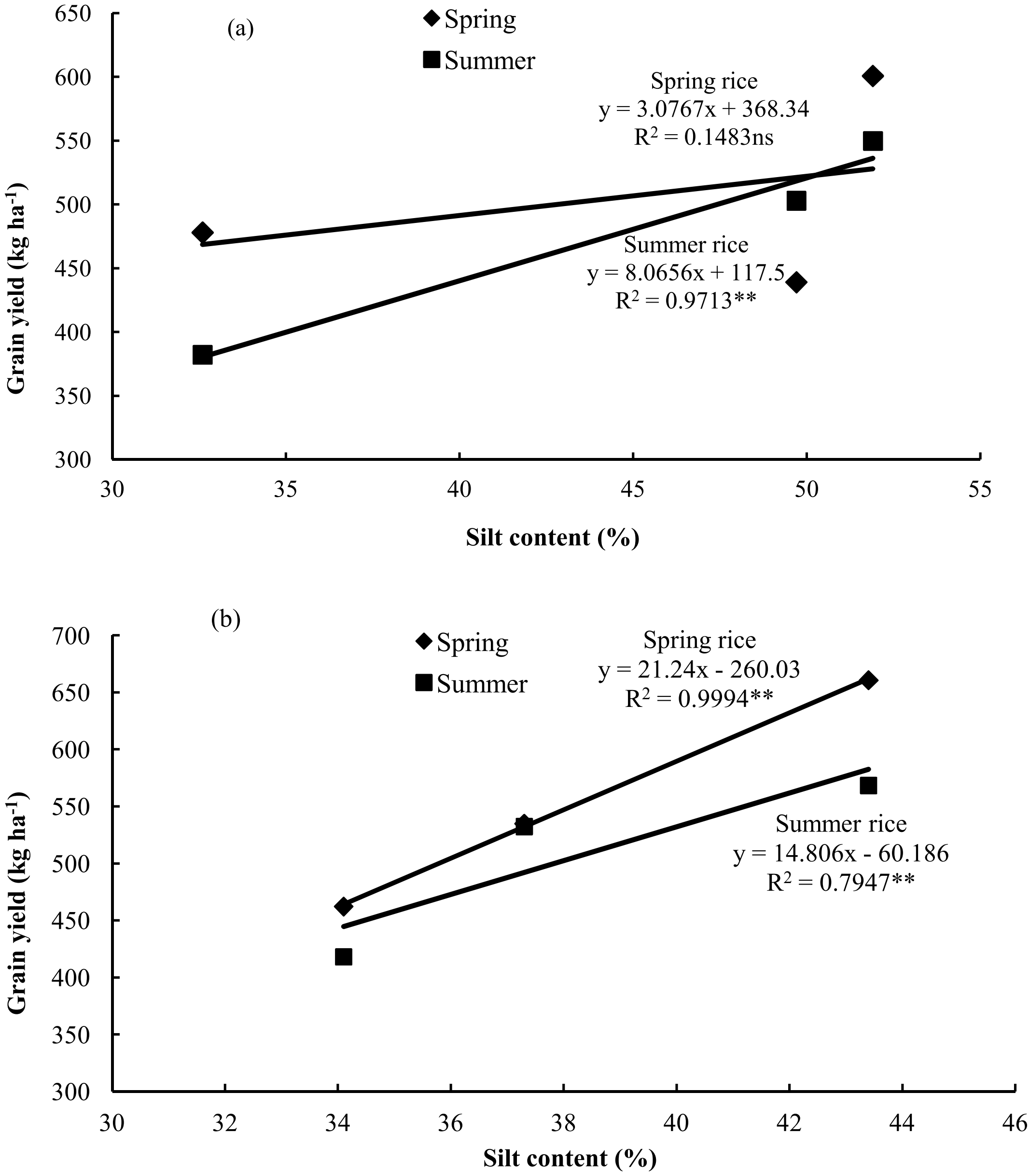


Fig 2.7 Relationship between grain yield and silt content (a) Cascade 1 and (b) Cascade 2

Chapter 3

Toposequential variation in methane emissions from double-cropping paddy rice in Northwest Vietnam

3 Toposequential variation in methane emissions from double-cropping paddy rice in Northwest Vietnam

3.1 Introduction

In Northern Vietnam, 0.7 million ha are under paddy rice cultivation, of these 60% are located in hilly areas on terrace forming interconnected cascades. Within cascades, the lower positioned fields are influenced by upper positioned field including sediment deposits from uplands (General Statistics Office of Vietnam, 2008). The downward movement and deposition of sediments derived from erosion of intensively cultivated upland fields play a key role for lowland rice production. Soil fertility parameters, such as SOC content, and related rice yield tend to increase with descending position of paddies in the landscape (Tsubo et al., 2006; Schmitter et al., 2010). The study by Schmitter et al. (2011) demonstrated that spatial variation of rice production within cascades could be linked to sediment induced soil fertility and textural changes in the topsoil. Furthermore, the yearly amount of organic C entering paddies with the irrigation water was estimated at 0.8 Mg ha^{-1} as well as 0.7 Mg N ha^{-1} (Schmitter et al., 2012) which might foster elevated greenhouse gas emissions.

Even though spatial differences in soil fertility and texture have been shown to occur within rice cascades, there is still limited information about the C and N cycle in the rice field cascade. For example, paddy rice fields account for up to 12% of total anthropogenic CH_4 emission (IPCC 2007). Field experiments have shown that there are large variabilities in CH_4 emissions from rice fields, both spatially, with variability between different fields, and temporally, with seasonal and diurnal variation (Holzapfel-Pschorn and Seiler, 1986; Schütz et al., 1989; Sass et al., 1991). However, to date more focus has been paid on the temporal variability, while there is very limited information about the spatial variation according to toposequential differences of paddy rice fields along cascades in mountainous watersheds. Most studies reported on large-scale spatial variation comparing sites which are far away from each other and with very different soil properties, climate and environmental conditions (Kimura et al. 1991; Yang and Chang 2001). On the other hand, Sass et al. (2002) reported within field spatial variation in CH_4 emissions from rice fields. In particular, recent land use intensification in upland areas, construction of reservoirs and increased irrigation and management of paddies have led to enhance sediment delivery and hence exacerbated spatial heterogeneity in rice cascades in mountainous areas (Schmitter et al., 2010). However, the variations in CH_4 emission among different field positions in the cascade have not been investigated thoroughly yet. More research is necessary to understand the temporal and spatial variation among the different field positions of paddy rice cascades to be able to estimate regional CH_4 budget and identify effective mitigation measures.

It is well known that CH_4 emission is a net product of production and oxidation, both are affected by N and other nutrients directly or indirectly (Schimel, 2000). For example, several field scale studies have demonstrated that addition of N fertilizers increased CH_4 emissions in the rice soils probably due to stimulation of methanogens by greater production of crop biomass by N fertilizers than control (Banik et al., 1996; Shang et al., 2011). In contrast, others have reported that inhibition of CH_4 emissions with addition of ammonia-based non-sulfate fertilizer (Dong et al., 2011) and ammonium sulfate fertilizers (Cai et al., 1997) to the rice soils. Till to date, no single consensus exists on net impact of N fertilizers on CH_4

emissions in the rice soils (Cai et al., 1997; Dong et al., 2011). In order to assess the net effect of ammonium based and sulfate containing fertilizers on CH_4 emission from paddy rice ecosystem, we used the recommended types of fertilizers by local extension services for rice production which commonly include urea and sulfur containing potassium sources. The study by Schmitter et al. (2011) showed that on average, the fertilized fields yielded continuously more than the fields without fertilizer in Chieng Khoi area. It is necessary to know the sediment induced toposequential variation in CH_4 emissions and the influence of mineral fertilizers on plant growth related CH_4 emission from the rice fields. Therefore, this experiment was conducted to evaluate (i) the spatio-temporal variation in CH_4 emission related to field positions among the paddy rice field cascades and (ii) the influence of mineral fertilizer on CH_4 emission among the field positions of paddy rice cascade from double-cropping paddy rice in Chieng Khoi Commune, Yen Chau district, Northwest Vietnam.

3.2 Materials and Methods

3.2.1 Study site and experimental design

The field experiments were carried out from February until November, 2011, during two rice cropping seasons in the Chieng Khoi commune (350 masl, 21º 7′60″N, 105º40′0″E), Yen Chau district, Northwest Vietnam. The studied area is located in the tropical monsoon belt with cool and dry winter and spring with 201 mm rainfall (monitored during November, 2010-April, 2011) and very hot and rainy summer and autumn with 858 mm rainfall (May-October, 2011) amounting to an annual precipitation of 1059 mm in 2011.

Two rice cascades (Cascade 1 and 2) were selected for this experiment (Fig. 3.1). The length and altitude differences were 83 m and 7 m for cascade 1 and 87 m and 5 m for cascade 2, respectively. Both cascades contained 5-6 successive paddy fields, covering a total of 0.8 ha. The uppermost field of the cascades received water directly from the irrigation channel. All other fields received water from a single inlet from the above lying field and drained via a single outlet to the lower situated field.

The experiment was laid out in a split plot design with three replications at each site. All fields in both cascades were divided into two parts resulting in two strips per cascade. Two sets of factors included in this experiment were as follows: different toposequence positions as the main plot and with (+F) and without (-F) fertilizer application as the subplot. The investigated cascades had 5-6 fields and among them the fields at the top, middle and bottom positions were chosen as shown in Figure 3.1. The applied chemical fertilizers were 213 kg N ha^{-1}, 150 kg P ha^{-1} and 93 kg K ha^{-1} per rice season with split applications according to the local recommendations by extension service. The first dressing, at transplanting, contained 56% N, 100% P and 34% K of the total amount of fertilizer applied in the form of NPK and urea. Second and third dressings contained 22% N and 33% K of the total amount of fertilizer in the form of urea and Kali (K_2SO_4– 40% K_2O) which were applied at active tillering and at heading stage.

Soil type was Gleysols (silty loam in the different horizons) (UNESCO, 1974). Soil particle analysis was done by pipette method (Gee and Bauder, 1986). Total N and TC contents were analyzed by using a 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). Electrical conductivity of the soil water was measured in the supernatant suspension of a 1:5 soil:water mixture using EC meter (OM-51, Horiba, Japan). Table 3.1 showed basic soil properties among the different toposequence positions of the experimental site before transplanting of spring rice, 2011. In both cascades, sand was the dominant texture in the top fields with lower TN and TC content. Middle and bottom fields showed higher silt content with higher TN and TC content when compared to top fields. There was no statistical difference in clay content in cascade 1 between top and bottom fields, but significantly higher clay content in middle and bottom fields of cascade 2 than in the top field. Soil pH ranged from 8.0 to 8.4 in both rice cascades. A higher electrical conductivity (EC) value was found in top field than in others in both rice cascades.

The sticky rice variety (O*ryza sativa* L. var. Nep 87) was used in both cropping seasons for both cascades. 18 days old seedlings were transplanted into the well-puddled fields. Rice seedlings were transplanted on February 28 and harvested on June 30, 2011 for the spring rice and the corresponding dates for the summer rice were July 28 and November 7, 2011, respectively. Before transplanting the spring rice, all crop residues left from the previous summer rice were incorporated into the soil. After harvesting the spring rice, all fresh crop residue leftovers were incorporated into the soil by plowing and harrowing. All management practices were following farmer practices in both cropping seasons. For spring rice, the field was flooded 15 days before puddling on February 7, 2011. The puddling was conducted with buffalo and basal fertilizers were mixed at that time. After transplanting, irrigation water was kept at 3-7 cm depth and the field was continuous flooded till 14 days before harvest on June 16, 2011. For summer rice, the field was flooded 21 days before puddling on July 7, 2011. The puddling was also conducted with buffalo and basal fertilizers were mixed at that time. After transplanting, irrigation water was kept at 3-7 cm depth and the field was continuous flooded till 14 days before harvest on October 25, 2011. Previous to this experiment, all fields were used similarly for continuous double-cropping paddy rice for several years.

3.2.2 Sample collection, soil parameters, and CH_4 analysis

Methane fluxes were measured in triplicate at 10 day intervals from 7 DAT until harvest throughout the spring and summer rice growing seasons, using the closed chamber method (Lu et al., 1999). 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 stop cock using an airtight syringe of 50 ml volume at 0, 15 and 30 minutes after closure. The air inside the chamber was thoroughly mixed by flushing the syringe three times before collection the gas samples. The sample gases were then transferred to 10 ml vacuum glass vials with rubber stoppers and kept cool and dark till analysis. The temperature inside the chamber was recorded at the time of sampling by using a micro-temperature thermometer (PC-9125, AS ONE Co., Tokyo, Japan). Methane concentrations in the collected gas samples were analyzed by 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 in CH_4 concentration vs time regression when their linear correlation coefficient was significant at 0.05 level.

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 electrode into the soil under investigation to a root zone depth of 5 cm throughout the growing season. Soil temperature at a depth of 10 cm was recorded at the time of gas sampling. Grain yield was determined from 1 m^2 sampling area at harvest and was expressed as rough (unhulled) rice at 14% moisture content. Above ground straw yield was determined after drying the plant materials at 80°C for two days.

3.2.3 Statistical analysis of data

The experimental data were analyzed by the ANOVA using CROPSTAT 7.0 statistical software program. The treatment mean comparison was tested at 5% level of probability using the LSD test by Fischer. Spearman correlation analysis was done by using Sigma plot 11.0 statistical software program.

3.3 Results

3.3.1 Time course of soil environmental factors and crop yields

The soil temperature was lowest during the early growing period (min. 16.6ºC) and increased gradually during the middle and late growing periods of spring rice (up to 28.9ºC; Fig. 3.2c and 3.3c). During spring rice period, there were significant differences in soil temperature among the field positions at all sampling times in cascade 1 and all times except 63 DAT in cascade 2. The bottom fields had higher soil temperature especially between 33 DAT and 103 DAT in both cascades. For summer rice, soil temperature was higher during early and middle growing periods decreasing by the end of the growing period in both cascades to about 23.8ºC (Fig. 3.2d and 3.3d). There were significant (P<0.05) differences among the field positions at all sampling times except 57 DAT in cascade 1 and 67 DAT in cascade 2. There was no significant difference in soil temperature between the cascades in both rice cropping seasons. Soil Eh values were mostly lower than -150 mV throughout the growing seasons except at harvest time of spring rice in cascade 1, summer rice in cascade 2 and later growing period in summer rice of cascade 1 (Fig. 3.2e, 3.2f and 3.3e, 3.3f). During both cropping seasons, bottom fields in both cascades showed mostly lower average soil Eh values than top field positions. Soil pH ranged between 7.4 and 8.4 in this study (Fig. 3.2g, 3.2h and 3.3g, 3.3h). There were no major significant differences among field positions in average soil pH throughout the growing seasons in both rice cascades.

The highest rice straw and grain yields were found in the middle field positions followed by the bottom one, while the lowest yields were found in the top fields in both cropping seasons (Table 3.2). Straw and grain yields were significantly higher in fertilized fields than in non-fertilized parts in both cropping seasons and cascades.

3.3.2 Seasonal variation in CH_4 flux

Seasonal changes of CH_4 fluxes throughout the growing seasons differed among the field positions (Fig. 3.2a, 3.2b and 3.3a, 3.3b). Seasonal variation of CH_4 fluxes generally showed one peak in each rice growing season. For spring rice, CH_4 fluxes increased during middle and late growing stages (53-93 DAT in cascade 1 and 53-103 DAT in cascade 2) decreasing thereafter to the end of the growing period (Fig 3.2a and 3.3a). The peaks of CH_4 flux in middle and bottom fields were higher than those of top field positions in both rice cascades especially during 53-93 DAT. In summer rice, considerable temporal variation was observed among field positions (Fig 3.2b and 3.3b). Here, the peak of CH_4 flux appeared after rice transplanting (7-27 DAT) and then gradually decreased to the end of the growing period for both cascades.

The bottom fields showed the highest CH_4 emission peaks while the lowest was observed at the top fields. The maximum emission rates of top, middle and bottom fields in average of two cascades were 5.4, 8.7 and 11.3 mg CH_4 m^{-2} h^{-1} in spring rice and 8.1, 12.1 and 21.4 mg CH_4 m^{-2} h^{-1} in summer rice, respectively.

In cascade 1, there was high temporal variation of CH_4 fluxes ranging from 0.22 to 6.11 mg CH_4 m^{-2} h^{-1} during the spring rice and from 0.13 to 20.1 mg CH_4 m^{-2} h^{-1} during the summer rice season. Higher averages of CH_4 fluxes were observed in cascade 2 ranging from 0.07 to 16.1 mg CH_4 m^{-2} h^{-1} during the spring rice and from 0.24 to 22.6 mg CH_4 m^{-2} h^{-1} during the summer rice season.

3.3.3 Cumulative CH_4 flux

The cumulative amounts of CH_4 emissions in the spring rice of top, middle and bottom fields were 3.1, 7.1 and 8.0 g CH_4 m^{-2} for cascade 1 and 4.8, 9.8 and 13.7 g CH_4 m^{-2} for cascade 2, respectively (Table 3.3). The cumulative CH_4 emissions of bottom fields were significantly ($P<0.01$) higher than those of the top fields in both cascades for spring rice. In the summer rice, the highest average CH_4 emission rate of the two rice cascades was observed for the bottom fields (8.5 mg CH_4 m^{-2} h^{-1}) and the lowest average rate was found in the top field (3.7 mg CH_4 m^{-2} h^{-1}). The cumulative CH_4 emissions among the different field positions on average of rice cascade 1 and 2 were 8.9, 11.6 and 19.7 g CH_4 m^{-2} for top, middle and bottom field, respectively. The cumulative CH_4 emission of bottom field from summer rice was significantly ($P<0.01$) higher than that of the top field positions.

Spring season accounted for 38.3% and the summer season for 61.7% of the total emission from double-cropping paddy rice on average. The highest total cumulative CH_4 emissions, on average of both cascades over both cropping seasons, were observed in bottom fields (30.8 g CH_4 m^{-2}) while the top fields had the lowest total CH_4 emissions (12.6 g CH_4 m^{-2}).

3.3.4 Influence of fertilization on CH_4 fluxes

Seasonal variation of CH_4 fluxes from fertilized (Urea, NPK and K_2SO_4) and non-fertilized fields showed similar trends and patterns throughout the growing seasons (data not shown). Average CH_4 fluxes over both cascades for non-fertilized and fertilized plots were 3.6 and 1.8 mg CH_4 m^{-2} h^{-1} in spring rice and 6.7 and 4.1 mg CH_4 m^{-2} h^{-1} in summer rice, respectively (Table 3.3). As a result, the average cumulative CH_4 emissions of both cascades were higher for the non-fertilized plots with 11.5 and 15.7 g CH_4 m^{-2} if compared to the fertilized plots with 5.6 and 9.6 g CH_4 m^{-2} in spring and summer growing seasons, respectively. The cumulative CH_4 flux from fertilized plots was significantly lower ($p<0.05$) than that from non-fertilized plots in both cascades for summer rice and in cascade 2 for spring rice.

3.3.5 Influence of soil environmental factors on CH_4 flux

Soil temperature was significantly positively correlated with CH_4 emission for both rice crop seasons (Table 3.4). Significantly negative correlations between CH_4 emission and soil Eh were observed in this experiment except for summer rice in cascade 1. Soil pH showed positive correlations with CH_4 emission in both rice cascades during the spring and summer rice seasons. The average rate of CH_4 emission was positively correlated only with straw yield of cascade 2 and with grain yield of cascade 1 of summer rice.

3.4 Discussion

3.4.1 Seasonal variation in CH_4 emissions

Contrasting seasonal patterns of CH_4 emission were observed during spring and summer rice growing seasons (Fig. 3.2a, 3.2b and 3.3a, 3.3b). The lower CH_4 emissions during the early growing period of spring rice were probably mainly due to low soil temperatures for methanogenic activities to produce CH_4 during this period as also suggested by the strong correlation between CH_4 emission rate and temperature (Table 3.4). Additionally, there might have been a lower availability of easily degradable organic matter as source for methanogens as leftover crop residues from the previous summer crop of 2010 were already dried and some were partly decomposed or eaten by grazing buffalos and goats during winter fallow period (November 2010 to January 2011). Other studies also reported that the CH_4 peak appeared only in late growth stages of rice and considered it as a consequence of lower degradable soil organic matter content and lack of methanogens (Das and Baruah, 2008; Ahmad et al., 2009). However, Li et al. (2011) observed that CH_4 flux rate peaked about 1-2 weeks after transplanting of spring rice in double-cropping paddy rice systems in southeast China. This was caused by the fermentation of easily degradable soil organic matter and the flood condition for methanogenesis in the soil after transplanting while other influencing factors are consistent throughout the growing seasons (Li et al. 2011).

In our experiment the CH_4 flux peak occurred in the middle and later growing periods of spring rice in all toposequence positions in both cascades (Fig. 3.2a and 3.3a). This can be attributed to i) higher soil temperature and hence higher soil organic matter turnover due to increased microbial activities, ii) decomposition of recent decaying plant residues from shedded leaves and root turnover, and iii) the higher availability of root exudates in the rhizosphere. Similarly, Gogoi et al. (2008) reported that the CH_4 emission peak at 91 DAT (reproductive stage) was due to the additional organic matter from root exudates and root litter, which increased the carbon pool of the soil.

In contrast to the spring crop, the CH_4 flux peaked soon after transplanting in summer rice in both rice cascades (Fig. 3.1b and 3.2b), consistent with the previous studies by Li et al. (2011) and Yang et al. (2010) under double-cropping paddy rice systems in China. Higher temperature and increased availability of substrates favored methanogenic activities to decompose organic matter during the early summer cropping period. High temperatures could enhance the decomposition rate of organic matter (Khalil et al., 2008), CH_4 transportation (Xu et al., 2002) and reduce the amount of CH_4 dissolved in the soil solution (Minami and Neue, 1994).

Seasonal average rate of CH_4 flux during the summer rice season almost doubled than during the spring rice season (Table 3.3). Other reports (Huang et al., 2005; Khalil et al., 2008) showed similar emission pattern that CH_4 emissions increased during late rice season than early rice in double-cropping paddy rice system. There might be two possibilities for this result; first, incorporation of fresh crop residues from spring rice into the soil just after harvesting of spring rice, providing a large addition of organic materials under hot weather condition and second, the higher air and soil temperature during the summer season were favorable for quick decomposition inducing increasing methanogenic activity.

The cumulative CH_4 emission from paddy fields of the summer rice was much higher than that of the spring rice which was the same trend as reported by Yang et al. (2010). Other studies also reported that CH_4 flux from late rice fields was higher than that from early rice fields (Wassmann et al., 1993b, 1996; Lin et al., 2000; Cai et al, 2000). Cai et al. (2000) also showed that CH_4 flux from a late rice field, preceded by early rice, was significantly higher than that preceded by an upland crop. They discussed that the water status prior to the rice growing season is very important for CH_4 emission during the rice growing season. The soil that was flooded prior to late rice growing period was already reduced when rice was transplanted and thus Eh was low and favored for methanogenic activities (Trolldenier, 1995) which lead to high CH_4 emission. The range of cumulative seasonal CH_4 emission in this study (7.4 g m^{-2} to 37.2 g m^{-2}) were comparably lower than the reported cumulative CH_4 emissions from double-cropping paddy rice ranging from 65.9 g m^{-2} (from no-fertilizer as a control) to 121 g m^{-2} (from combined mineral and organic fertilizers such as Chinese milk vetch and rice straw at full rate) (Yang et al. 2010). The rather high emission reported by Yang et al. (2010) was derived due to poor field drainage conditions and extended flooded periods, while in our study the fields were located in different toposequence positions with good field drainage conditions and sometimes water shortage due to lower rainfall and wide range of soil properties among the field positions.

3.4.2 Influence of toposequence positions and soil environmental factors on CH_4 emission

Methane emissions were strongly influenced by field position within the cascade in this experiment (Fig 3.2a, 3.2b and 3.3a, 3.3b). The rate of CH_4 emission might be related to transportation and deposition of organic rich sediment materials among the toposequence positions. Schmitter et al. (2010) reported that the increase of SOC was related to an increase of clay and silt fractions which points to transportation of organic rich sediment material by the irrigation channel. The observed high rates of CH_4 emission from middle and particularly bottom fields (Table 3.3) were associated with their higher TN, TC and clay content compared to the top fields. The results of the Spearman correlation analysis confirmed that TN and TC were positively correlated with CH_4 emission in both cropping seasons (Table 3.2). This result is in agreement with Mitra et al. (2002), who reported that higher TN and TC stimulated CH_4 production. Yagi et al. (1990), on the contrary, found no correlation between CH_4 production rates and total C contents in soils. Another reason for the difference in CH_4 emission among cascade positions might be the higher clay content of lower lying fields. A more rapid decrease in Eh after flooding and permanency thereafter due to high C content in clay of lower lying soils appears to explain the greater CH_4 production potential (Fig. 3.2 and 3.3). Xiong et al. (2007) reported that clay soil produced much more CH_4 than loess soil during the flooding period. In this experiment, clay soil with high C content and N content attained negative Eh values within 2 weeks after submergence becoming more negative thereafter. Fields with less clay and C content took longer to attain similar Eh values. Another explanation by Xiong et al. (2007) that the extremely low CH_4 emission rate in Loess soils was the anaerobic oxidation of CH_4 coupled to denitrification.

The observed high CH_4 emission from bottom field was consistent with the previous study by Cai et al. (2000). They observed that CH_4 emissions from rice fields located on downslope was larger than from those on midslope and upslope in hilly areas, because depressive topography leads to invasion by side leaching water, and the rice field at the downslope was waterlogged and poor drainage condition, leading to more reduced condition than the upslope fields. In our study, the bottom fields of both cascades showed relatively low Eh than top field positions due to poor drained and water saturated or even flooded most of the time due to invasion by side leaching water and this was the reason that high CH_4 emission was observed in the bottom fields.

The rate and cumulative CH_4 emissions from cascade 2 were higher than that of cascade 1. Under similar trends of TC content between the cascades, the differences in CH_4 emission might be due to lower soil Eh and higher clay content of cascade 2 especially in the lower lying fields.

In this study, seasonal variation pattern of CH_4 emission was influenced by soil environmental factors such as soil pH, Eh and soil temperature (Fig. 3.1b-d and 3.2b-d). Positive correlations were observed between soil temperature, soil pH and CH_4 emission rate in both rice crop seasons (Table 3.4). This result supported the findings by Yang et al. (2010) that soil temperature and pH had a positive correlation with CH_4 emission. The higher soil temperature of lower lying fields favored higher CH_4 emission compared to top fields. The soil redox potential declined after flooding and fluctuated between -100 and -400 mV except final growing periods of spring and summer rice (Fig. 3.2e, 3.2f and 3.3e, 3.3f). Methane emission increased with the decrease of Eh from -194 to -381. The critical values of soil redox potential for initiation of CH_4 production in paddy soil is reported to be from -100 to -200 mV (Yagi and Minami, 1990). Therefore, the Eh range in this study was considerable more negative than the critical value and the soil conditions were favorable for CH_4 production. Negative correlations between CH_4 emissions and soil Eh in this study corresponded to the result of Xu and Hosen (2010) and Yang et al. (2010). Although the Eh conditions in relation to field positions were favorable for CH_4 production, there were variations in CH_4 emissions among the field positions.

3.4.3 Influence of management practices on CH_4 emission

Nitrogen fertilizers are commonly used in rice cultivation to increase crop yields. Numerous previous studies have demonstrated that the application of N may directly or indirectly influence CH_4 production, oxidation, and transport from the soil to the atmosphere (Cai et al. 2007; Dong et al. 2011; Banger et al. 2012). The negative effect of ammonium-based fertilizer is mainly attributed to the stimulation on CH_4 oxidation via enhancing the growth/activity of methanotrophs (Schimel, 2000; Bodelier et al. 2000a; Bodelier et al. 2000b), while the positive effect of N mainly results from the stimulation of CH_4 production and vascular transport capacity via enhancing methanogenic growth/activity and rice growth (Schimel, 2000; Xu et al. 2004). In this study, the results showed that application of ammonium-based N fertilizer (Urea) and K_2SO_4 as a potassium source inhibited the rate of CH_4 emission from rice fields when compared with non-fertilized treatment (Table 3.3). A similar result was reported by Xie et al. (2010) i.e. that the application of urea and compound fertilizer as N source inhibited CH_4 emission from rice fields by about 30%. Many studies reported that the use of sulfate containing fertilizers reduced CH_4 emission from rice fields (Schütz et al. 1989; Minami, 1994; Gon et al., 2001). Sulfate-containing fertilizers are known to decrease CH_4 emission as a result of competition between sulfate-reducing bacteria and methanogens for hydrogen and acetate substrates (Schütz et al., 1989; Hori et al., 1990; Hori et al., 1993). Hence, in our case, a reasonable explanation for observed results might be that the application of ammonium-based (urea in this study) and sulfate containing fertilizers resulted in a larger stimulation of CH_4 oxidation than CH_4 production (Bodelier et al. 2000a; Bodelier et al. 2000b; Gon et al. 2001). The product of sulfate reduction, hydrogen sulfide may poison methanogenic bacteria (Minami, 1994) and sulfate ions serve as an alternative to CO_2 as electron acceptors for the oxidation of organic matter and thereby reducing CH_4 production (Banger et al. 2012). In this experiment, reduction of CH_4 emission in all field positions were observed by mineral fertilization but the fertilizer management did not mitigate spatial variation pattern of CH_4 emissions among the field positions.

3.5 Conclusion

High spatio-temporal variation in CH_4 emissions among cascade positions were found in both rice cascades. Bottom fields showed the highest rate and cumulative CH_4 emissions in both rice cascades. The spatial variability in CH_4 emissions among the toposequence positions in this experiment were related to the different sediment deposition patterns across the cascade, which influenced physical and chemical properties of soil along the toposequence rice fields. The CH_4 flux of summer rice was higher than spring rice in all toposequence positions suggesting that fresh crop residue should not be incorporated into the soil during land preparation before transplanting of summer rice. Across various cascade positions, the application of mineral fertilizers mitigated CH_4 emission from paddy rice as compared to non-fertilized parts in this study. Recommended type of fertilizer management practice such as ammonium based fertilizers is an effective way to reduce CH_4 emission from toposequence rice fields but different management practices should be done for different toposequence positions to mitigate CH_4 emission in this watershed area.

Table 3.1 Physico-chemical properties of the experimental soils at different field positions of cascade 1 and 2 before transplanting of spring rice, 2011 (mean ± S.D.)

	Field position	Sand (%)	Silt (%)	Clay (%)	TN (g kg^{-1})	TC (g kg^{-1})	pH	EC (msm^{-1})
Cascade 1	Top	54.0±1.7	31.6±1.6	14.4±0.1	0.17±0.08	3.2±0.4	8.1±0.02	24.2±3.5
	Middle	23.3±1.1	51.9±2.3	24.8±1.1	0.32±0.12	4.4±0.1	8.0±0.06	25.3±4.9
	Bottom	31.9±2.8	49.7±0.5	18.5±2.3	0.29±0.06	4.8±1.2	8.3±0.09	21.7±6.6
	$LSD_{(0.05)}$	8.5	8.4	4.6	0.05	1.0	0.1	3.5
Cascade 2	Top	58.9±2.4	34.1±0.2	7.0±2.2	0.18±0.01	2.5±0.1	8.0±0.03	25.3±3.9
	Middle	25.5±1.6	43.4±0.6	31.2±0.9	0.29±0.04	5.6±1.4	8.2±0.11	23.4±2.4
	Bottom	40.3±3.4	37.3±1.7	22.4±1.6	0.26±0.07	5.3±0.6	8.4±0.15	17.6±4.0
	$LSD_{(0.05)}$	12.5	4.1	8.6	0.04	0.8	0.1	3.7

Table 3.2 Straw and grain yield at different field positions of cascade 1 and 2 in spring and summer rice (mean ± S.D.)

			Spring crop		Summer crop	
			Straw ($g\ m^{-2}$)	Grain ($g\ m^{-2}$)	Straw ($g\ m^{-2}$)	Grain ($g\ m^{-2}$)
Cascade 1	Treatment	-F	445.1±99.2	506.0±90.4	476.4±100.6	485.1±81.9
		+F	633.0±100.6	639.5±99.3	625.4±178.9	607.1±112.9
		$Lsd_{(0.05)}$	59.8	90.3	97.2	60.6
	Position	Top	490.1±36.9	478.0±72.9	385.5±35.4	382.2±24.4
		Middle	666.4±46.1	600.8±56.1	589.2±22.9	549.8±29.2
		Bottom	558.9±29.5	439.1±53.3	554.6±38.3	502.9±41.3
		$Lsd_{(0.05)}$	90.4	58.2	129.8	59.8
Cascade 2	Treatment	-F	546.7±58.1	560.6±105.8	511.9±184.4	506.4±70.3
		+F	588.6±112.9	649.1±85.5	661.2±159.9	592.4±101.2
		$Lsd_{(0.05)}$	49.8	84.3	77.4	23.1
	Position	Top	512.8±58.3	558.3±49.6	434.8±19.3	418.2±19.9
		Middle	636.9±70.8	688.8±55.6	631.0±37.3	568.5±17.9
		Bottom	590.4±19.5	585.0±58.1	670.1±41.2	532.5±24.4
		$Lsd_{(0.05)}$	128.2	76.8	116.4	56.2

-F and +F stand for non-fertilized and fertilized part, respectively

Table 3.3 Average rate and cumulative CH_4 fluxes at different field positions of cascade 1 and 2 in spring and summer rice (mean ± S.D.)

			Spring crop		Summer crop		Total emission per year ($g\ m^{-2}$)
			Rate ($mgm^{-2}\ h^{-1}$)	Cumulative ($g\ m^{-2}$)	Rate ($mgm^{-2}\ h^{-1}$)	Cumulative ($g\ m^{-2}$)	
Cascade 1	**Treatment**	-F	1.9±0.9	6.2±2.1	4.0±2.9	9.4±6.1	15.6
		+F	1.8±1.0	5.9±3.1	2.3±2.3	5.5±3.3	11.4
		$Lsd_{(0.05)}$	0.5	1.6	1.2	2.7	3.6
	Position	Top	1.0±0.4	3.1±1.3	1.8±2.5	4.3±0.8	7.4
		Middle	2.2±0.5	7.1±1.7	2.6±0.9	6.0±3.0	13.1
		Bottom	2.5±0.5	8.0±1.4	6.8±0.3	15.8±5.9	23.8
		Average	1.9	6.1	3.7	8.7	14.8
		$Lsd_{(0.05)}$	0.6	1.9	2.1	5.8	4.4
Cascade 2	**Treatment**	-F	5.3±3.0	16.8±6.6	9.5±1.4	22.0±3.2	38.8
		+F	1.7±1.2	5.4±3.1	5.9±3.2	13.7±7.4	19.1
		$Lsd_{(0.05)}$	1.1	3.5	1.7	3.8	5.5
	Position	Top	1.7±1.2	4.8±1.8	5.6±2.3	13.0±1.3	17.8
		Middle	3.6±0.8	9.8±2.8	7.4±2.7	17.2±1.9	27.0
		Bottom	5.1±1.4	13.7±4.3	10.1±1.8	23.5±1.3	37.2
		Average	3.5	9.4	7.7	17.9	27.3
		$Lsd_{(0.05)}$	2.1	5.6	3.3	7.8	6.8

-F and +F stand for non-fertilized and fertilized part, respectively

Table 3.4 Spearman rank order correlation between CH_4 emission rate and soil Eh, soil pH, soil temperature, total N, total C, straw, and grain yield in spring and summer rice

		Soil Eh	Soil pH	Soil T	TN	TC	Straw yield	Grain yield
Cascade 1	Spring	-0.60**	0.30 ns	0.76**	0.58**	0.66**	0.20 ns	0.32 ns
	Summer	-0.35ns	0.72**	0.86**	0.47*	0.59**	0.61 ns	0.75*
Cascade 2	Spring	-0.72*	0.55*	0.66**	0.18 ns	0.48*	0.45 ns	0.25 ns
	Summer	-0.89**	0.61**	0.73**	0.43 ns	0.53*	0.73*	0.37 ns

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

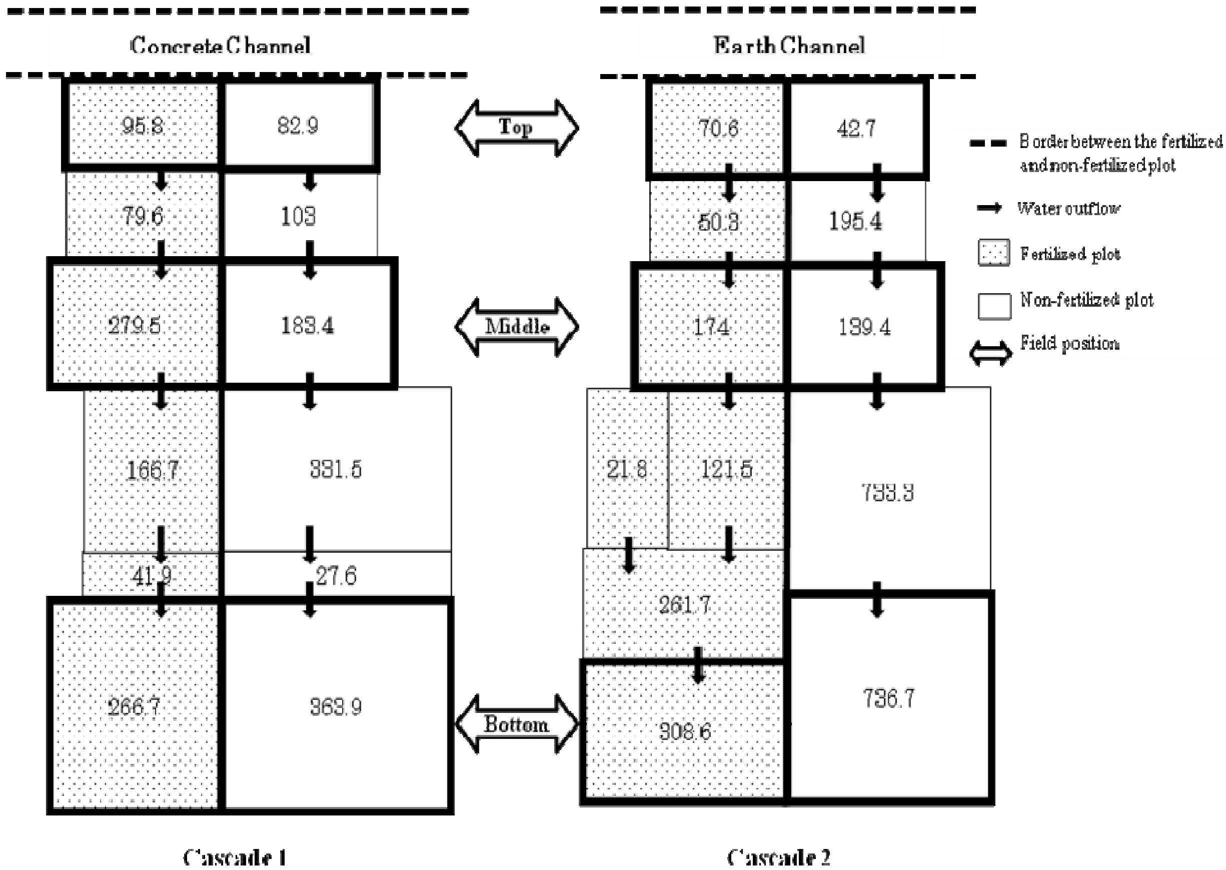


Fig 3.1 Schematic representation of two complete rice cascades (Cascade 1 and 2) for spring and summer rice (Area – m^2)

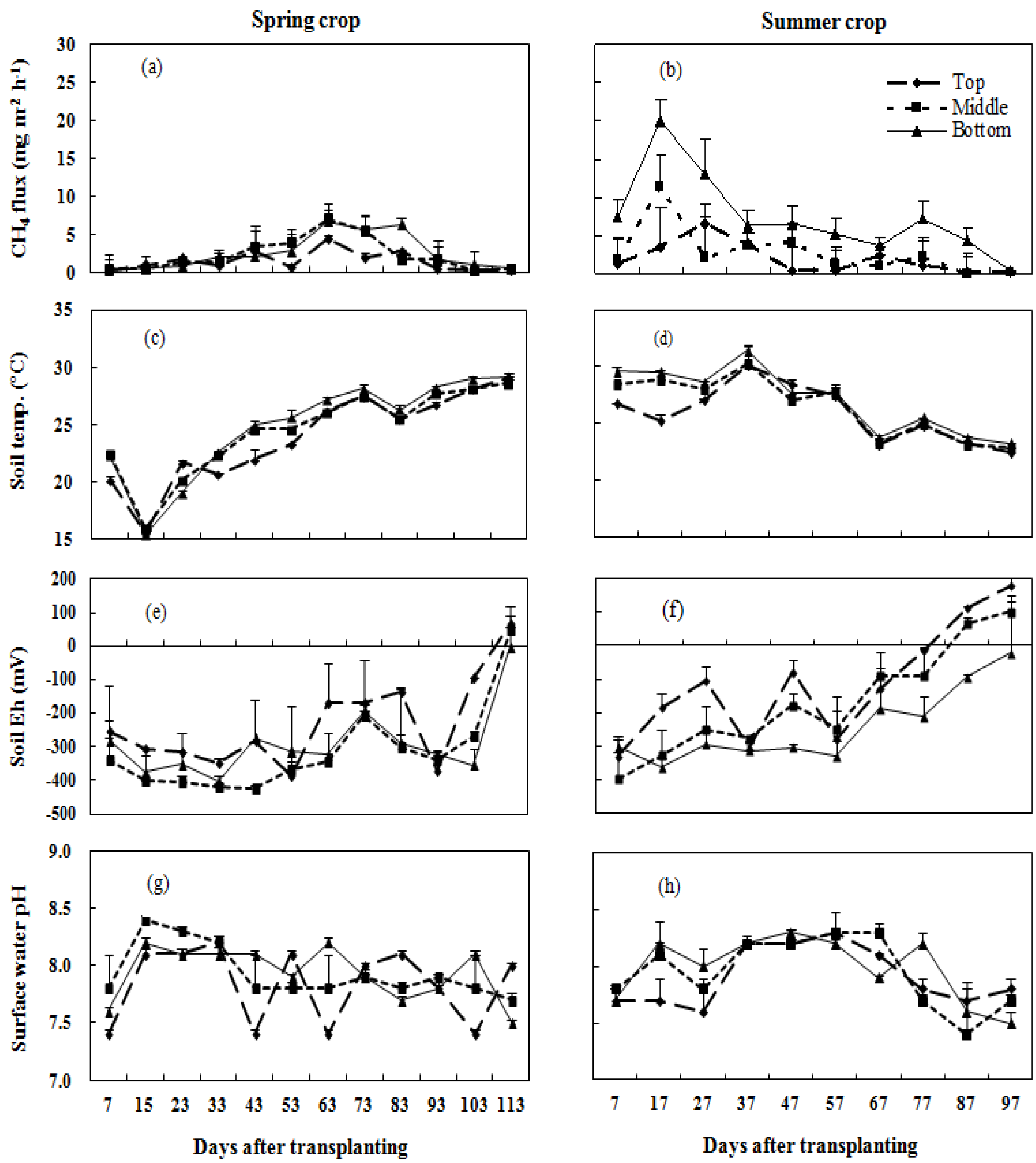


Fig 3.2 Seasonal changes in (a) and (b) CH_4 flux, (c) and (d) soil temperature, (e) and (f) redox potential (mV), and (g) and (h) surface water pH among the field positions in cascade 1 during the spring and summer growing periods in 2011. Error bars indicate standard deviation

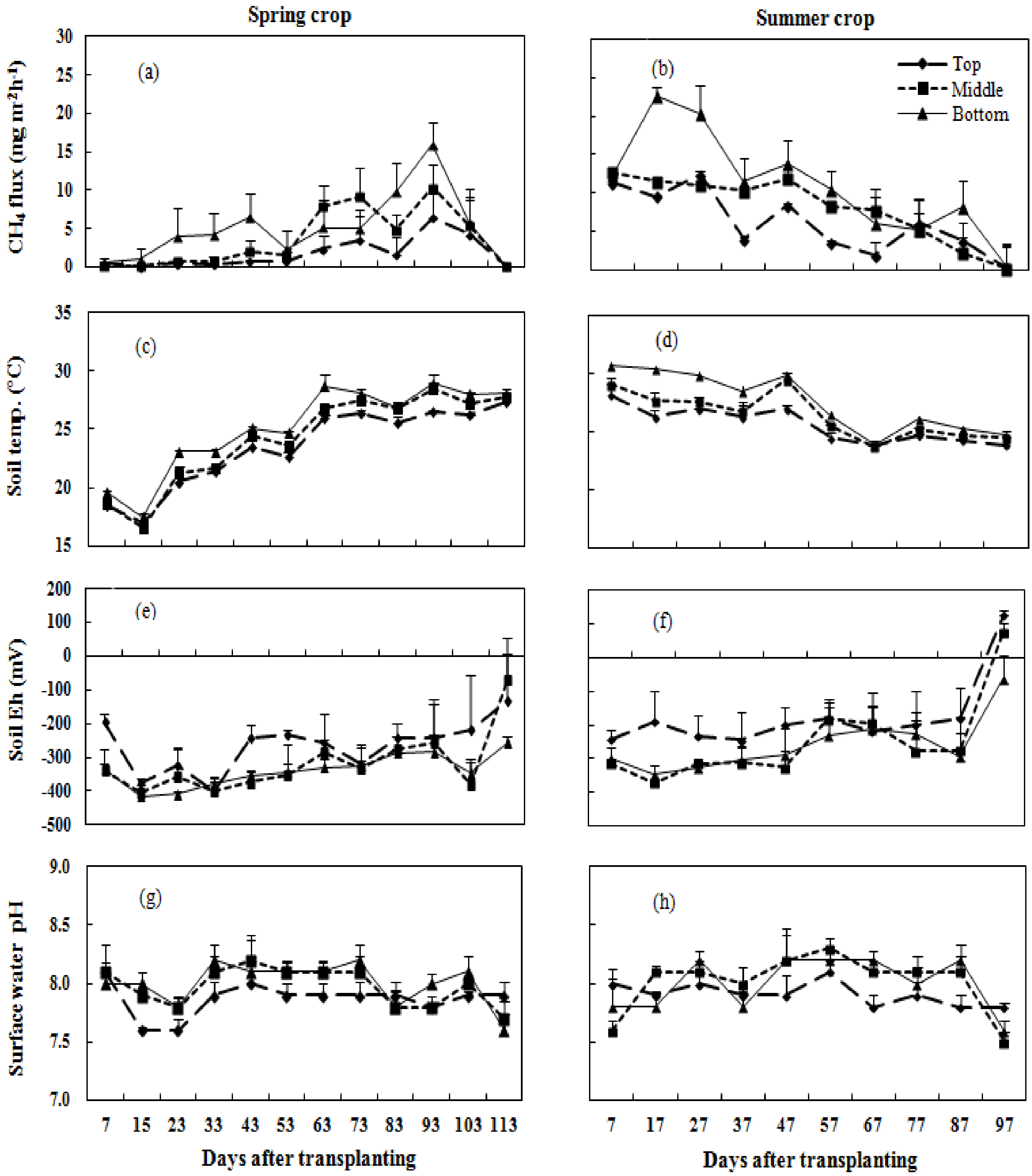


Fig 3.3 Seasonal changes in (a) and (b) CH_4 flux, (c) and (d) soil temperature, (e) and (f) redox potential (mV), and (g) and (h) surface water pH among the field positions in cascade 2 during the spring and summer growing periods in 2011. Error bars indicate standard deviation

Chapter 4

Within field spatial variations in soil properties, crop growth and yield of lowland rice in Myanmar

4 Within field spatial variations in soil properties, crop growth and yield of lowland rice in Myanmar

4.1 Introduction

Rice (*Oryza sativa* L.) has been the major crop in term of agricultural production and food consumption in Myanmar. Total area under paddy rice cultivation is 8.06 million ha; of these 68 percent are lowland rice cultivation areas (FAO, 2010). Rice fields are located on the gently sloping land with differences in elevation for a few centimeters in an undulating topography. The differences in position may lead to differentiation in soil properties and soil fertility status (Hseu and Chen, 2001; Tsubo et al., 2006) and therefore crop yield. Irrigated lowland rice is one of the major rice ecosystems in these regions especially in semi-rainfed lowland area. In irrigated rice fields, irrigation water has been identified as a considerable source of additional particulate N and organic C to be transported into irrigated fields depending on its origin (King et al., 2009). Redistribution of sediment rich organic materials by irrigation and runoff water throughout the rice fields will significantly influence the pattern of spatial variation in soil properties and crop yield within and between the fields.

In general, large within-field variations in soil fertility and rice growth are not desirable for rice production. Accessing within field variation is necessary for identifying and quantifying the limiting factors for rice growth, and addressing the spatial variability of rice yield. Studies have been recently conducted on the variability of soil properties and yield in rice production systems, which may potentially lead to site-specific management of paddy fields (Moritsuka et al. 2004 and Shoji et al. 2005).

Factors contributing to spatial variability depend strongly on the spatial scale. Puddling is one of the main factors at field level affecting the dynamic soil-water system by altering the plough pan and therefore hydraulic conductivity and anaerobic conditions (Lennartz et al., 2009). The redistribution of nutrients through sedimentation process will play significant role in within field spatial variability in soil properties and crop growth. Beside internal runoff and soil deposition processes in rice paddies, it is important to understand the impact of external sediment contributions as an additional source of nutrient deposits regarding specific fertilizer recommendations for improving resource use and crop management (Schmitter et al. 2010). Sediments could increase N use efficiency of applied fertilizer by increasing cation exchange capacity, clay content and soil organic matter (Mingzhou et al., 2007).

The within-field variability is caused by many parameters such as soil, nutrition, water availability, slope, local microclimate, and farmer's management (amount and type of fertilizer input, choice of cultivars, etc.). Plowing also affects the flatness of a field which is one of the most manageable factors in both modern and traditional rice farming at a given scale in the field. Differences in elevation affect not only depth of water when the field is fully irrigated, but also the availability of water or the aeration of the soil when the field is drained. Husson et al. (2000a, b) have demonstrated that micro-elevation ranges of 300 mm caused changes in chemical soil properties and therefore affected plant growth and grain yield in sulphate soil environments of Vietnam. Despite there were many investigations on variability within the field, spatial variations in soil properties and crop yield among the positions within the field based on water flow were not investigated thoroughly.

Measuring within-field growth variability is very important for precision farming. Farmers and scientists generally recognize that soil properties and crop growth are not uniform within a field (Yamagishi et al., 2003). Spatial variability of rice yield in a paddy field results from inhomogeneity of management practice and soil properties and their complex interaction (Casanova et al., 2002). To obtain the basic information for site-specific soil management to improve nutrient use efficiency of plants, spatial variability of grain yield response to soil properties should be evaluated. Although understanding the importance of the spatial and temporal variation within a field for site specific management to improve crop yield, there is very limited information about spatial variability within paddy rice field in lowland rice area of Myanmar.

The purpose of this study was to understand the impact of different positions within the field based on water flow pattern related to lowland rice cultivation on the alteration of soil characteristics and plant growth within rice field. Therefore, this experiment was conducted with the objectives of to assess 1) the spatial variations in soil properties and crop yield among the positions within the field; 2) the effect of distance of the field from the irrigation channel on soil fertility and crop growth and 3) the effect of farmer practice of fertilization on growth and yield of lowland rice and in Myanmar.

4.2 Materials and methods

4.2.1 Study site

The field experiment was carried out from June to November, 2012 during monsoon rice growing season in Dawmakwin Village, Kanyutkwin District, Pago Division, Myanmar (18°48′43″ N, 96°43′57″ E). The field had been under a monsoon rice (Oryza sativa L.) and blackgram (Vigna mungo) rotation for 25 year. The soil was classified as Fluvisol (alluvial soil) (UNESCO, 1974) which contain large amount of silt. The weather in study area was tropical monsoon climate with annual rainfall of 2545.4 mm and minimum and maximum temperature of 19.6°C and 32.2°C, respectively in year 2012.

4.2.2 Experimental design and sample collections

Two successive rice fields (referred to as 1st field and 2nd field hereafter) with total length of 120 m, covering a total of 0.5 ha were selected for this experiment. The 1st field received water directly from the channel with single inlet and drained water via single outlet. The 2nd field received water from a single inlet from the above lying field and drained via a single outlet to the lower situated field. According to this water flow pattern, the field was divided into three positions; inlet, middle and outlet within the field.

The experiment was laid out in a split plot design with three replications at each field. All fields were divided into two parts resulting in 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 subplot. The positions were the inlet, middle and outlet for the two fields referred to as 1^{st} inlet, 1^{st} middle, 1^{st} outlet for the 1^{st} field, and 2^{nd} inlet, 2^{nd} middle and 2^{nd} outlet for the 2^{nd} field. The applied chemical fertilizer was 250 kg ha^{-1} in the form of NPK (15-5-5) compound fertilizer with two split applications according to the local recommendations by extension service. The first dressing was conducted at transplanting with 50% of the total amount of fertilizer. Second dressings contained the remaining 50 % of the total amount of fertilizer which were applied at heading stage.

Indica rice variety (O*ryza sativa* L. var. Sinthukha) was used in this experiment. 30 days old seedlings were manually transplanted into the well-puddled fields. Rice seedlings were transplanted on June 29 and harvested on October 11, 2012. All farming practices were done following the local farmer`s regimes. The fields were flooded 21 days before puddling on June 7, 2011. After transplanting, the fields were continuous flooded till 14 days before harvest since mid-season drainage was not successful due to continuous rainfall in that period. After harvesting the rice, short duration crop such as black gram (*Vigna mungo*) was planted with residual moisture as double cropping every year.

Top soil samples at 0-10 cm depth were taken before rice transplanting to analyze for physical and chemical properties of soil. Soil particle analysis was done by pipette method (Gee and Bauder, 1986). Total N and TC contents were analyzed by using a NC analyzer (Sumigraph NC-80; Sumika Chemical Analysis Service Co., Japan). Soil organic matter contents were analyzed by hydrogen peroxide method (Schultz et al., 1999). 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). Electrical conductivity of the soil water was measured in the supernatant suspension of a 1:5 soil: water mixture using EC meter (OM-51, Horiba, Japan).

Tiller number, plant height and chlorophyll contents were recorded as growth parameters. Leaf chlorophyll contents were measured using a SPAD analyzer (SPAD 502; Minolta Corp., Tokyo). Seven samples hills were collected from each plot for collection of data on plant characters and yield components. Grain yield was determined from 1 m^2 sampling area at harvest and was expressed as rough (unhulled) rice at 14% moisture content.

4.2.3 Statistical analysis of data

All data were subjected to analyze by using CROPSTAT 7.2 statistical software program. The treatment mean comparison was tested at 5% level of probability using the LSD test by Fischer. Spearman rank order correlation analysis and simple linear regression analyses were done by using Sigma plot 11.0 statistical software program.

4.3 Results

4.3.1 Soil properties

Soil physical properties varied significantly among the positions of the fields (Table 4.1). Sand was the dominant type in the 1st inlet of 1st field containing 37.8 % followed by the 1st middle; 19.9 % and then it showed decreasing trend to the 2nd outlet position. Silt content showed increasing trend from 1st inlet to 2nd outlet with the highest 52 % in 2nd outlet; the furthest position from the channel. High clay content was observed in 1st middle, 1st outlet, 2nd inlet and 2nd middle followed by 2nd outlet and 1st inlet positions of the fields. Significant ($p<0.01$) differences in soil pH among the positions were observed in this experiment. High soil pH was observed in 1st outlet and 1st middle position followed by 1st inlet and the lowest was in the 2nd outlet position. Soil EC showed significant ($p<0.05$) variations among the positions with the highest values were observed in 1st outlet and 2nd inlet positions. Soil organic matter content ranged from 4.2 to 5.5 % among the positions with high content in 1st inlet, 1st middle, 1st outlet and 2nd inlet positions.

Soil TC content varied significantly among the positions and it ranged from 1.1 to 2.5 g kg^{-1} in both experimental fields (Fig. 4.1). The 1st outlet and 2nd inlet showed significantly ($p<0.05$) higher TC content than that of other positions. Soil TN contents were higher in 1st inlet, 1st middle and 1st outlet of the 1st field than that of all positions of the 2nd field (Fig. 4.1).

4.3.2 Plant height, no. of effective tiller and chlorophyll content

Significant ($p<0.05$) differences in plant height among the positions within the field were observed in this experiment (Table 4.2 and 4.4). Among the positions, the highest plant height was observed in 1st inlet and 1st outlet followed by 1st middle, 2nd inlet and the lowest was in 2nd outlet and 2nd middle positions. There was no significant difference in plant height but numerically higher due to farmer practice of fertilization. There were significant ($p<0.01$) differences in effective tiller number per hill among the positions in this experiment (Table 4.2 and 4.4). The higher effective tiller number was observed in 1st inlet, 1st middle and 1st outlet of the 1st field than that of all positions in the 2nd field. Farmer practice of fertilization increased in no. of effective tiller than non-fertilized part. Chlorophyll contents were significantly ($p<0.05$) different among the positions at active tillering and flowering stages (Table 4.2 and 4.4). During these growth stages, 1st inlet, 1st middle and 1st outlet positions of the 1st field showed higher chlorophyll content than that of all positions in the 2nd field. Significant ($p<0.05$) difference in chlorophyll content due to fertilization was observed only at flowering stage.

4.3.3 Yield component parameters

Significant ($p<0.05$) variations in panicle length but not in grains $panicle^{-1}$ were observed among the positions of the field (Table 4.3 and 4.4). All positions in the 1st field showed higher panicle length and grains panicle^{-1} than that of all positions in the 2nd field. Significant higher panicle length and grain panicle^{-1} were observed in fertilized part than non-fertilized part.

There were significant ($p<0.05$) differences in filled grain % and 1000 grain weight among the positions of the field (Table 4.3 and 4.4). 1st middle, 2nd middle and 2nd outlet showed higher filled grain % than other positions. All positions in the 1st field and 2nd inlet of the 2nd field showed higher 1000 grain weight than other positions. No significant difference in filled grain % was observed due to fertilization but significant higher 1000 grain weight was observed in fertilized part than that of non-fertilized part.

4.3.4 Grain yield

Grain yield of rice significantly ($p<0.01$) and differently responded to different positions in the fields (Table 4.4 and Fig. 4.2). Significant higher grain yields were observed in 1st inlet, 1st middle and 1st outlet positions than other positions of the 2nd field. Within the 1st field, there were no significant differences in grain yield among the positions. Within the 2nd field, significant higher grain yield was observed in 2nd inlet and then yield showed decreasing trend towards the 2nd outlet positions. The lowest grain yield was observed in 2nd outlet which located the longest distance from the channel in this experiment. In non-fertilized parts, average grain yields across positions in the 1st field and 2nd field were 521.8 g m^{-2} and 439.8 g m^{-2}, respectively.

Farmer practice of fertilization increased grain yields in all positions in both fields. But among the positions within the 1st field, there were no significant effect on grain yield due to fertilization. Within the 2nd field, fertilized parts of all positions showed significant higher grain yield than that of non-fertilized parts. Application of mineral fertilizers increased yields over non-fertilized parts on average by 6.4 g m^{-2} and 53 g m^{-2} in the 1st field and 2nd field, respectively.

4.3.5 Relationship between distance from the channel and soil properties

Significant negative relationship was observed between distance from channel and sand content of the soil which showed the more distance from channel the less sand content with the equation of $y = 0.2246x + 29.591$ where y represented sand content and x represented distance from channel (Fig. 4.3). Silt content showed significant relationship with distance from channel with increasing trend from the channel towards the last positions with the equation of $y = 0.2246x + 2.591$ where y represented silt content and x represented distance from channel in this experiment (Fig. 4.3).

Decreasing trend of TC content from channel was observed with the equation of $y = -0.0088 x + 2.5161$ where y represented TC content and x represented distance from channel (Fig. 4.4). Soil TN content also showed decreasing trend from the channel towards the last positions with the equation of $y = -0.0256 x + 3.351$ where y represented TN content and x represented distance from channel in this experiment (Fig. 4.4).

4.3.6 Relationship between distance from the channel and grain yield

Grain yield showed decreasing trend from 1st inlet to 2nd outlet position which meant the more distance from channel the less grain yield was observed. According to linear regression analysis, significant negative relationship was observed between grain yield and distance from channel with the equation of $y = -1.2384x + 544.3$ where y represented grain yield and x represented distance from channel in this experiment (Fig 4.5). Farmer practice of fertilization did not change the decreasing trend of grain yield from 1st inlet to 2nd outlet which meant high yields were observed in the positions near the channel than far away positions. Significant negative relationship was also observed for fertilized part between grain yield and distance from channel with the equation of $y = -0.6342x + 542.98$ where y represented grain yield and x represented distance from channel in this experiment.

Observed grain yields among the positions were significantly (R^2= 0.872, p<0.01) related with total N content of the soil with the equation of $y = 30.769 x + 429.3$ where y represented the grain yield and x represented total N content of the soil (Fig. 4.6a). Grain yield was not significantly (R^2= 0.46, p>0.05) related with TC content of the soil but increasing trend was observed with the equation of $y = 48.248 x + 392.31$ where y represented the grain yield and x represented total C content of the soil (Fig. 4.6b).

4.3.7 Correlation of growth, yield component parameters and grain yield

The results of the spearman rank order correlation analysis showed that grain yield was significantly (p<0.05) and positively correlated with growth and yield components parameters except grain panicle^{-1} (Table 4.5). Plant height was significantly correlated with chlorophyll content (p<0.05) but not related with yield component parameters. Chlorophyll content was significantly correlated with no. effective tiller (p<0.05), panicle length (p<0.05), filled grain proportion (p<0.05) and 1000 grain weight (p<0.05).

4.4 Discussion

4.4.1 Influence of positions on soil properties

Differences were substantial in soil texture among the positions in the fields based on water flow pattern which might be related with the downward movement and deposition of soil particles along with irrigation and runoff water (Table 4.1). As a result, sand content showed decreasing trend from the channel which deposited faster due to heavier than other particles. High silt contents were observed in far away positions from the channel. Schmitter et al. (2010) also reported that the downward movement of finer nutrient rich soil material along with irrigation and runoff water from upland were deposited to the lower lying fields of the cascades.

The result showed that there was a high degree of spatial variability related with TN and TC content among the positions in both rice fields (Fig. 4.1). Within the 1st field, TN and TC content were increasing trend from 1st inlet to 1st outlet. But decreasing trend was observed from 2nd inlet to 2nd outlet position of the 2nd field. This might be related with water flow pattern and transportation and disposition of organic rich sediment materials during irrigation. Oo et al. (2012) reported that spatial variation in TN and TC content among the field positions in toposequence rice fields were related with transportation and deposition of sediment during irrigation. In irrigated rice fields, irrigation water has been identified as a considerable source of additional particulate N and organic C to be transported into irrigated fields depending on its origin (King et al., 2009). Increase in TN and TC in the 1st middle and 1st outlet positions were related to increase in clay and silt fraction in the 1st field. Most of the nutrient rich sediment deposited in the 1st middle and 1st outlet positions due to low water velocity as its higher TN and TC with high clay and silt content. Less sediment water flowed via 2nd inlet until 2nd outlet position of the 2nd field which showed lower TC and TN content especially in 2nd middle and 2nd outlet of the 2nd field.

4.4.2 Influence of fertilizer and positions on growth parameters

The increase in plant height, chlorophyll content and effective tiller number in fertilized parts were probably due to enhanced availability of nutrients (Table 4.2). The variation in plant height among the positions was considered to be due to variation in TN and TC content, and soil pH in this experiment. The higher plant height and chlorophyll content in all positions of 1st field might be related with higher TN content and higher soil pH than that of all positions of 2nd field. Although not significant, increased in plant height due to farmer practice of fertilization might be due to availability of major nutrients. Siavoshi et al. (2011) discussed that the available nutrients might have helped in enhancing leaf area, which thereby resulted in higher photo-assimilates and more dry matter accumulation.

Effective tiller number was also an important trait for rice production and is thereby an important aspect in grain yield of rice. The variation in effective tiller number within the field might be due to variation in different soil properties among the positions. Higher effective tiller number was achieved in 1st middle and 1st outlet positions which showed high TN content and soil pH. The result showed that farmer practice of fertilization increased in no. of effective tiller than non-fertilized part due to enhanced availability of nutrients. Miraza et al. (2010) reported more number of tillers per square meter might be due to the more availability of N, which plays a vital role in cell division.

4.4.3 Influence of positions on yield and yield component

In lowland rice, positions in the fields and distance from the channel, which dominated the distribution of soil particles and soil fertility, was closely related with rice productivity. The result data showed that there was a high degree of spatial variability in grain yield of rice among the positions in the fields (Fig. 4.2). Variation in grain yield among the positions observed in this study showed a clear different, dependence on the distance from the irrigation channel (Fig. 4.5). In the 1st field, the increase in grain yield in 1st inlet, 1st middle and 1st outlet positions which showed closer to channel resembled the soil TN content, organic matter content and soil pH observed in the top soil (Table 4.1). Ahn et al. (2005) also reported that the effect of spatial variability of yield within rice field which was mainly caused by organic matter, TN, silica and cation exchange capacity. Broadbent (1979) and Murayama (1979) reported that 60-70% of the N assimilated by lowland rice originates from the soil or irrigation water. In all positions in the 1st field which showed closer to the channel, there were higher in TN and TC contents than that all positions in 2nd field (Fig. 4.1). The result of the linear regression analysis between distance from the channel and soil properties confirmed that TN content showed significant relationship with grain yield in this study. King et al. (2009) demonstrated that irrigation water enriched with sediments and dissolved organic C resulted in a net increase in total C and N loads in irrigated fields. In the 2nd field, the decreasing trend of grain yield from 2nd inlet to 2nd outlet positions which were significantly related with distance from the channel (Fig. 4.4). The lower TN content, organic matter and soil pH resulted in decreasing grain yield in all positions of the 2nd field.

High grain yields were observed in all positions in the 1st field which were closer to the channel. This could be attributed to the increase in panicle length, grain panicle^{-1} and 1000 grain weight in these positions. Thakur (1993), Channabasavanna and Setty (1994) and Behera (1998) also reported findings indicating improvements in grain yields attributed to increments in yield components. Kumar and Rao (1992) and Thakur (1993) reported that increase in yield components are associated with better nutrition, plant growth and increased nutrient uptake. Increasing the growth parameters such as effective tiller number, plant height and chlorophyll content might have increased grain yield of rice in all positions in the 1st field.

4.4.4 Influence of fertilization on yield and yield component

Farmer practice of fertilization increased grain yields over non-fertilized parts but it was spatially dependent (Fig. 4.2). Schmitter et al. (2011) and Oo et al. (2012) also reported that on average, the fertilized fields yielded continuously more than the fields without fertilizer in Chieng Khoi watershed area, Vietnam. In all positions in the 2nd field, significant higher grain yields were observed due to fertilization over non-fertilized part. This might be associated with increasing panicle length, filled grains per panicle, larger grain, number of effective tiller and chlorophyll content due to fertilization in the 2nd field. Since native soil fertility status was low (low in TN, TC, soil organic matter content of all positions in 2nd field when compare with that of all positions in 1st field), response to applied fertilizer showed significant effect on grain yield in all positions in 2nd field.

In all positions in the 1st field, no significant difference in grain yield due to farmer practice of fertilization might be higher availability of indigenous nutrients due to closer with channel. All these positions showed high TN content which was significantly related with high grain yield in these positions according to linear regression analysis (Fig. 4.6a). Cassman et al. (1998) and Dobermann et al. (2000) reported that N deficiency is a general feature of all irrigated rice systems, although, because of the large N input from indigenous sources, non-fertilized yields sustained at 2-4 t ha^{-1} for decades in Southeast Asia. Rice yield without applying N ranged from <2 to >6 t ha^{-1} (Cassmann et al. 1996; Wopereis et al. 1999) due to N input from indigenous sources. Moreover, the higher organic C (3.0%) and higher native total N (0.28%) contents observed on the surface soil of the experimental field (Mulugeta Seyoum, 2000) have also negatively affected crop response and increment in rice grain yield at higher application does of mineral N (>60 kg N ha^{-1}) fertilizer. Haefele and Konboon (2009) also reported that the results from Kumpa-Oong, Thailand also showed that the limited average fertilizer response was mainly caused by low or even negative responses in fields with a high control yield, that is, higher indigenous nutrient supply.

It can be concluded that spatial variation in grain yield among the positions under fertilization might be due to different availability of native indigenous nutrients in these positions which were related to water flow and deposition of sediment within and between fields and also influenced by distance from channel.

4.5 Conclusion

This is the first study that assessed spatial variation in soil properties and crop yield among the positions in the field based on water flow pattern of lowland rice, Myanmar. Large within field spatial variations among the positions were observed in sand, silt and clay content, TN, TC and organic matter content, and their influence on rice growth and grain yield which were significantly related with distance from the channel. The positions near the channel showed better soil fertility status as well as better growth performance in this study. The effect of application of mineral fertilizer on crop response and increment in rice grain yield largely depend on indigenous nutrient supply of the soil. Only significant high grain yields were observed in all positions in the 2nd field due to fertilization. The results highlighted that fertilizer management practice should be site specific management that more mineral fertilizers should be given in positions far away from the channel with increasing trend of application rate.

Table 4.1 Physico-chemical properties of the experimental soils at different positions within the field before transplanting of lowland rice, 2012

		Sand (%)	Silt (%)	Clay (%)	Organic matter (%)	pH	EC (ms m^{-1})
1st field	Inlet	37.8±5.7	28.0±5.9	34.2±9.1	5.1±0.6	6.0±0.1	0.44±0.03
	Middle	19.9±1.2	37.4±4.2	42.7±3.5	5.3±0.6	6.4±0.2	0.41±0.09
	Outlet	10.8±1.0	44.5±2.9	44.7±3.3	5.5±0.2	6.2±0.1	0.58±0.04
2nd field	Inlet	10.2±1.9	36.0±15.1	53.8±13.7	5.4±0.2	5.7±0.2	0.56±0.20
	Middle	8.3±2.6	48.7±11.0	43.0±8.8	4.7±0.2	5.7±0.1	0.39±0.06
	Outlet	9.7±1.7	52.0±4.6	38.4±3.3	4.2±0.1	5.9±0.1	0.32±0.05

Table 4.2 Influence of fertilizer and positions on plant growth and chlorophyll content of lowland rice

		Tiller number		Plant height (cm)		Chlorophyll content			
						Active tillering		Flowering	
		- F	**+ F**	**- F**	**+ F**	**- F**	**+ F**	**- F**	**+ F**
1st field	Inlet	9.1±0.8	9.0±1.0	89.2±0.8	81.5±2.2	38.9±2.2	37.8±2.8	33.4±0.5	29.8±1.9
	Middle	9.3±0.3	10.1±1.4	82.1±6.0	79.9±3.0	37.5±1.4	37.7±3.5	32.1±0.9	35.3±2.7
	Outlet	8.7±0.5	10.5±1.6	84.7±2.0	81.4±4.9	36.3±1.2	36.4±3.1	33.1±1.0	33.3±3.6
2nd field	Inlet	8.6±1.0	9.3±1.1	80.5±4.3	79.1±2.4	34.3±3.9	35.1±2.6	30.3±2.3	31.3±1.2
	Middle	7.9±0.3	7.7±1.7	71.4±	73.1±1.3	34.0±3.2	35.7±4.0	29.2±0.9	33.5±0.8
	Outlet	7.6±0.4	7.8±0.9	75.5±4.1	85.6±14.2	34.8±3.4	36.5±3.2	30.4±1.1	30.8±4.7

-F and +F stand for non-fertilized and fertilized part, respectively

Table 4.3 Influence of fertilizer and positions on yield component parameters of lowland rice

		Panicle length (cm)		Grains $panicle^{-1}$		Filled grain%		1000-grain weight (g)	
		- F	+ F	- F	+ F	- F	+ F	- F	+ F
1^{st} field	Inlet	21.6±1.3	22.2±1.0	121.7±2.1	122.9±8.6	90.3±1.7	90.0±1.0	21.7±1.2	22.2±0.4
	Middle	21.9±1.2	22.7±0.7	122.3±6.3	129.6±7.4	91.1±3.0	91.3±3.7	21.6±1.2	23.1±0.5
	Outlet	21.9±1.4	22.0±0.3	130.5±18.0	131.2±6.7	87.5±5.2	86.6±3.6	21.5±1.7	21.5±0.2
2^{nd} field	Inlet	20.1±1.2	20.4±0.6	111.4±17.6	119.8±9.4	90.5±2.8	90.7±1.0	21.8±1.1	22.2±0.7
	Middle	20.9±1.2	21.6±0.6	115.6±11.2	123.9±4.3	91.1±0.7	90.2±1.9	20.5±0.8	20.8±0.3
	Outlet	21.0±0.1	22.0±0.3	114.8±14.7	118.8±21.7	91.0±1.7	90.1±0.8	20.0±1.0	20.3±0.4

-F and +F stand for non-fertilized and fertilized part, respectively

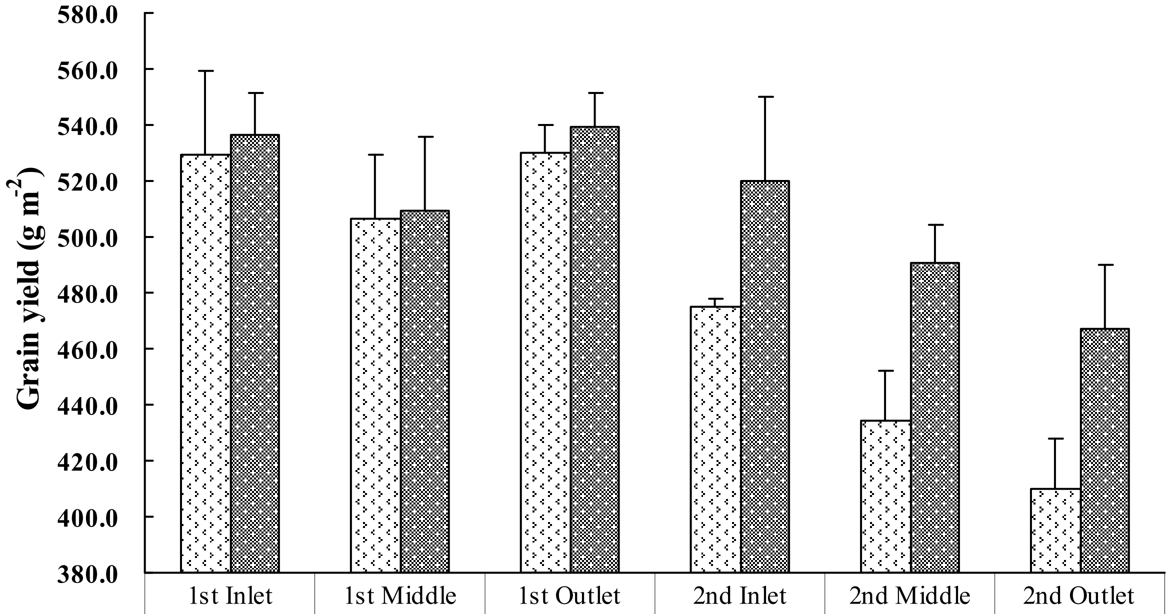
Table 4.4 Analysis of variance for plant growth, yield and yield components of lowland rice

Parameters	Mean squares for source of variation			
	Fertilizer	**Position**	**Fert. x Position**	**Error**
Grain yield	12469.4**	9213.2**	1944.9 ns	1396.4
Tiller number	2.7 ns	4.3**	0.9 ns	1.0
Panicle length (cm)	13.2**	3.1*	0.64 ns	0.8
Grain panicle^{-1}	647.1*	284.1 ns	237.9 ns	150.5
Filled grain (%)	11.6 ns	27.0*	5.5 ns	7.4
1000 grain wt.	0.1**	0.03**	0.01 ns	0.005
Chlorophyll content at tillering	0.5 ns	74.3*	13.2 ns	115.7
Chlorophyll content at flowering	35.6*	19.5*	5.1 ns	5.3
Plant height	23.7 ns	116.5**	55.8**	13.8

Table 4.5 Spearman rank order correlation analysis results among grain yield and yield attributes of rice

	Effective tiller	Panicle length	Grain panicle^{-1}	Filled grain %	1000 seed wt	Chloro. content	Plant height
Grain yield	0.54**	0.33*	0.27^{ns}	0.31*	0.42**	0.48**	0.34*
Effective tiller		0.30*	0.31*	0.15^{ns}	0.32*	0.41*	0.10^{ns}
Panicle length			0.67**	0.22 ^{ns}	0.30*	0.42*	0.09^{ns}
Grain panicle^{-1}				0.08ns	0.31^{ns}	0.15^{ns}	0.14^{ns}
Filled grain %					0.24^{ns}	0.29*	0.23^{ns}
1000 seed wt						0.38*	0.06^{ns}
Chloro. content							0.39*

Fig 4.1 Total carbon and nitrogen content among the positions in the 1st and 2nd field of lowland paddy soil



	1st Inlet	1st Middle	1st Outlet	2nd Inlet	2nd Middle	2nd Outlet
Unfertilized	529.0	506.3	530.3	475.2	434.3	410.0
Fertilized	536.3	509.3	539.0	520.3	491.0	467.0

Fig 4.2 Grain yield in fertilized and non-fertilized plots at different positions within the field of lowland paddy rice (Error bar - standard deviation)

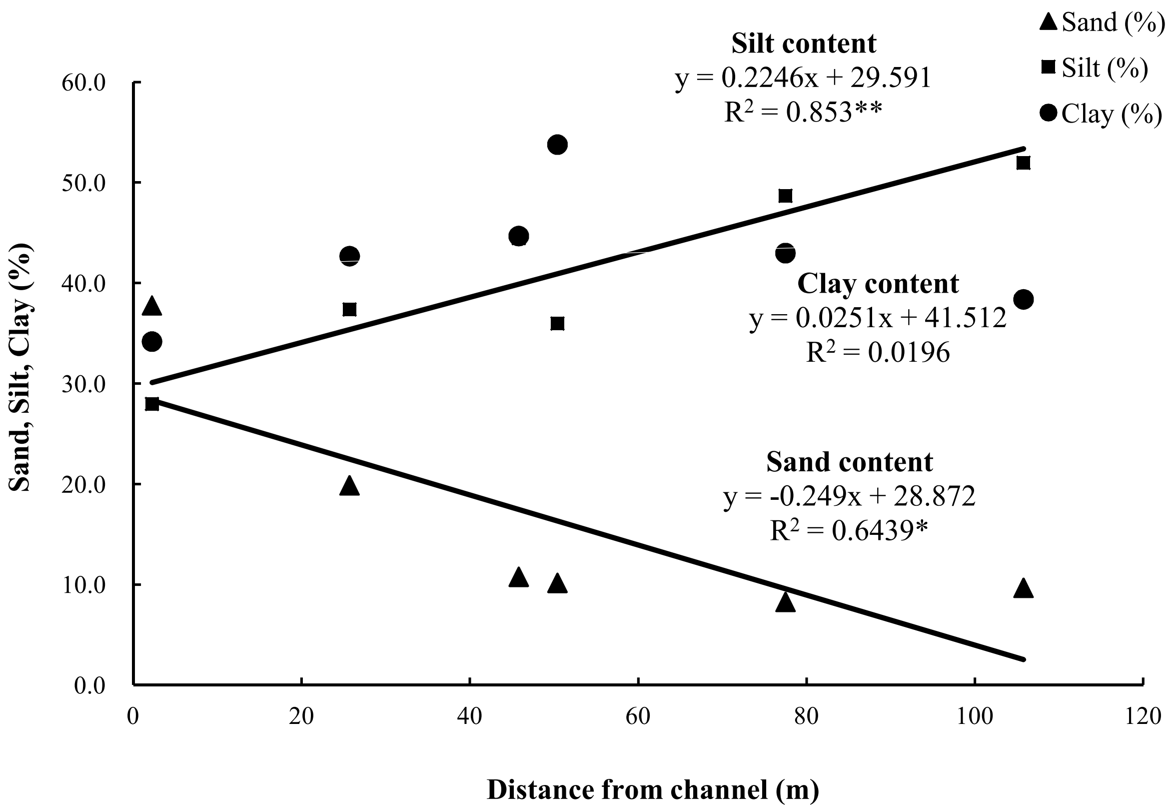


Fig 4.3 Relationship between distance from channel and sand, silt and clay content of soil before transplanting of lowland rice

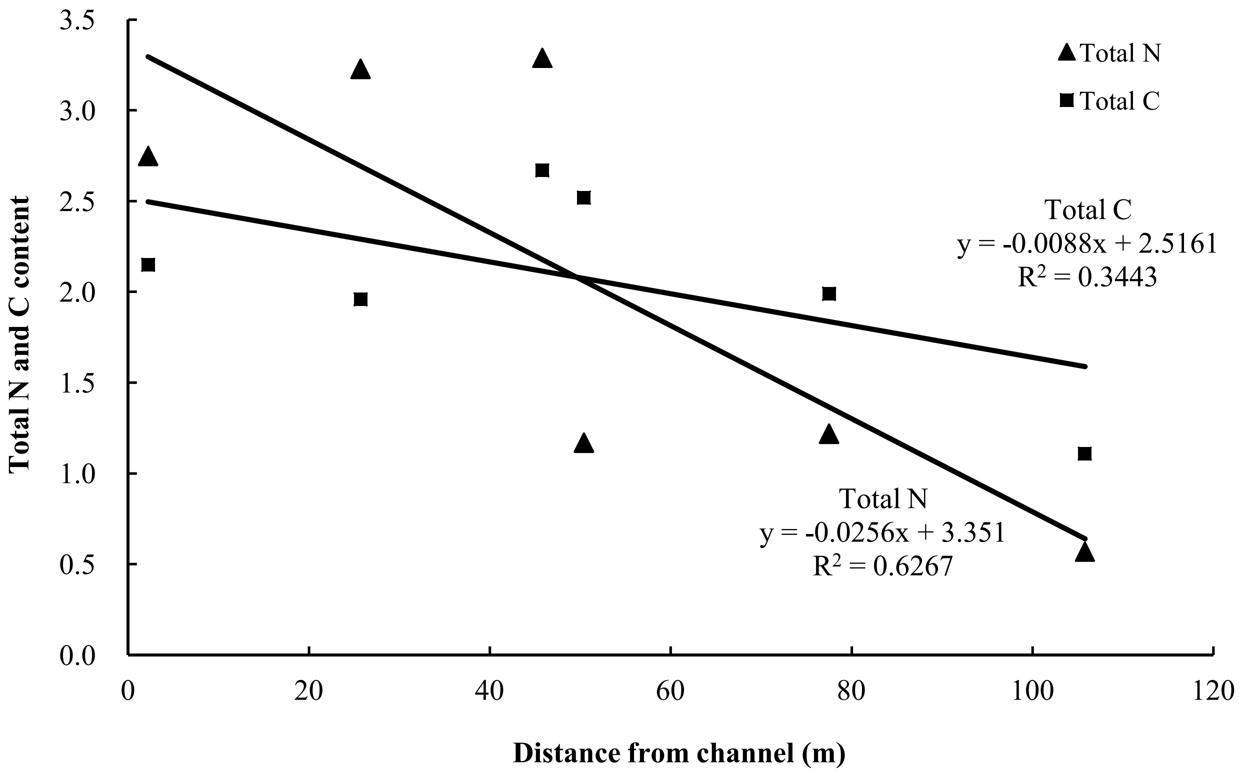


Fig 4.4 Relationship between distance from channel and total N and C content of soil before transplanting of lowland rice

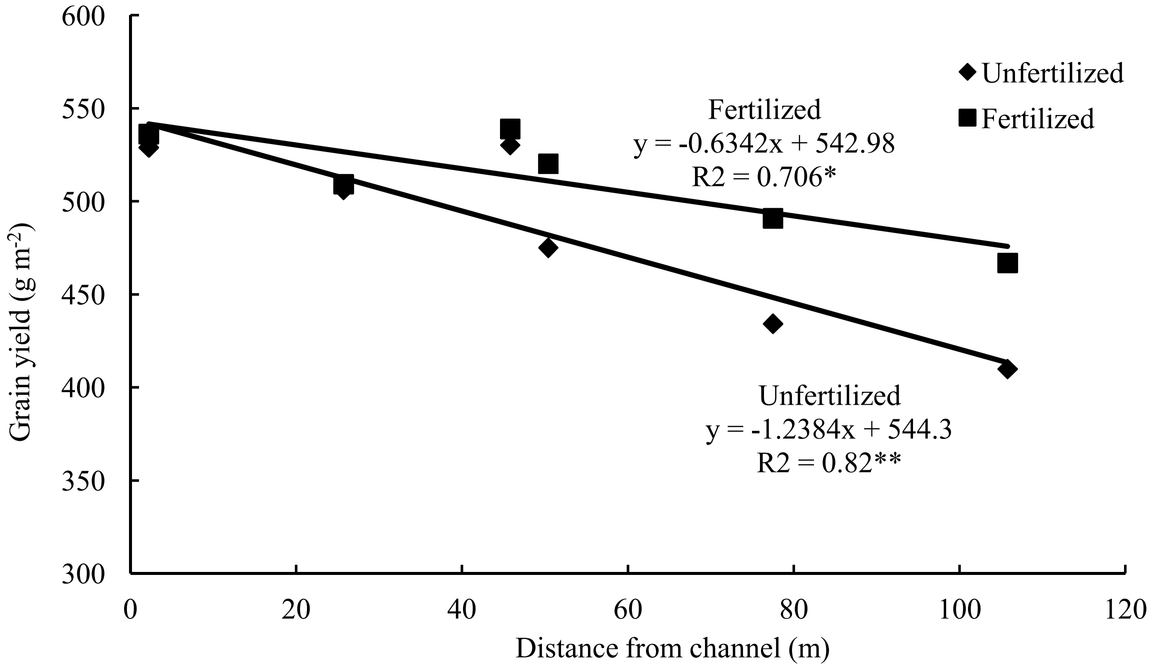


Fig 4.5 Relationship between distance from channel and grain yield of lowland paddy rice

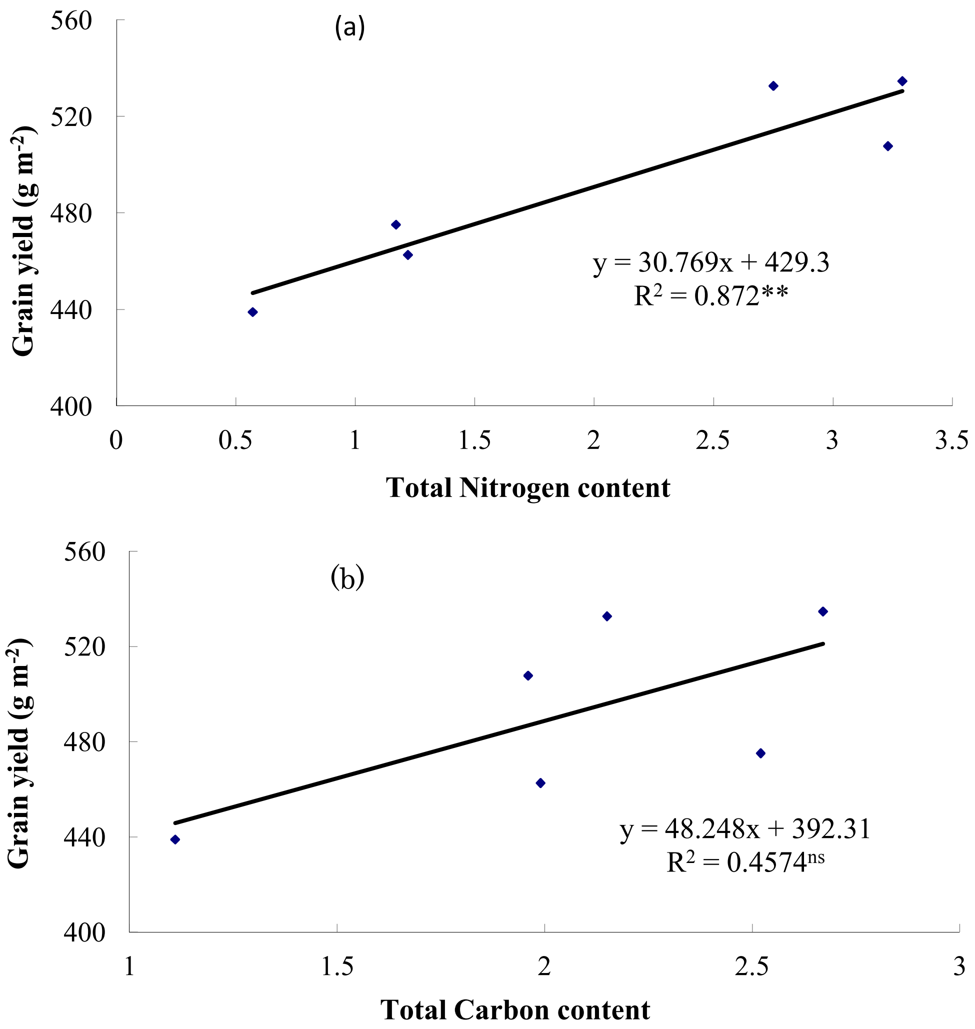


Fig 4.6 Relationship between (a) soil total nitrogen and (b) total carbon contents and grain yield of lowland rice

Chapter 5

Spatial and temporal variations in methane emissions within paddy rice fields of lowland rice in Myanmar

5 Spatial and temporal variations in methane emissions within paddy rice fields of lowland rice in Myanmar

5.1 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 percent 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 are connected as successive fields in lowland areas with a few centimeters of difference in elevation. The differences in position may lead to differences in soil properties and soil fertility status (Hseu and Chen, 2001; Tsubo et al., 2006), and therefore crop yield. Furthermore, organic compounds present in the water will also influence soil fertility in paddy rice fields. In irrigated rice fields, irrigation water has been identified as a considerable source of additional particulate N and organic C transported into irrigated fields depending on its origin (King et al., 2009). For example, the yearly amount of organic C entering paddies with irrigation water in Northwest Vietnam was estimated at 0.8 Mg ha^{-1} and 0.7 Mg N ha^{-1} (Schmitter et al., 2012), which might foster elevated greenhouse gas emissions, and it was found that methane (CH_4) emission is related to different sediment deposition patterns across a rice cascade (Oo et al., 2013).

Paddy rice fields are one of the important sources of CH_4 emissions (IPPC, 2007). More than 50% of the global annual CH_4 emission is derived from anthropogenic origin (IPCC, 2007), and cultivation of rice accounts for 10–20% of total anthropogenic CH_4 emission with an annual global emission ranging from 50–100 Tg CH_4 per year (Reiner and Milkha, 2000). However, there is no information concerning CH_4 emission from lowland rice fields of Myanmar, and the contribution of Myanmar rice production, especially from lowland rice fields, to the global CH_4 budget is unknown.

It is well known that CH_4 emission from paddy rice fields is a net product of CH_4 production and oxidation. Methane emission fluxes from paddy rice fields during the growing season are significantly affected by water management, organic matter application, soil organic matter, C content, soil pH, preseason water status and climate (Yan et al., 2005). Methane emission fluxes are also affected by N and other nutrients directly or indirectly (Schimel, 2000). For example, at the plant or ecosystem level, ammonium-based fertilizers can stimulate rice plant growth, which may increase CH_4 emission by providing more methanogenic substrates and enhancing the efficiency of CH_4 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 CH_4 emissions in rice soils (Banik et al., 1996; Shang et al., 2011). In contrast, others have reported that CH_4 emissions were inhibited with N fertilizer (Xie et al., 2010; Dong et al., 2011). There is no single agreement regarding the net effect of mineral fertilizers on CH_4 emission from paddy rice soil. It is therefore necessary to assess the net effect of N fertilizers on CH_4 emission in order to design effective mitigation strategies from the paddy rice ecosystem.

Spatial and temporal variation of CH_4 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). Due to the interactive effects of soil, climatic and cultural factors, the uncertainty in estimating CH_4 emission from rice fields is increasing. The upscaling of flux rates is hampered by this uncertainty and the pronounced spatial and temporal variations (Van Bodegom et al., 2000; Sass et al., 2002). There is an urgent need to evaluate the interaction between CH_4 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. More research is necessary to understand the temporal and spatial variation in CH_4 emission within paddy rice fields in order to develop a reliable regional and global CH_4 budget and identify effective mitigation measures.

The most important objective of studies on CH_4 emission from paddy rice fields is the mitigation of global warming at the regional scale (Minamikawa et al., 2006). Kimura et al. (1991) and Yang and Chang (2001) reported large-scale spatial variation. Gaihre et al. (2012) reported variation in CH_4 emission across nearby fields in relation to changes in soil, water and plant properties. The spatial variability in CH_4 emissions among the toposequence positions in a paddy rice cascade of Northwest Vietnam was related to different sediment deposition patterns across the cascade, which influenced the physical and chemical properties of soils along the toposequence rice fields (Oo et al., 2013). However, spatial variations in CH_4 emission due to positions in the field according to water flow pattern and soil, as well as water and plant environment within a paddy rice field, have not been investigated thoroughly. In particular, the interaction of soil and management practices in tropical semi-rainfed rice fields is not well understood, despite their huge CH_4 production potential. Therefore, this study aimed to assess the spatial and temporal variations in CH_4 emissions from different positions within a field in relation to water flow pattern and mineral fertilizers in Kanyutkwin, Pago Division, Myanmar.

5.2 Materials and methods

5.2.1 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, Pago Division, Myanmar (18º48′43″ N, 96º43′57″ E). The field had been under a monsoon rice (*Oryza sativa* L.) and blackgram (*Vigna mungo*) rotation for 25 years. The soil was classified as a fluvisol (alluvial soil) (UNESCO, 1974), which contained a large amount of silt. The weather in the study area was of a tropical monsoon climate with an annual rainfall of 2545 mm, and minimum and maximum temperatures of 19.6ºC and 32.2ºC, respectively, in 2012 (Fig. 5.1).

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 (Fig. 5.2). 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: an inlet, middle and outlet position.

The experiment was laid out in a split-plot design with three replications for each field (Fig. 5.2). 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. Chemical fertilizer was applied at 250 kg ha^{-1} in the form of NPK (15-5-5) compound fertilizer with two split applications according to local recommendations by the extension service. The first dressing was conducted at transplanting using 50% of the total amount of fertilizer. The second dressing contained the remaining 50% and was applied at the heading stage.

The indica rice variety (O*ryza 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 21 days before puddling on June 7, 2011. The puddling was conducted with cattle and basal fertilizer was mixed at the time. 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.

5.2.2 Sample collection, soil parameters, and CH_4 analysis

Methane fluxes were measured in triplicate at 10-day intervals from 7 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 sample gases 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 CH_4 concentration vs. time regression when their linear correlation coefficients were significant at the 0.05 level.

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 TN andTC 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 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 electrode into the soil under investigation to a root-zone depth of 5 cm throughout the growing season. Plant height and tiller number were recorded as growth parameters, and grain yield was determined from a 1-m^2 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 80ºC for two days.

5.2.3 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 LSD test by Fischer. Spearman rank order correlation analysis was performed using the SigmaPlot 11.0 statistical software program.

5.3 Results

5.3.1 Soil environmental factors

Sand was the dominant type with 37% in the 1st inlet position. 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 (Table 5.1). 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 of the 1st field and 2nd inlet of the 2nd field showed a significantly ($p<0.05$) higher TC content than that of other positions. Soil TN contents 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 (Figs. 5.3a and 5.3b). 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 32ºC (Figs. 5.3c and 5.3d). 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 later growing periods. Surface water pH ranged between 6.5 and 8.5 throughout the growing season (Figs. 5.3e and 5.3f). Significant ($p<0.05$) differences in surface water depth among positions were observed throughout the growing season (Figs. 5.3g and 5.3h). 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.

5.3.2 Plant growth and crop yield

There were significant ($p<0.01$) differences in tiller number and plant height among the positions within a field, but no significant difference was observed due to fertilization (Table 5.2). All positions in the 1st field showed a higher tiller number and plant height compared to that of any position in the 2nd field. The highest rice straw and grain yields were found for all positions of the 1st field, while the lowest grain yield was observed in the 2nd outlet position. Significantly ($p<0.05$) higher grain yields were observed only in the fertilized part of all positions in the 2nd field compared to those of the non-fertilized part, but there was no significant difference due to fertilization in regard to straw weight.

5.3.3 Influence of position on seasonal and temporal variation in CH_4 flux

Methane flux from all positions in both fields generally showed two peaks during the growing season (Figs. 5.4a and 4b). 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 flux 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 later growing period.

5.3.4 Influence of position and fertilizer on rate and cumulative CH_4 flux

Methane emissions showed significant (p<0.01) differences among positions in both rice fields (Table 5.3). The highest average CH_4 emission was 28.5 and 30.0 mg CH_4 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 8.5 mg CH_4 m^{-2} h^{-1} was recorded for the 1st middle position of the 1st field. The cumulative CH_4 emissions during the rice growing season exhibited the following order of magnitude: 2nd inlet > 1st outlet > 2nd middle > 2nd outlet > 1st middle > 1st inlet. The seasonal cumulative CH_4 flux values for the 1st outlet and 2nd inlet were 71.1 and 72.2 g CH_4 m^{-2}, respectively, which were 2 to 2.5 times significantly higher than that of other positions. The average CH_4 emission rate of all positions in the 1st field was 15.5 mg CH_4 m^{-2} h^{-1}, which did not differ statistically from that of the 2nd field (16.6 mg CH_4 m^{-2} h^{-1}). The cumulative amounts of CH_4 emission for the 1st and 2nd fields were 38.7 g m^{-2} and 41.5 g m^{-2}, respectively.

Seasonal variation in CH_4 emission from fertilized and non-fertilized parts showed similar trends and patterns throughout the growing seasons, and thus only the average and cumulative amount is shown for fertilized emission (Table 5.3). Reductions in CH_4 emission due to fertilization were observed in the 1st inlet (18.1%), 1st outlet (50.4%), 2nd inlet (15.9%) and 2nd outlet (13.4%). But an increase of CH_4 emission due to fertilization occurred in the 1st middle (43.8%) and 2nd middle (7.7%). The average CH_4 emission rate for all positions of the fertilized part (13.1 mg CH_4 m^{-2} h^{-1}) was significantly ($p<0.05$) lower than that of the non-fertilized part (16.1 mg CH_4 m^{-2} h^{-1}). As a consequence, the seasonal cumulative CH_4 emission in the fertilized part was reduced significantly ($p<0.05$) relative to that of the non-fertilized part considering the average value of all positions.

5.3.5 Influence of soil environmental factors and plant growth on CH_4 emission

Surface water pH was significantly correlated with CH_4 emission for both rice fields (Table 5.4). Surface water depth showed a significant and positive correlation with CH_4 emission in the 1st field, but there was no significant correlation for the 2nd field. The CH_4 emission rate was positively correlated with TC content in both rice fields. Significant negative correlations between CH_4 emission rate and soil Eh were observed in both rice fields. Soil temperature was significantly and positively correlated with CH_4 emission only in the 1st field. No correlation was observed between CH_4 emission and TN, or plant growth and yield parameters, for either of the rice fields.

5.4 Discussion

5.4.1 Seasonal variation in CH_4 emission

Contrasting spatial and temporal patterns of CH_4 emissions were observed among positions in both rice fields (Figs. 5.4a and 5.4b). 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). Suryavanshi et al. (2012) reported that a higher CH_4 emission at the tillering stage is generally due to lower rhizospheric CH_4 oxidation and more effective transport mediated by rice plants. 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 CH_4 emission at 37 DAT was probably mainly due to low soil temperature and continuous rainfall during this period (Fig. 5.1). Temperature can also affect concentrations according to Henry`s law, since more gas can be dissolved as entrapped bubbles at low temperature. Tokida et al. (2012) reported that the gaseous CH_4 pool plays an important role in controlling CH_4 emission under a drop in air pressure due to rainfall. The second emission peak occurred at maximum tillering (47 DAT) and the late growing period. This can 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 (Adhya et al., 1994; Mitra et al., 2005).

In our study, the seasonal average value of the CH_4 emission rate ranged from 8.5 to 28.9 mg CH_4 m^{-2} h^{-1} (Table 5.3). This is higher than that of the different toposequence positions in the Yen Chau district of Northwest Vietnam as reported by Oo et al. (2013), which ranged from 0.22 to 6.11 mg CH_4 m^{-2} h^{-1} during the spring rice season and from 0.13 to 20.1 mg CH_4 m^{-2} h^{-1} during the summer rice season. The rather low emission reported by Oo et al. (2013) was due to the field positions, which were located in different toposequence positions with good field drainage conditions in upper and middle parts, and sometimes experienced water shortage due to lower rainfall and low soil temperature during the crop growing seasons. The fields in our study were located in a lowland area with poor field drainage conditions under high rainfall and high soil temperature, which favored high CH_4 emission. Another reason for the higher CH_4 emission of our study might be the continuous flooding throughout the rice growing season, which involved a high risk of CH_4 emissions since mid-season drainage was not successful due to frequent rainfall. Hadi et al. (2010) suggested that intermittent irrigation and drainage can be a suitable option to reduce greenhouse gas emission from paddy soil in Japan and Indonesia. In China, water management by flooding with mid-season drainage and frequent water logging without the use of organic amendments was found to be an effective option for mitigating CH_4 emission in comparison to that occurring with continuous flooding (Zou et al., 2005).

The range of cumulative seasonal CH_4 emissions in this study was 21.2 to 71.1 g CH_4 m^{-2} (Table 5.3). 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 CH_4 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 CH_4 emissions between two locations were also shown by Zhang et al. (2009), who reported high spatial variability in CH_4 emissions from rice fields in the Taihu Lake region of China, and demonstrated higher annual CH_4 emissions on the plains compared to the hilly regions.

5.4.2 Influence of different positions within a field and soil environmental factors on CH_4 emission

The rice fields of this study were located in a lowland area, and slope differences among the positions within and between fields were only a few centimeters. As a consequence, the water flow velocity was relatively low and the sediment deposition rate was high in the upper positions. Irrigation water carried a substantial amount of organic rich materials and deposited this content throughout the rice field. Irrigation water shows an average concentration of 2 mg l^{-1} organic C and 1.5 mg l^{-1} total N when no rain occurred in the Cheing Khoi area of Northwest Vietnam (Schmitter et al., 2010), providing C sources for methanogens. Our research showed clearly that most of the sediments were deposited in the 1^{st} field (Table 5.1). As a result, sand showed a decreasing trend with the highest content in the 1^{st} inlet, silt showed an increasing trend with the highest content in the 2^{nd} outlet, and the highest clay content was observed in the 1^{st} outlet and 2^{nd} inlet positions. Since the water flow velocity was low, conditions for the 1^{st} outlet and 2^{nd} inlet were similar, as demonstrated by the fact that most of the soil properties of the 2^{nd} inlet were similar to those of the 1^{st} outlet, and both positions showed high clay, TC, soil EC, organic matter content, and low sand content (Table 5.1).

Many studies have reported that soil properties of paddy rice have a strong influence on CH_4 emission from rice fields (Mitra et al., 2005; Oo et al., 2013). In this experiment, CH_4 emissions were influenced by the position within a field (Figs. 5.4a and 5.4b), which might be related to the pattern of sediment deposition among the positions and their associated soil properties. Oo et al. (2013) reported that spatial variability of CH_4 emissions among toposequence positions was related to transportation and deposition of organic-rich sediment materials within toposequence rice fields. In the current study, the observed high rates of CH_4 emission from the 1^{st} outlet and 2^{nd} inlet positions were associated with a high clay, TC and organic matter content. In these positions, the higher clay and TC contents favored methanogenic activities (Mitra et al., 2002; Xiong et al., 2007; Gaihre et al., 2011). A spearman rank order correlation analysis confirmed that TC content was positively related with CH_4 emission in both rice fields (Table 5.4). Mitra et al. (2002) reported that higher TC content stimulated CH_4 production in rice soil, and Oo et al. (2013) observed that TC content was positively correlated with CH_4 emission from toposequence rice fields. Another reason for the high rates of CH_4 emission from the 1^{st} outlet and 2^{nd} inlet might be the lower Eh values due to a high water depth in these positions (Figs. 5.3g and 5.3h), which were negatively correlated with CH_4 emission in this study (Table 5.4). It has been shown that 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 of clay in the 1st outlet and 2nd inlet might explain the greater CH_4 production.

In this study, seasonal variation in CH_4 emission was influenced by soil environmental factors such as soil Eh, surface water pH, soil temperature, and surface water depth (Figs. 5.3a-h). The soil redox potential declined after flooding and fluctuated between -150 and -450 mV in both fields throughout the growing season (Figs. 5.3a and 5.3b). Negative correlations between CH_4 emissions and soil Eh existed for both rice fields (Table 5.4). Yagi and Minami (1990) reported that the critical values of soil Eh for initiation of Eh are from -100 to -200 mV. The Eh range in this study was considerably more negative than the critical value, and soil conditions were more favorable for methane production. Although a positive correlation between soil temperature and CH_4 emission was observed only for the 1st field (Table 5.4), the temperature range in this experiment is within the optimum temperature range for methanogens of 25–37ºC (Schütz et al., 1990). There were significant relationships between CH_4 flux and surface water pH, but opposite trends were found when comparing the 1st and 2nd fields. Methanogenic bacteria are pH sensitive and can grow well in a relatively narrow pH range of 6–8 (Oremland, 1988). The pH in our study ranged from 6.5 to 8.4 throughout the growing season, and was optimal for the growth and activity of methanogenic bacteria involved in CH_4 production (Figs. 5.3e and 5.3f).

A significant relationship between CH_4 flux and surface water depth was found only for the 1st field (Figs. 5.5c and 5.5d). Under flooded conditions, a negative redox status was already established (Figs. 5.3a and 5.3b) and variation in surface water depth during the growing season may not have affected the large differences in soil redox status (Figs. 5.3g and 5.3h). Gaihre et al. (2011) reported that the contribution of floodwater depth was not significant in their study because they maintained a continuously flooded field, and the small variation in depth may not have affected CH_4 emissions to a large extent.

5.4.3 Influence of mineral fertilizer on CH_4 emission

Many paddy rice fields in Myanmar rely on mineral fertilizers to increase crop yields (FAO, 2010). The commonly used mineral fertilizer in the study area is an ammonium-based compound fertilizer according to the local agricultural extension service. Nitrogen fertilizers stimulate crop growth and provide more C substrates (via organic root exudates and sloughed-off cells) to methanogens for CH_4 production (Aulakh et al., 2001, van der Gon et al., 2002; Inubushi et al., 2003). Singh et al. (1998) reported that the rate of CH_4 flux was significantly and positively related with shoot height and weight, the number of tillers, and root weight. However, a spearman rank order analysis conducted in our study for the seasonal rate of CH_4 flux in relation to plant parameters indicated that there was no relationship between CH_4 emission and either the number of tillers, plant height or plant weight (Table 5.4). Therefore, factors other than the increase in plant growth influenced the change in CH_4 emission due to fertilization.

Liou et al. (2003) reported that the effect of N fertilizers on CH_4 emission depends on the form and amount of fertilizer, as well as the mode and time of application. Banik et al. (1996) and Shang et al. (2011) demonstrated that addition of N fertilizer increased CH_4 emissions in rice soils and suggested this was probably due to the result of stimulation of methanogens by greater production of crop biomass under N fertilization. In contrast, N fertilizers have stimulated the activities of methanotrophs that resulted in greater CH_4 oxidation with N fertilizer (Bodelier et al., 2000a, b). Kimura (1992) found that the CH_4 emission rates from a pot experiment with ammonium sulfate treatment was the lowest, followed by those resulting from the application of ammonium chloride, and then urea fertilization. Cai et al. (1997) also reported that CH_4 emission was 30–50% lower following application of ammonium sulfate compared to urea-treated rice plots. In general, the sulfate ion serves as an alternative to CO_2 as an electron acceptor for the oxidation of organic matter and thereby reduces CH_4 production (Banger et al., 2012).

In this experiment, significant inhibition of CH_4 fluxes with addition of ammonium sulfate-containing fertilizer was found for the 1st inlet, 1st outlet, 2nd inlet and 2nd outlet positions of the paddy rice fields (Table 5.3). A reasonable explanation for the observed results might be the application of ammonium-based sulfate-containing fertilizers, which are known to decrease CH_4 emission as a result of competition between sulfate-reducing bacteria and methanogens for hydrogen and acetate substrates (Hori et al., 1993). Wide ranges of reduction from 13.4 to 50.5% due to fertilization were observed in this experiment. It appears that other factors such as soil properties and soil environmental factors, as demonstrated by the spearman rank order correlation analysis (Table 5.4), also influenced the degree of reduction in CH_4 emission due to fertilization.

However, the 1st middle and 2nd middle positions showed a higher CH_4 emission flux due to fertilization. In these positions, a high micro-elevation was found due to the low water depth of these positions (Figs. 5.3g and 5.3h). Micro-elevation led to differences in water depth among the positions in the fields. A lower water depth is known to result in a higher loss of N as ammonia volatilization, and ammonia is lost at a faster rate from shallow water than deep flood water due to the higher ammonium N concentrations and higher temperatures (Freney et al., 1988). Another reason for the observed results might involve stimulation of methanogens by N fertilization (Banik et al., 1996; Shang et al., 2011), but this does not provide a mechanism whereby the effect of fertilizer application on positions with high micro-elevation increases the cumulative CH_4 emission from both middle positions. It is important to note that our experiment was conducted at only one site and for one season, and additional *in situ* observations are therefore needed to assess the increase of CH_4 emission due to the application of sulfate-containing N fertilization in high micro-elevation positions within rice fields.

5.5 Conclusion

The results of the current research indicate that considerable spatial variations in CH_4 emissions exist, even across nearby positions, due to water flow pattern and resulting differences in soil properties and soil environmental conditions. The spatial variability in CH_4 emissions among the positions in this experiment were related to water flow-based deposition patterns across the fields, which significantly influenced the physical and chemical properties of soil among the positions. Application of ammonium-based sulfate-containing fertilizers is an effective way to reduce CH_4 emission from paddy rice soil, but the reduction was spatially dependent within the field. Positions with high micro-elevation showed increased CH_4 emission due to fertilization in this study. The high spatial variations in CH_4 emission among positions within a field were due to the position-dependent effect of fertilization on CH_4 reduction, and it is therefore suggested that different management practices be adopted for different positions to mitigate CH_4 emissions from lowland rice fields.

Table 5.1 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	2.8 a	2.2 ab	5.1 a	6.0 bc	0.44 ab
	Middle	19.9 b	37.4 b	42.7 bc	3.2 a	2.0 b	5.3 a	6.4 a	0.41 b
	Outlet	10.8 c	44.5 ab	44.7 ab	3.3 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	1.2 b	2.5 a	5.4 a	5.7 d	0.56 a
	Middle	8.3 c	48.7 a	43.0 bc	1.2 b	2.0 b	4.7 ab	5.7 d	0.39 b
	Outlet	9.7 c	52.0 a	38.4 bc	0.6 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

Table 5.2 Influence of fertilizer and positions on plant growth and yield of lowland rice

		Tiller number		Plant height (cm)		Grain ($g\ m^{-2}$)		Straw ($g\ m^{-2}$)	
		- F	**+ F**	**- F**	**+ F**	**- F**	**+ F**	**- F**	**+ F**
1st field	Inlet	9.1 a	9.0 a	89.2 a	81.5 a	529.0 a	536.3 a	710.6 a	635.3 a
	Middle	9.3 a	10.1 a	82.1 b	79.9 a	506.3 a	509.3 a	636.0 a	659.7 a
	Outlet	8.6 a	10.5 a	84.7 ab	81.4 a	530.3 a	539.0 a	630.0 a	578.3 ab
2nd field	Inlet	8.6 a	9.3 a	80.5 b	79.1 a	430.0 b	520.3 a	508.3 b	505.0 b
	Middle	7.9 b	7.7 b	71.4 c	73.1 b	434.3 b	491.0 ab	397.0 c	450.3 bc
	Outlet	7.6 b	7.8 b	75.5 c	85.6 a	410.3 b	467.7 b	416.7 bc	479.0 bc

-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

Table 5.3 Influence of fertilizer and positions on average rate and cumulative CH_4 fluxes of lowland rice

		Rate of CH_4 flux ($mg\ m^{-2}\ h^{-1}$)		Cumulative CH_4 flux ($g\ m^{-2}$)		Reduction % due to fertilization
		- F	**+ F**	**- F**	**+ F**	
1st field	Inlet	9.5 b	7.8 c	23.8 b	19.5 c	- 18.1
	Middle	8.5 b	12.2 bc	21.2 b	30.5 bc	+ 43.8
	Outlet	28.5 a	14.2 b	71.1 a	35.3 b	- 50.4
2nd field	Inlet	28.9 a	24.3 a	72.2 a	60.7 a	- 15.9
	Middle	10.5 b	11.2 bc	26.1 b	28.1 bc	+ 7.7
	Outlet	10.5 b	9.1 c	26.2 b	22.7 c	- 13.4

-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

Table 5.4 Spearman rank order correlation between CH_4 emission rate and soil and plant parameters of lowland rice

	Soil temp.	Surface water pH	Water depth	Soil Eh	TN	TC	Grain	Straw
1st field	0.51*	-0.68**	0.54*	-0.67**	0.34^{ns}	0.55*	0.04^{ns}	0.03^{ns}
2nd field	0.29^{ns}	0.71**	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

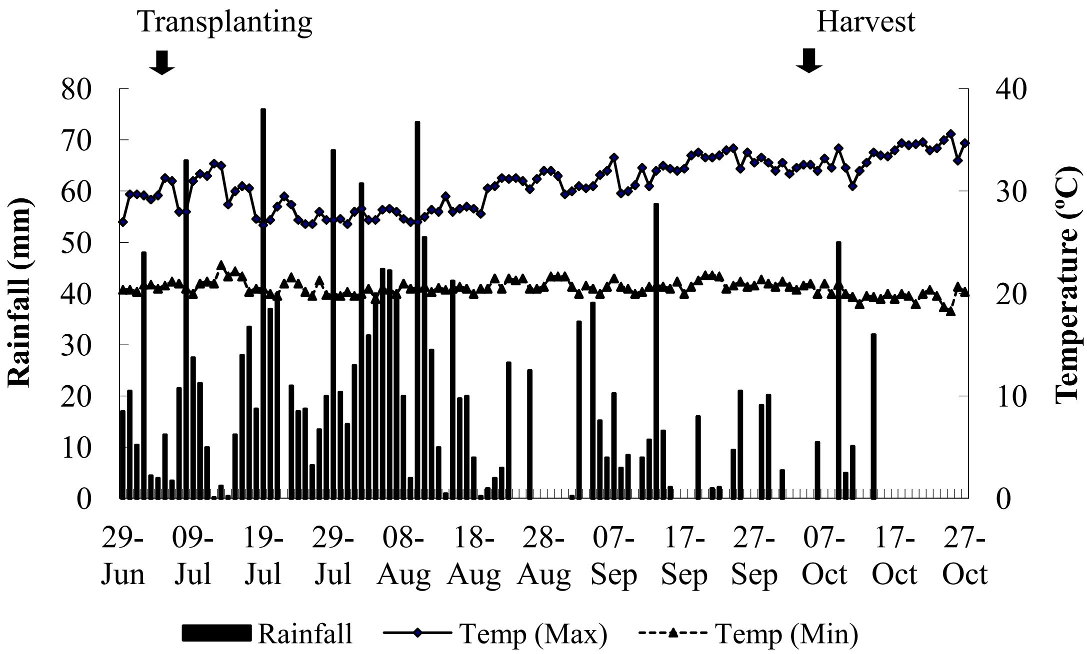


Fig 5.1 Daily rainfall distribution, maximum and minimum temperatures during monsoon rice growing season for 2012 at experimental site of Kanyutkwin, Phyu City, Myanmar

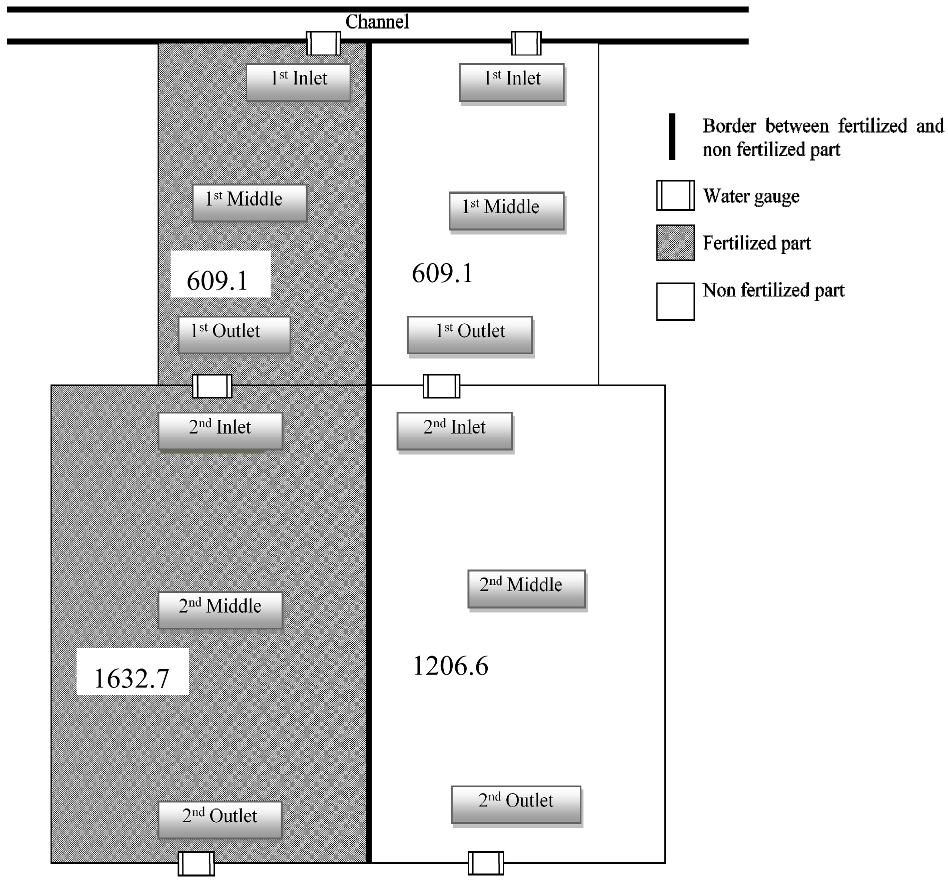


Fig 5.2 Schematic representation of experimental layout with two successive lowland rice fields, Kanyutkwin, Myanmar (Area – m^2)

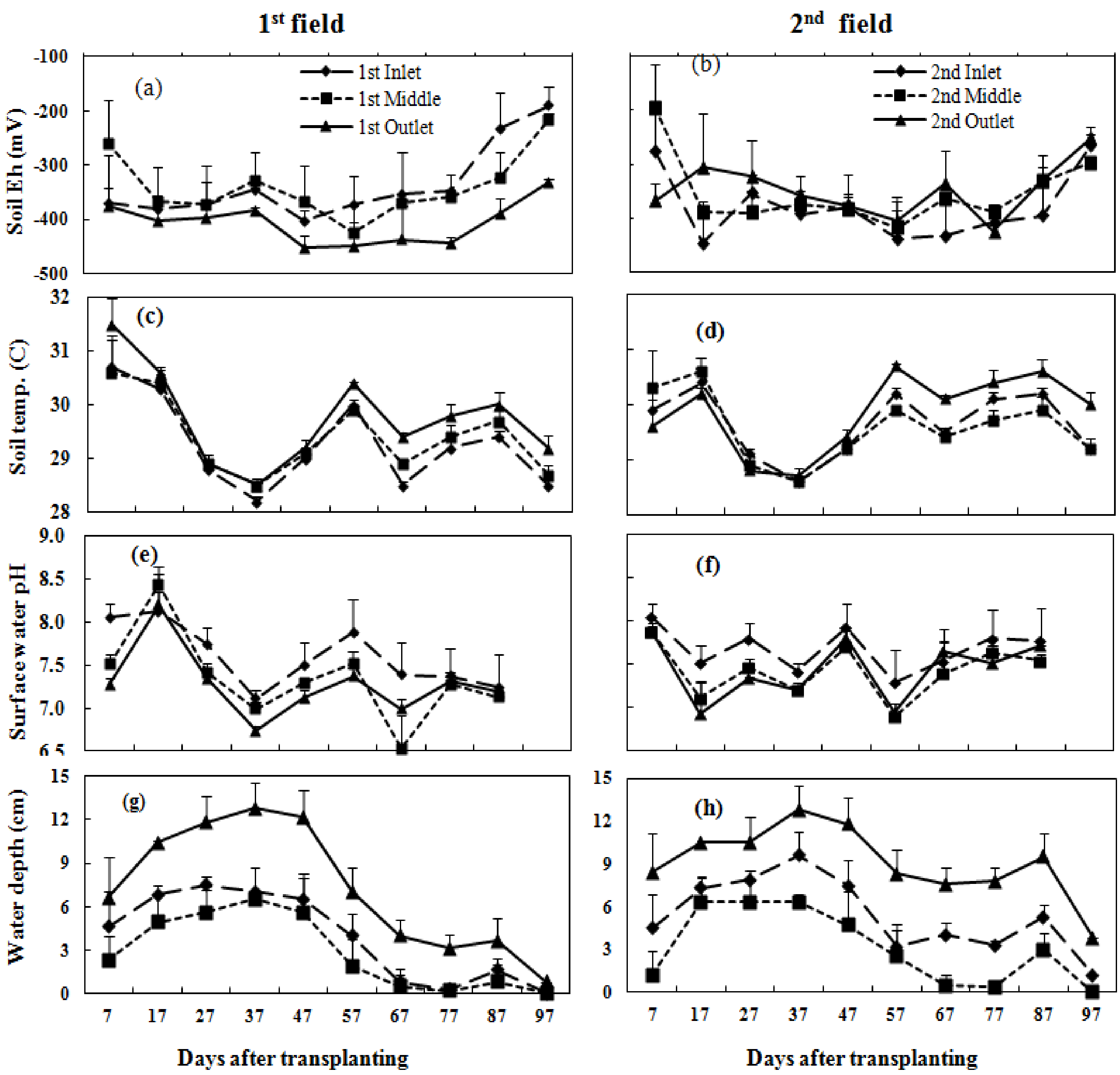
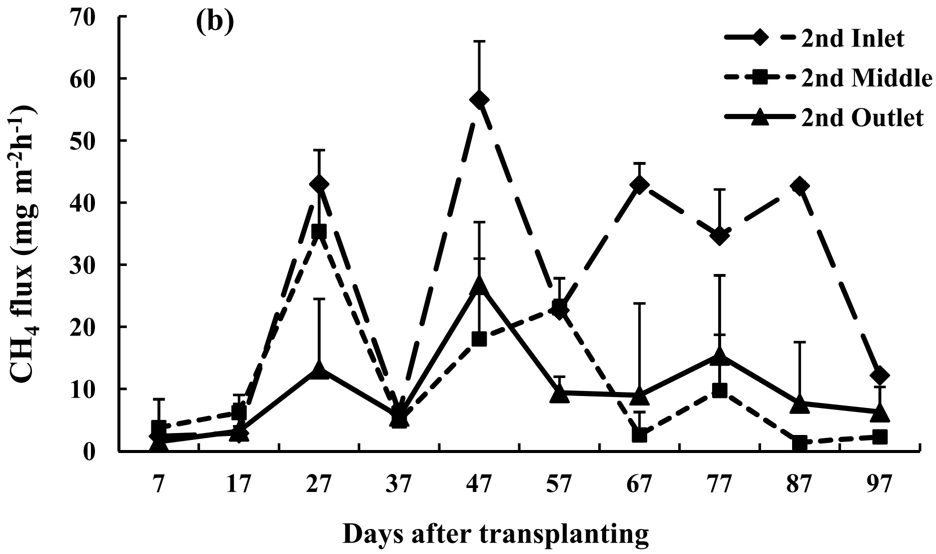


Fig 5.3 Seasonal changes in (a) & (b) soil Eh, (c) & (d) soil temperature, (e) & (f) surface water pH and (g) & (h) surface water depth among the positions of 1st and 2nd field, respectively, during rice growing seasons (Bars-standard deviation)



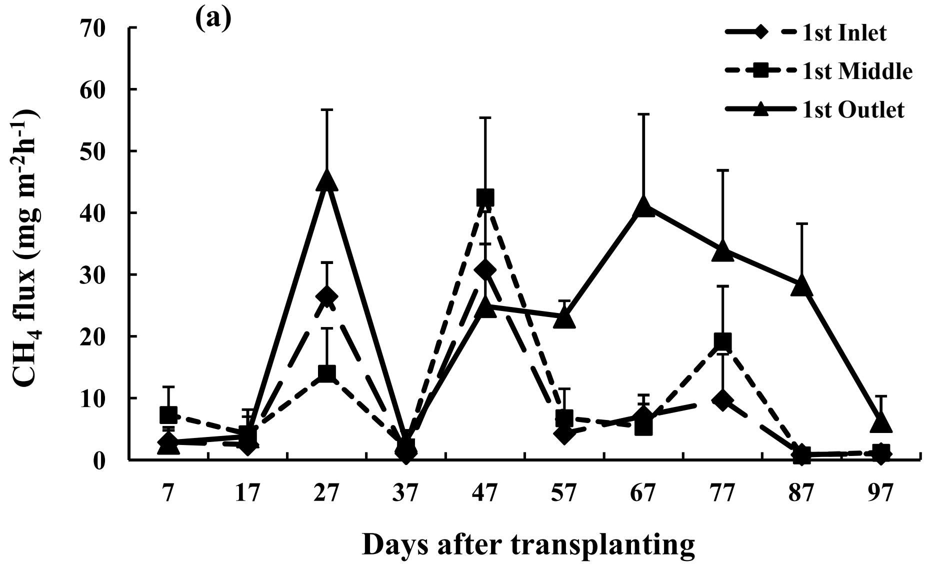


Fig 5.4 Seasonal changes in CH_4 emission flux among the positions within the (a) 1st field and (b) 2nd field of lowland rice during rice growing season (Bars- standard deviation)

Chapter 6

Eco-balance analysis of paddy rice production among the field positions in irrigated lowland rice ecosystems in Southeast Asia

6 Eco-balance analysis of paddy rice production among the field positions in irrigated lowland rice ecosystems in Southeast Asia

6.1 Introduction

The interest in the sustainability of agricultural and food systems can be traced to environmental concerns that began to appear in the 1950s–1960s (Rasul and Thapa, 2003). Concerning about sustainability centre on the need to develop agricultural technologies and practices are that: (i) do not have adverse effects on the environment (partly because the environment is an important asset for farming), (ii) are accessible to and effective for farmers, and (iii) lead to both improvements in food productivity and have positive side effects on environmental goods and services. Sustainability in agricultural systems incorporates concepts of both resilience (the capacity of systems to buffer shocks and stresses) and persistence (the capacity of systems to continue over long periods), and addresses many wider economic, social and environmental outcomes. For sustainability and sustainable development, the idea of the interconnectedness of natural and socioeconomic systems is fundamental.

The three basic features of sustainable agriculture are (i) maintenance of environmental quality, (ii) stable plant and animal productivity, and (iii) social acceptability. Consistent with this, Yunlong and Smith (1994) have also suggested that agricultural sustainability should be assessed from ecological soundness, social acceptability and economic viability perspectives. ''Ecological soundness'' refers to the preservation and improvement of the natural environment, ''economic viability'' to maintenance of yields and productivity of crops and livestock, and ''social acceptability'' to self-reliance, equality and improved quality of life.

Many social, economic and environmental aspects can occur from paddy rice production. Rice cultivation plays a significant portion in methane emission from paddy soil and cultivation of irrigated rice accounts for up to 12% of its efflux (IPCC, 2007). Methane produced from rice paddies accounts for up to 20% of global methane missions in the world (Thitakamol, 2008). The emission of methane from rice fields is dependent on many factors such as fertilizers, rice characteristics and soil environment (Mitra et al., 1999). The use of fertilizers increases pollution of the ecosystem; N_2O, a kind of greenhouse gas are generated from the rice field. The use of agricultural machines saves labor uses but enhance the use fossil fuels with the use of machines. Labor can allocate to other works and/or join other social activities under different farming systems. On the other hand, use of fossil fuel leads to emission of CO_2. An evaluation method is required that can provide decision criteria and insights into how environmental impacts and production can be balanced. Based on the consensus definition of "sustainable growth" (World Commission on Environment and Development 1987), analysis of production systems has been conducted to achieve the highest economic productivity with the least environmental loads and social acceptance.

There are some analysis methods namely ecological footprint and carbon footprint analysis. Ecological footprints only carbon dioxide emissions from energy are considered, other greenhouse gases which have a more damaging effect per unit volume and emissions from other sources are not taken into account. For carbon footprint, it only shows the amount of greenhouse gases and specifically carbon dioxide emitted by something (as a person's activities or a product's manufacture and transport) during a given period.

To compare the environmental load to the productivity to analyze the relationship between them, the eco-balance analysis method was proposed by Kimura and Hatano (2007). The analysis of the relation between production and environmental load has been defined as "eco-balance" (Kimura and Hatano 2007). The study by Kimura et al (2010) showed that using eco-balance analysis, incentives to choose land use combinations with lower environmental load can be created.

In this study, eco-balance analysis will be conducted to evaluate the relation between production, income and environmental load with different growing area. The objective of this study is to conduct a quantitative analysis of the relation of grain yield and greenhouse gas emission to the economic benefit of the different growing regions for rice production in Northwest Vietnam and Lowland area in Myanmar.

6.2 Materials and methods

Two field experiments were conducted in Chieng Khoi commune (350 masl, 21º 7′60″N, 105º40′0″E), Yen Chau district, Northwest Vietnam from February until November, 2011, during two rice cropping seasons and Dawmakwin Village, Kanyutkwin, Pago Division, Myanmar (18º48′43″ N, 96º43′57″ E) from June to November, 2012 during the monsoon rice growing season. Grain yield data were obtained from field experiment in both study sites. Methane gas fluxes were measured among the positions of paddy rice field in two countries by using close chamber method. (See for detail - Chapter 3 and 5).

Research Questionnaire

To get basic information of economic parameters such as total cost per unit area, price of rice and net income, etc., questionnaires were conducted with nine farmers in each study area. Questionnaire includes: 1) Cultivated area, 2) cropping system (crop rotation), 3) amount and type of organic and inorganic fertilizer applied, 4) cost for land preparation, seed, transplanting, fertilizer, weeding, pesticide and harvest, 5) grain yield, 6) grain price, 7) gross revenue and 8) return to home labor and land (net income), etc..

We calculated gross revenue and net income per ha with the following equations.

Total expense = seed cost+ land preparation + labor + fertilizer + pesticide + cost for irrigation

Gross revenue = Grain yield per ha x Unit price of rice grain

Net income = Gross revenue – Total expense

6.3 Results

6.3.1 Total cost and net income per unit area

Rice production in Northwest Vietnam was dominated by small, irrigated farm in lowland valley. The use of short cycle sticky rice variety and a reservoir and an open channel irrigation system allowed farmers to produce two cycle of rice per year.

In Northwest Vietnam, farmers owned land less than 0.5 ha per capital according to questionnaire results (Table 6.1). They practiced intensive rice farming system which is characterized by a short fallow period and the high use of inputs such as capital, labor, or heavy use of pesticides and chemical fertilizers relative to land area. High use of labor with intensive farming made the production cost high (93.5 USD ha^{-1}). Harvesting and threshing were major components of labor cost followed by transplanting cost those accounted approximately 25% of the total cost of cultivation. Pesticides and fertilizers were major component of material costs which accounted 40% to total cost of cultivation. Other inputs were irrigation, weeding and cost for seeds which accounted 13% of total cost of production. The highest net incomes were achieved in both middle positions followed by bottom fields of both fertilized and unfertilized parts in Northwest Vietnam (Table 6.3). Net income increase due to farmer practice of fertilization over non-fertilized parts largely depended on position of the fields. Top and middle positions in spring rice showed lower net income due to fertilization than that of non-fertilized parts. In summer rice, higher net incomes were observed by fertilization in top and middle positions than that of non-fertilized parts. The net income ranged from 272.5 to 733.7 USD ha^{-1} in unfertilized part and 346.7 to 685.9 USD ha^{-1} in fertilized part among the field positions (Table 6.3). Average net income for spring rice among the positions for non-fertilized part was 530 USD ha^{-1} which was higher than that for fertilized part; 494 USD ha^{-1}. But in summer rice, fertilized part showed higher net income; 489 USD ha^{-1} than that of non-fertilized part; 456 USD ha^{-1} in average of all positions. When compared two crop seasons, non-fertilized parts of spring rice showed higher net income than that of summer rice. The net incomes due to farmer practice of fertilization in both crop seasons showed no big differences in average of the positions.

In Myanmar site, farmers practiced traditional farming system by transplanting old seedlings and low inputs of chemical. With traditional farming system, it needed high labors for uprooting the old seedlings, transporting within the field and transplanting the seedlings (Table 6.2). Among the labor cost, transplanting and harvesting showed the highest followed by uprooting and threshing costs. The labor costs were the major components of rice production cost that accounted approximately 45% of total cost of rice production. Fertilizer was one of the major components of material costs which accounted 15% to total cost. Other inputs were land preparation and weeding, cost for seeds which accounted 30% of total cost of rice production. The highest net incomes were achieved in all positions in the 1st field for both fertilized and unfertilized parts in lowland, Myanmar (Table 6.4). The low net incomes were observed in all positions in the 1st field due to fertilization when compared with non-fertilized parts in the 1st field. But higher net incomes were observed in 2nd middle and 2nd outlet positions due to fertilization than that of non-fertilized parts. The net return ranged from 243.9 to 440.5 USD ha^{-1} in unfertilized part and 262.0 to 379.7 USD ha^{-1} in fertilized part among the field positions.

The two rice cultivation systems were compared in term of cost and net income of rice production. Seed cost per hectare was higher in Vietnam than that in Myanmar due to the use of sticky rice variety which cost 0.5 USD kg^{-1}. Land preparation cost was higher in Myanmar than Vietnam due to longer land preparation period (from mid-May to mid-July) since rice was grown as monsoon crop in rainy season. In Vietnam, farmer planted two crops per year and had only short period to prepare land with one plough and two harrow times before final puddling for transplanting. But in Myanmar, farmer ploughed two times in May and June and harrowing was followed after each ploughing. One week before transplanting in July, two times harrowing were done and followed by final puddling.

Since Vietnam`s farmer used a lot of fertilizers and pesticides, the material cost were much higher than that in Myanmar site. Harvesting and threshing costs are comparable between two experimental sites. In general, the cost of rice production per ha was higher in Vietnam cascade rice fields than that of Myanmar lowland rice production due to high input of agricultural chemicals. The net income was also higher in Vietnam due to higher yield and higher unit grain yield price than that of lowland, Myanmar.

6.3.2 Relationship between grain yield and net income of paddy rice production

In Northwest Vietnam site, the results showed that farmer practice of fertilization increased grain yield over non-fertilized parts in both spring and summer rice seasons (Fig 6.1). Lower grain yield and net income was observed in fertilized and non-fertilized parts of top positions and non-fertilized part of bottom field in both crop seasons. For these positions, the required yield to get high income was above 6000 kg ha^{-1}. Fertilized parts of bottom fields showed higher grain yield than that of unfertilized parts but average net income was observed in both rice seasons. High net income and grain yield was achieved in fertilized and non-fertilized parts of middle fields in both crop seasons. According to regression analysis, the net income was significantly related with grain yield with the equation of $y = 5.0x + 2639.5$ and $y = 5.0x + 3586.1$ for non-fertilized and fertilized parts, respectively, where y represent grain yield and x represent net income. To increase net income due to fertilization in all positions, the required yield increase over non-fertilized parts must be above 1050 kg ha^{-1} due to fertilization for both crop seasons.

In lowland Myanmar, application of mineral fertilizer increased grain yield over non-fertilized parts in both rice fields (Fig 6.2). The lower grain yields as well as low net incomes were observed in all positions in the 2nd field except fertilized part of 2nd inlet position. For these positions, the required yield to get high net income was above 5200 kg ha^{-1}. The indigenous nutrient status of soil in these positions showed lower than that of all positions in the 1st field. The lower total nitrogen content, organic matter and soil pH resulted in decreasing grain yield in all positions of the 2nd field. High grain yield and net income was observed in both fertilized and non-fertilized parts of all positions in the 1st field. According to linear regression analysis, the net income was significantly related with grain yield with the equation of y = 6.1x + 2607.4 and y = 6.1x + 3066.3 for non-fertilized and fertilized parts, respectively, where y represent grain yield and x represent net income. To increase net income due to fertilization in all positions, the required yield increase over non-fertilized parts must be above 485 kg ha^{-1} due to fertilization for both crop seasons.

When compared the two study sites, grain yield was higher in all positions except the top field in both crop seasons in Northwest Vietnam than that in Myanmar site. But yield differences among the positions were higher in cascade rice fields of Vietnam than that of lowland rice field of Myanmar. According to regressing analysis, the slope of cascade rice was 5.1 which showed lower than the slope value of 6.1 for relationship analysis in lowland Myanmar. Due to higher slope in Myanmar, net income was lower when compared with net income of cascade rice in Vietnam. The y intercept value was similar in non-fertilized parts for both study sites (2639.5 and 2607.4 in Vietnam and Myanmar, respectively). This meant that for both study sites the grain yield should be above 2600 kg ha^{-1} to get higher net income for non-fertilized parts. When we compared the fertilized parts of both study sites, y intercept value; 3586.1 for Vietnam was higher than the value; 3066.3 for Myanmar. This meant that to get higher net income due to fertilization in cascade rice, the yield must be higher than 3586 kg ha^{-1} while in lowland it needed 3066 kg ha^{-1} and above for higher net income. Net income differences among the positions were also higher in toposequence rice fields; the highest income 733.7 USD ha^{-1} in middle position and the lowest income 272.5 USD ha^{-1} in top position, while in lowland Myanmar, the higher net incomes were observed in all positions in the 1st field. In Vietnam site, fertilized and non-fertilized parts of middle positions showed higher grain yield as well as high net income while in Myanmar, all positions in fertilized and non-fertilized parts of the 1st field showed higher net income and grain yield. When compare two locations, net income from toposequence rice fields showed much higher than that of lowland rice field in Myanmar.

6.3.3 Relationship between methane emission and net income of paddy rice production

In Northwest Vietnam, non-fertilized part of top positions in both rice seasons showed lowed CH_4 emission flux with low net income (group A) (Fig 6.3). Although farmer practice of fertilization reduced CH_4 emission in top positions over non-fertilized parts, the net income was still lower than the average value in both crop seasons. Non-fertilized parts of bottom fields showed high emission flux with average net income for both rice seasons (group B). Fertilization reduced CH_4 flux to certain level but still higher than the average value in bottom position of spring rice. Fertilized part of bottom positions in summer rice showed very low CH_4 flux with average net income as it showed the outlier. For middle positions, non-fertilized parts showed high net income but average and high total emission flux for summer and sprig rice, respectively while in fertilized part; it significantly reduced CH_4 emission over non fertilized part with high net income in both crop seasons (group C).

In lowland Myanmar, low CH_4 emission flux and low net income was observed in both fertilized and non-fertilized parts of middle and outlet positions in the 2nd field (Group I) (Fig 6.4). High total CH_4 emission flux was observed in non-fertilized part of 1st outlet and 2nd inlet position while these showed high and average net income, respectively (Group II). Fertilization reduced CH_4 flux in these position but still higher than average value with average net income in 2nd inlet while the 1st outlet showed average CH_4 flux with high net income. Non-fertilized 1st inlet and 1st middle showed high net income with low flux (Group III). Fertilization reduced flux as well as net income in 1st inlet but increased CH_4 flux and reduced net income lower than average value.

The highest emission flux was observed in bottom field positions of cascade rice in Northwest Vietnam while in Myanmar, it was observed in 1st outlet and 2nd inlet positions of the fields. When compare CH_4 emission flux from two different locations, total CH_4 emission flux was relatively higher in lowland paddy rice of Myanmar than toposequence rice fields of Northwest Vietnam.

6.4 Discussion

6.4.1Relation between grain yield and net income

Intensive rice farming system in Northwest Vietnam characterized by double-cropping paddy rice per year and high use of inputs such as high amount of chemical fertilizers and pesticides led to high cost of paddy rice production in this area (Table 6.1). Traditional rice cultivation system in lowland area of Myanmar had less use of chemical fertilizers and no use of pesticides (Table 6.2) which led to a lower cost when compared with Northwest Vietnam`s intensive rice farming system. In terms of grain yield, higher yields were observed in cascade rice fields of Northwest Vietnam than that of lowland rice in Myanmar. Farmers in Northwest Vietnam owned less than 0.5 ha per capita of agricultural land that led to more and more intensive cropping system and pushed them to use more fertilizers and pesticides. Farmers in lowland area of Myanmar possessed more than 2 ha per capita and they practiced traditional farming system with low fertilizer input (less than 50 kg N ha^{-1}) and no use of pesticides (Table 6.2). Higher yield in Vietnam mainly attributed to the use of high yielding sticky rice variety and more chemical inputs per unit area than that of lowland rice in Myanmar that led to higher gross revenue in Northwest Vietnam than that of lowland, Myanmar.

Generally higher grain yield achieved higher net income in both study sites. The middle positions in Northwest Vietnam (Fig 6.1) and all positions in the 1st field in Myanmar site (Fig 6.2) were recommended positions to get high yield as well as high net income. For top positions in toposequence, the yield needed for high net income was above 5700 kg ha^{-1}. For this position, it is necessary to change management method such as alternate wetting and drying instead of continuous flooding and the use of organic fertilizer combining with mineral fertilizer to get higher net income. For all positions in the 2nd field of lowland Myanmar, the yield needed to get higher net income was above 5200 kg ha^{-1}. To get this yield in these positions, more fertilizer should be applied together with alternate wetting and drying method.

Due to higher grain yield in Northwest Vietnam, higher net income per unit area was achieved than that of lowland in Myanmar. The price of rice grain was 3 times higher in Vietnam than that from Myanmar site, since they growth sticky rice variety in their land which had a higher market price. High grain yields with high net incomes were achieved in positions with high native indigenous nutrient status of soils in both study sites (i.e middle positions in both rice cascades of Northwest Vietnam and all positions in the 1st field in Myanmar site). Net income increment due to farmer`s practice of fertilization was not consistent among the positions in toposequence rice fields in Northwest Vietnam, but the net income of farmer practice of fertilization was even lower that of non-fertilized parts in lowland Myanmar. To increase net income due to fertilization, less yield increase (above 485 kg ha^{-1}) was required over non-fertilized parts of lowland, Myanmar than that for Vietnam (above 1050 kg ha^{-1}) which might be due to high indeginous soil fertility in Vietnam site.

6.4.2Relationship between methane emission and net income

Besides that economic issues concerning spatial variability, the spatial variability of environmental aspect is of same importance. The purpose of this study was to compare net income and environmental load among the positions. For this purpose, the eco-balance analysis was used to compare different environmental loads with farm productivity (Kimura and Hatano 2007). The highest CH_4 emissions were observed in down-slope positions especially bottom fields of toposequence in Northewest Vietnam (Fig 6.3). The bottom fields of both cascades showed relatively low Eh than top field positions due to poor drained and water saturated or even flooded most of the time due to invasion by side leaching water and this was the reason that high CH_4 emission was observed in the bottom fields. Similar trend of CH_4 emission was also observed in lowland rice of Myanmar but only the end downslope position (1st outlet and 2nd inlet) of the 1st field. The 1st outlet and 2nd inlet positions showed high clay and TC content with low Eh which showed significant relationship with CH_4 emissions in lowland rice of Myanmar.

In Northwest Vietnam, both fertilized and non-fertilized top positions showed environmentally good with low emission flux but in term of net income, it showed lower than average income (group A) (Fig 6.3). Low emission was due to high content of sand and low TC content while low net income was due to low yield related to low indigenous nutrient status of top positions with high sand content. Similar result of low emission with low net incomes were observed in both fertilized and non-fertilized middle and outlet positions in the 2nd field of Myanmar due to low TC content and low indigenous nutrient status of soil in these positions (group I) (Fig 6.4). These positions should pay attention by changing management practices such as alternate wetting and drying, and or change in rice cultivation methods to increase net income while sustaining low CH_4 emission flux in these positions.

Fertilized and non-fertilized parts of bottom fields in Northwest Vietnam showed average net income with high emission flux due to highly reduced condition in rice soil except fertilized bottom of summer rice which showed low CH_4 flux (group B) (Fig 6.3). In lowland Myanmar, fertilized and non-fertilized parts of 2nd inlet of the 2nd field showed high flux with average income and non-fertilized part of 1st outlet showed high net income but high emission flux (group II) (Fig 6.4). These positions should pay attention both to reduce flux by practicing frequent drainage and to increase net income per unit area for sustainable production. In these positions, net income can still be increase by changing the management method such as frequent draining with decrease in input leads to higher redox potential of the soil and will reduce CH_4 emission and promote plant growth.

Non-fertilized middle positions in Northwest Vietnam (group C) (Fig 6.3) and 1st inlet and 1st middle positions in lowland Myanmar (group III) (Fig 6.4) showed low CH_4 emission with high net income in both crop seasons due to low redox status of soil with high nutrient status. Farmer practice of fertilizations in these positions of both study sites showed lower CH_4 emission but it could not improve net income and even lowered income than non-fertilized parts. These positions showed high indigenous nutrient status of soil, it is necessary to reduce the rate of fertilization up to 50% to achieve low emission with high net income due to low cost of fertilizer.

Generally, high net income with low environmental load was achieved in positions with high indigenous nutrient status of paddy soil. High indigenous nutrient favored better growth and yield while low redox status due to elevation and water depth in these positions favored low CH_4 emission. For sustainable rice production, i) application of N fertilizer as a site specific and change of management methods such as mid-season drainage and use of alternate wetting and drying irrigation system reduce CH_4 emission without lower grain yield from paddy rice field.

6.5 Conclusion

Higher cost of rice production was observed in Northwest Vietnam than Lowland Myanmar due to high use of inputs and intensive labor use. High grain yield was achieved in field positions with high indigenous nutrient status of soil in both study sites. Farmer practice of fertilization increased grain yield over non-fertilized parts but net income and CH_4 emission due to fertilization largely depend on the positions of the fields. High net income with low CH_4 emission flux was achieved in the positions with high native indigenous nutrient status of paddy rice soil. Fertilization in the positions with high indigenous nutrient status showed lower CH_4 emission but net income decreased due to higher cost of fertilizer. To increase net income in these positions, it is necessary to reduce the rate of fertilizer application in both study sites. To reduce environmental load and to increase net income, fertilization should be site or positions specific depending on native soil fertility status and frequent field drainage should be done especially lower lying positions in both study sites.

Table 6.1 Total expense calculation for spring and summer rice 2011 in Northwest Vietnam

	Rate (ha^{-1})	Unit price (USD)	Cost (USD/ ha)	
			Fertilized	Unfertilized
Seed	100 kg	0.5	50.0	50.0
Land preparation	4 times	13.1	52.5	52.5
Uprooting	2 labor/day	2.75	5.5	5.5
Transplanting	15 labor/day	4.0	60.0	60.0
Fertilizer cost				
Urea	300 kg	0.35	105	0.0
NPK	400 kg	0.2	80	0.0
Kali (Potassium)	50 kg	0.5	25	0.0
Weeding	7 labor/day	4.0	28.0	28.0
Pesticide	4 times	44.0	175.8	175.8
Irrigation	One season	34.8	34.8	34.8
Harvest (carrying, threshing etc.)	30 labor/ 2day	4.0	120.0	120.0
Total expense			736.6	527.9

Table 6.2 Total expense calculation for lowland rice 2012 in Kanyutkwin district, Myanmar

	Rate (ha^{-1})	Unit price (USD)	Cost (USD/ ha)	
			Fertilized	Unfertilized
Seed	90 kg	0.18	16.2	16.2
Land preparation	2 times	22.5	44.1	44.1
Harrowing and puddling	4 times	22.5	88.2	88.2
Seed bad preparation	2 times	5.85	11.7	11.7
Uprooting	15 labor/day	2.0	30.0	30.0
Transplanting	30	2.6	79.4	79.4
Fertilizer cost (NPK)	150 kg	0.52	77.6	0
Weeding	7 labor/day	2.1	14.7	14.7
Harvest	30 labor/2day	2.6	79.4	79.4
Threshing	10 labor/day	4.1	41.1	41.1
Others (unspecified)			35.2	35.2
Total expense			517.6	440.0

Table 6.3 Grain yield, expense and net income (USD) per hectare of paddy rice production in Northwest Vietnam

		Yield kg/ha		Gross revenue (USD/ ha)		Total expense (USD/ ha)		Net income (USD/ ha)	
		-F	**+F**	**-F**	**+F**	**-F**	**+F**	**-F**	**+F**
Spring	Top	4702	5342	940.4	1068.4	527.9	736.6	412.5	331.8
	Middle	6308	7009	1261.6	1401.8	527.9	736.6	733.7	665.2
	Bottom	4870.5	6120	974.1	1224	527.9	736.6	446.2	487.9
Summer	Top	4002.0	5313	800.4	1062.6	527.9	736.6	272.5	326.0
	Middle	5591.5	6925.5	1118.3	1385.1	527.9	736.6	590.4	648.5
	Bottom	5177	6153	1035.4	1230.6	527.9	736.6	507.5	494.0

Table 6.4 Grain yield, expense and net income (USD) per hectare of paddy rice production in lowland Myanmar

		Yield kg/ha		Gross revenue (USD/ ha)		Total expense (USD/ ha)		Net income (USD/ ha)	
		-F	**+F**	**-F**	**+F**	**-F**	**+F**	**-F**	**+F**
1st field	Inlet	5290.0	5360.3	864.5	876.4	440.0	517.6	424.5	358.8
	Middle	5060.3	5090.3	827.4	832.3	440.0	517.6	387.4	314.7
	Outlet	5300.3	5390.0	866.6	880.8	440.0	517.6	426.6	362.2
2nd field	Inlet	4750.2	5200.3	776.6	850.3	440.0	517.6	336.5	332.7
	Middle	4340.3	4910.0	709.7	802.4	440.0	517.6	269.7	284.8
	Outlet	4100.0	4670.0	670.0	763.2	440.0	517.6	230.0	245.6

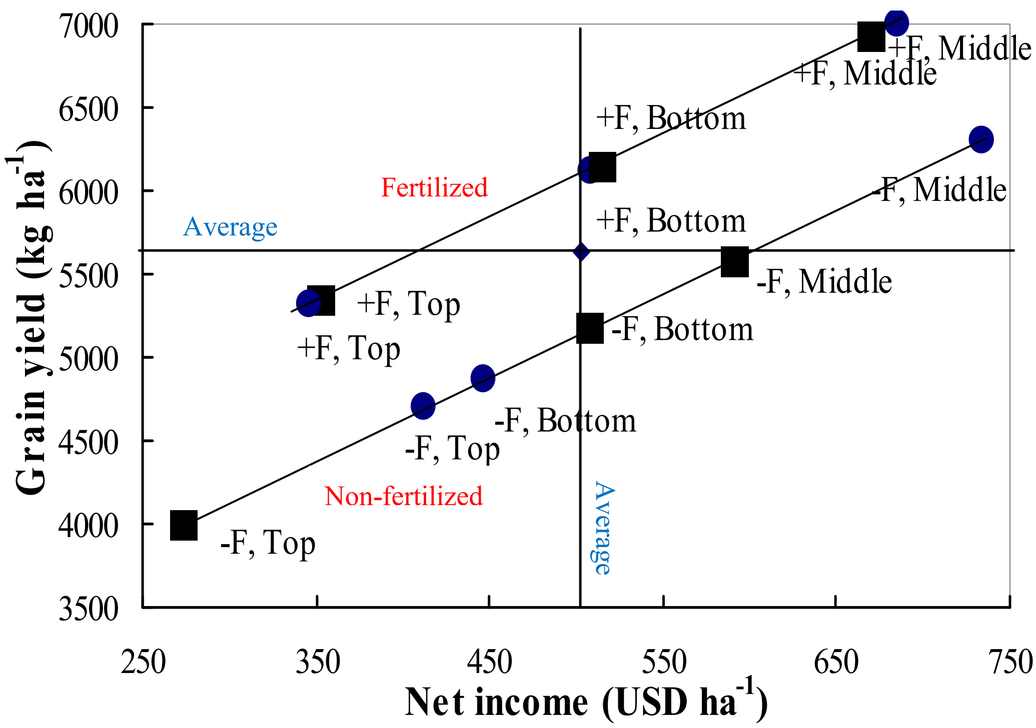


Fig 6.1 Relationship between grain yield and net income of spring and summer rice in Northwest Vietnam, ■ summer rice, ● spring rice

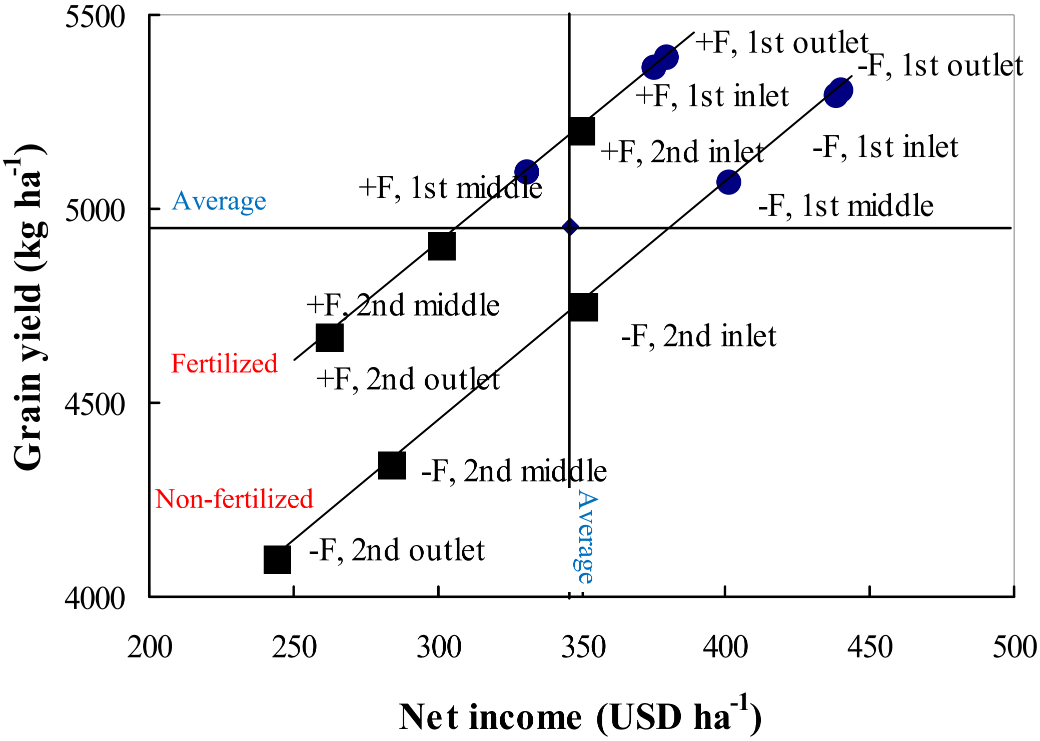


Fig 6.2 Relationship between grain yield and net income of monsoon rice in lowland area, Myanmar,

● 1st field, ■ 2nd field

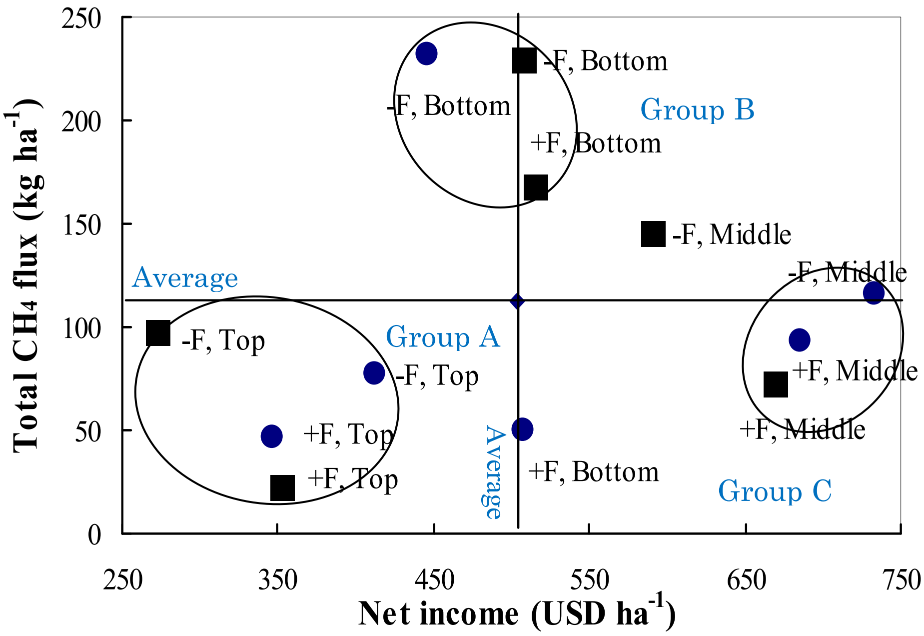


Fig 6.3 Relationship between methane flux and net income of spring and summer rice in Northwest Vietnam, ■ spring rice, ● summer rice

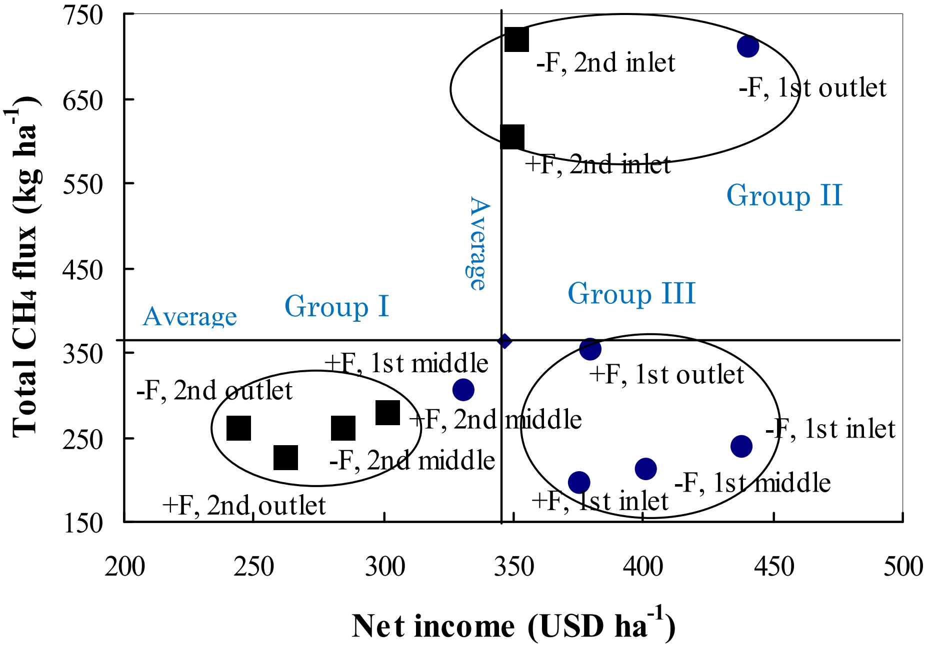


Fig 6.4 Relationship between methane flux and net income of monsoon rice in lowland area, Myanmar, ● 1st field, ■ 2nd field

Chapter 7

General Discussion

7 General discussion

7.1 Spatial variation in soil parameters and crop growth in Southeast Asia

Considering the spatial variability of soil properties is important to evaluate the plant production potential of that area, and to optimize profitability, sustainability and protection of the environment. The variations in soil characteristics must be monitored to sustain soil quality and enable agricultural production. The extent of soil spatial variability depends on the variations of soil forming factors and the management practices (McGraw 1994; Mulla & McBratney 2000). The spatial and temporal variability of important soil properties and plant biomass production are also useful developing effective sampling schemes for future site specific management (Mulla et al 1992). The characteristics of soil properties are considered to influence the yield and growth performance of rice (Ahn et al., 2005). Another study in Spain where factors such pH and TN gave the information needed for 54% of the rice yield variation (Nguyen Tuan Ahn et al., 2005). The spatial variations were also confirmed in our results.

In Vietnam site, the downward movement of finer nutrient rich soil materials along with irrigation and runoff water from upland were deposited to the lower lying fields of the rice cascades (Table 2.1). Beside internal runoff and soil deposition processes in rice paddies, the impact of external sediment contribution through erosion-sedimentation processes in upland-lowland areas is important to understand spatial variation in soil properties among the field positions (Schmitter et al. 2010). Due to shorter and scarcer fallow periods in upland with dominating continuous annul cropping systems in accessible upland areas, it induces severe erosion on steep slopes, with presumably negative on- and off-site impacts on soil fertility, related crop productivity and pollution of streams (Wenzel et al., 2002). The impact of external sediment contribution along with irrigation water in lowland rice field of Myanmar also influence the indigenous nutrient supply of irrigated rice paddy field. While small and moderate nutrient rich sediment deposition into downstream cultivated land might be beneficial, large sediment delivery could rapidly become a damaging incident, burying the original fertile soil under low quality sediment (Lantican et al., 2003). Wang & Shao (2011) demonstrated that the spatial distribution and spatial dependence of soil physical properties within a watershed were complex, and influenced by environmental factors as well as land use and topography. Schmitter (2011) showed that spatial variability in soil chemical properties was found within and between cascades indicating that the C and N fluxes provided by the irrigation water were not equally distributed.

Higher silt and clay contents were observed in lower lying fields than top field position of toposequence in Northwest Vietnam (Table 2.1). The increasing trend in clay content from top to bottom field along the toposequence was also observed by Eshett et al. (1989) in Nigeria and Posner and Crawford (1992) in Senegal and Boling et al. (2008) in Thailand and Indonesia. Similar trend of silt and clay content was observed in lowland Myanmar rice fields. Zhang et al. (2011) discussed that soil C/N ratio is a sensitive indicator of soil quality and for assessing the C and N nutrition balance of soils. King et al. (2009) demonstrated that irrigation water enriched with sediments and dissolved organic C resulted in a net increase in total C and N loads in irrigated fields. We studied soil C and N content in toposqeunce and lowland rice area. The results showed that increasing trend of C and N in toposequence rice field but in Myanmar, higher C and N were observed in positions near the irrigation channel. Due to irrigation water flow velocity and runoff water, there was uneven distribution of sediment throughout the rice fields in both study sites. Beside irrigation water, the redistribution of sediments through runoff within the landscape and its alterations on soil fertility was influenced on downstream crop production in rice cascade. Therefore, the impact of external sediments on rice production should be taken into account when assessing the environmental impact of land use in order to give land use planning and fertilizer recommendations.

The spatial variation in grain yield observed in both cascades showed a clear difference depending on the different positions within each season in Northwest Vietnam. The results of this research revealed that irrigation management is an important input factor when investigating C and N balance in paddy terraces as the sustainability of rice production systems is highly depending on the nutrient in-and output (Maruyama et al., 2008; 2010). In both rice cascades, the grain yield increased along the cascade with increasing distance from the irrigation channel, which resembled the distribution of soil particles, and TN and TC content within the cascade. Schmitter et al. (2011) stated that the increase in grain yield towards the bottom fields of toposequence was related to an increase in soil organic C and decrease in sand content in Chieng Khoi area. In lowland rice, positions in the fields and distance from the channel, which dominated the distribution of soil particles and soil fertility, was closely related with rice productivity. Variation in grain yield among the positions observed in this study showed a clear different, dependence on the distance from the irrigation channel. Different result was observed in Myanmar site that the positions near the channel showed better growth than the positions far away from channel. In the 1st field, the increase in grain yield in 1st inlet, 1st middle and 1st outlet positions which showed closer to channel resembled their high soil TN content, organic matter content and soil pH observed in the top soil.

When compared two locations, there were high range of spatial variations in soil parameters and plant growth in Northwest Vietnam than that in lowland Myanmar. The main reason might be due to elevation differences among the positions for two sites. In cascade rice of Vietnam, the elevation differences among the positions was up to 6 m while in lowland Myanmar, the differences showed only a few centimeters among the positions. Since cascade rice fields are interrelated with upland fields, nutrient rich runoff water entered into the lowland rice fields and deposited among the different field positions (Table 2.1). But in Myanmar site, only irrigation water enter into the lowland rice fields which carried substantial amount of C and N, deposited in the fields. Grain yield in cascade rice showed the highest in middle positions followed by bottom field and the top positions showed the lowest grain yield. While in Myanmar, higher grain yield was observed in positions near the irrigation channel. Variation in grain yield largely depended on physical and chemical properties of soil which were influenced by irrigation and runoff water (Schmitter et al. 2010, 2011). In both study sites, the external nutrient sources played important role due to significant different in soil properties among the positions deciding the soil fertility status among the positions. If experts have the knowledge about spatial variability of nutrients within the field they can give correct and precise site-specific recommendations for the application of fertilizer. Hence, for crop management it is also very important to point out and to document how the rice crop responds to this spatial variability.

7.2 Influence of positions on methane emission from paddy rice in Southeast Asia

In both study sites, there were high spatial variations in CH_4 emission among the positions. In

Northwest Vietnam, the observed high rates of CH_4 emission from middle and particularly bottom fields were associated with their higher TN, TC and clay content compared to the top fields (Chapter 3). The high rates of CH_4 emission was also observed in 1st outlet and 2nd inlet positions which were associated with their higher TC and clay content (Chapter 5) in lowland Myanmar. Variation in soil TN and TC among the position were one of the influencing factors for high spatial variation in CH_4 flux among the positions in both study sites since high TN and TC content in soil stimulated CH_4 production from paddy rice soil (Mitra et al. 2002). Kaewpradit et al. (2008) discussed that the addition of N and C through irrigation water is of high importance for sustainability of paddy rice fields. According to Gillabel et al. (2007) and King et al. (2009), organic C addition through irrigation water has to be taken into account when calculating C sequestration in irrigated agricultural systems. In our study, according to spearman correlation results, soil TC was significantly correlated with CH_4 emission in both study sites. The question whether irrigation enhances C sequestration or rather increases greenhouse gas emissions remains uncertain and is highly depending on climate, soil type, tillage practices, crop and irrigation management practices (Entry et al., 2002; Lal, 2004; Gillabel et al. 2007).

In lowland Myanmar, the seasonal average value of the CH_4 emission rate ranged from 8.5 to 28.9 mg CH_4 m^{-2} h^{-1}. This was higher than that of the different toposequence positions in the Yen Chau district of Northwest Vietnam, which ranged from 0.22 to 6.11 mg CH_4 m^{-2} h^{-1} during the spring rice season and from 0.13 to 20.1 mg CH_4 m^{-2} h^{-1} during the summer rice season. The rather low emission in Vietnam was due to the field positions, which were located in different cascade positions with good field drainage conditions in upper and middle parts, and occasionally water shortage due to lower rainfall and low soil temperature during the crop growing seasons. The fields in Myanmar were located in a lowland area with poor field drainage conditions under high rainfall and high temperature, which favored high CH_4 emission. Another influencing factor of high spatial variations in CH_4 emissions were soil redox status and soil temperature which were significantly correlated with CH_4 emission from paddy rice soil in both study sites. Xu and Hosen (2010) and Yang et al. (2010) also reported that CH_4 emission was negatively correlated with the redox status of the soil. Generally the positions with low redox status and high soil temperature showed high CH_4 emission. Since lowland rice fields in Myanmar showed higher soil temperature with low redox status than that in Vietnam cascade soil, CH_4 emission was higher in lowland rice soil than that in cascade rice soil.

Differences in CH_4 emissions between two locations were also shown by Zhang et al. (2009), who reported high spatial variability in CH_4 emissions from rice fields in the Taihu Lake region of China, and demonstrated higher annual CH_4 emissions on the plains compared to the hilly regions. Similar result was observed in our study. The range of cumulative CH_4 emissions in lowland, Myanmar; 21.2 to 71.1 g CH_4 m^{-2} (Table 5.3), was comparatively higher than for toposequence rice fields cultivating double-cropping paddy rice in Northwest Vietnam, which ranged from 7.4 g m^{-2} to 37.2 g CH_4 m^{-2} (Table 3.3). The higher emissions in lowland might be due to higher soil temperature, low Eh with higher TC content than those from cascade rice in Northwest Vietnam.

7.3 Influence of fertilizer on plant growth related methane emission

Several field scale studies have demonstrated that addition of N fertilizers increased CH_4

emissions in the rice soils (Banik et al., 1996; Dong et al. 2011; Shang et al, 2011). Dong et al. (2011) reported that CH_4 emissions have decreased by 38-49% with addition of ammonia-based non sulfate fertilizers (150-250 kg N ha^{-1}) in the rice soils. In this study, N fertilizers stimulated activities of methanotrophs that resulted in greater CH_4 oxidation in N fertilizer than control treatment in the rice soils (Bodelier et al., 2000a, b). Application of ammonia sulfate fertilizers has shown to decrease CH_4 emission by inhibiting the activities of methanogens in the rice soils (Schutz et al., 1989; Cai et al., 1997).

Our result showed that, significant inhibition of CH_4 fluxes with addition of urea and ammonium based sulfate-containing fertilizer was found in both spring and summer rice crop seasons in Vietnam, 2011 (Table 3.3) and lowland rice in Myanmar, 2012 (Table 5.3). This result was in agreement with Dong et al. (2011); Bodelier et al. 2000; Schutz et al. (1989) and Cai et al. (1997). A reasonable explanation for the observed results might be the application of ammonium-based sulfate-containing fertilizers, which are known to decrease CH_4 emission as a result of competition between sulfate-reducing bacteria and methanogens for hydrogen and acetate substrates (Hori et al., 1993). Sulfate containing in applied fertilizers acts as an electron acceptor under anaerobic conditions, which depresses CH_4 production through competition for electrons (Schutz et al. 1989; Scheid et al. 2003). Moreover, the product of sulfate reduction, H_2S, may poision methanogenic bacteria and further depress CH_4 production (Minami 1994).

Similar result of inhibition of CH_4 fluxes due to ammonium based sulfate containing fertilizer application was observed in lowland, Myanmar but it was spatial dependent and significantly related with micro-elevation of positions within the field (Table 5.3). In Vietnam, since the field size was small and no big differences in water table among the positions, the effect of fertilizer showed similar in all positions in cascade rice. We assumed that higher emission might be found, too in cascade rice, if low water table are there. In lowland rice Myanmar, positions with low micro-elevation showed reduction in CH_4 emission due to N fertilization. High micro-elevation positions showed increase in CH_4 emission due to fertilization (Table 5.3). A lower water depth is known to result in a higher loss of N as ammonia volatilization, and ammonia is lost at a faster rate from shallow water than deep flood water due to the higher ammonium N concentrations and higher temperatures (Freney et al., 1988). Another reason for the observed results might involve stimulation of methanogens by N fertilization (Banik et al., 1996; Shang et al., 2011). Micro-elevation in positions within the field on CH_4 emissions in paddy rice soils much be taken into account for evaluation of CH_4 emission.

7.4 Eco-balance analysis of paddy rice production

Eco-balance analysis of paddy rice production for both study sites was conducted to understand the relationship between rice production, net income and CH_4 emission among the positions of paddy rice soil. Higher cost of rice production was observed in Northwest Vietnam when compared with lowland, Myanmar. To reduce the cost in Northwest Vietnam, site specific adjusted fertilizer applications are necessary. Moreover farmer in Vietnam used frequent spraying of pesticides without checking whether it should be done or not because they wanted to be sure for high rice productivity. Higher grain yield in Northwest Vietnam mainly attributed to the use of high yielding sticky rice variety and more chemical inputs per unit area than that of lowland rice in Myanmar. High grain yield and net income were observed in middle positions of cascade rice, Northwest Vietnam and all positions in the 1st field of lowland rice, Myanmar. To increase yield and net income for other positions in both study sites, site specific adjusted fertilizer application should be practiced together with alternate wetting and drying instead of continuous flooding the whole crop season.

For both study sites, the relationship between CH_4 emissions and net incomes showed three group (Fig 6.1 and 6.2). The first group; low emission and low income were observed in top positions in cascade rice and middle and outlet positions in 2nd field of lowland rice. The second group; high emission and average income were observed in bottom positions in cascade rice and 1st outlet and 2nd inlet positions of lowland rice. These positions should pay attention by changing management practices such as site specific adjusted fertilizer application together with alternate wetting and drying, and or change in rice cultivation methods to increase net income while sustaining low CH_4 emission flux in these positions. The third group; low emission and high income were observed in middle positions in cascade rice and 1st inlet and 1st middle positions in lowland rice. To increase fertilizer use efficiency and net income due to fertilization in these positions, it is necessary to reduce the rate of fertilization to achieve low with high net income due to low cost of fertilizer.

Summary

Summary

Understanding the spatial variations in soil parameters, plant growth and methane (CH_4) emission is essential for site specific management recommendation to increase grain yield, net income and mitigate CH_4 emission from paddy rice in Southeast Asia. For this purpose, two field experiments were conducted; (I) in Northwest Vietnam (2011) and (II) in Pago Division, Myanmar (2012).

Research objective for experiment (I) was to access the spatial differences in soil properties, crop yield and CH_4 emission at cascade level affected by either sediment induced or farmers' fertility practice. The research was conducted in Cheing Khoi watershed area during spring and summer seasons with two different cascades. The cascades had fertilized and non-fertilized parts and all the measurements were conducted at the top, middle and bottom field of each part. Research objective for experiment II was to assess the spatial variations in soil properties and crop yield among the positions within the field. The research was conducted in lowland Myanmar. For this purpose, two successive rice fields were divided into fertilized and non-fertilized parts and all measurements were conducted at inlet, middle and outlet positions for both fields.

In experiment (I), there were high spatial variations in soil properties among the field positions in both rice cascades. The lower lying field positions showed higher total N and C content than that of top field position in both cascades. The positions near the irrigation channel showed high sand content and low indigenous nutrient status than that of lower lying field positions. Different result was observed in experiment (II) that high indigenous nutrient status was observed in the positions closer to the irrigation channel. Decreasing trend of TN and TC content was observed from irrigation channel towards the farthest positions.

Due to high indigenous nutrient status of lower lying field positions in experiment (I), plant growth and yield component parameters showed better performance in these positions in both rice cascades. High grain yield was observed in middle positions followed by bottom field in both crop seasons. Farmer practice of fertilization increased grain yield over non-fertilized parts but the degrees of increase largely depended on indigenous nutrient status of soil among the positions. In experiment (II), plant growth and grain yield were higher in all positions near to irrigation channel. Farmer practice of fertilization showed higher grain yield than non-fertilized parts and a significant increase was observed in all positions in the 2nd field.

Spatio-temporal variation in CH_4 emission among the positions was also observed in both study sites. In experiment (I), the result showed that there were high spatial variations in CH_4 emission among the field positions in both crop seasons. The bottom fields showed highest emission than that of other positions in both crop seasons might be due to relatively low Eh, poor drained and water saturated or even flooded most of the time due to invasion by side leaching water. Cumulative CH_4 emissions for spring rice were

lower than that of summer rice. The higher values for summer crops were due to incorporation of fresh crop residues from spring rice into the soil just after harvesting of spring rice, providing a large addition of organic materials under higher temperature (30-35°C) condition. Farmer fertilizer practice inhibited the rate of CH_4 emission when compared with non-fertilized part. In experiment (II), there were high spatial-temporal variation in CH_4 emission among the positions which was influenced by Eh, surface water pH, soil temperature, surface water depth, and TC content of soil. The CH_4 flux of the outlet of the 1st field and inlet of the 2nd field were 2 to 2.5 times higher than that of other field positions. Significant inhibition of CH_4 fluxes with addition of ammonium sulfate-containing fertilizer was found for the inlet and outlet of both fields. However, an increase in CH_4 emission due to fertilization occurred in the middle positions of both fields. The higher emission in fertilized parts might be related to micro-elevation in the middle of the field, which led to a high loss of N as ammonia volatilization due to a shallow water depth.

Eco-balance analysis was conducted in both study sites to understand the relationship between grain yield interns of net income to environmental load from paddy rice production. In experiment (I), middle fields had high yield and showed same net income for no fertilizer as well as fertilized field at bottom position while in the bottom fields, had high CH_4 emission and average income. High net income with low CH_4 emission flux was observed in fertilized middle and bottom fields. In experiment II, High grain yields and net income were observed in all positions in the 1st field and fertilized part of 2nd inlet position. There were high CH_4 emissions in 1st outlet and 2nd inlet positions, while it showed moderate net income. High net income with low CH_4 emissions was observed in all position in the 1st field.

It can be concluded that (i) Soil fertility status, crop yield and CH_4 emission largely depends on positions and related with sediment transport and deposition among the positions, (ii) farmer practice of fertilization increased grain yield among the positions but the yield increase largely depend on the position and indigenous nutrient status of soil, (iii) fertilizer management practices reduced CH_4 emission in Vietnam, but it was spatial dependent in Myanmar site, (iv) high grain yields and net incomes with low CH_4 emission fluxes were observed in positions with high indigenous nutrient in soil and (v) the result of comparison between two sites showed that high grain yield and net income in Vietnam site while high CH_4 emission in Myanmar site. As recommendation, to increase grain yield and net income for both study sites, fertilization should be site specific depending on native soil fertility status of soil and frequent draining should be done for sustainable rice production.

References

References

ADB (Asian Development Bank). 2009. The economics of climate change in Southeast Asia: a regional review. Manila

Adhya, T.K., Rath, A.K., Gupta, P.K., Rao, V.R., Das, S.N., Parida, K.M., Parashar, D.C., Sethunathan, N., 1994. Methane emission from flooded rice fields under irrigated conditions. Biology and Fertility of Soils 18, 245-248.

Ahmad, S., Li, C., Dai, G., Zhan, M., Wang, J., Pan, S., Cao, C., 2009. Greenhouse gas emission from direct seeding paddy field under different rice tillage systems in central China. Soil and Tillage Research 106, 54-61.

Ahn, N.T., Shin, J.C., Lee, BW., 2005. Analysis of within field spatial variation of rice growth and yield in relation to soil properties. Korean Journal of Crop Science 50(4):221-237.

Aulakh, M.S., Wassmann, R., Bueno, C., Rennenberg, H., 2001. Impact of root exudates of different cultivars and plant development stages of rice (*Oryza sativa* L.) on methane production in a paddy soil. Plant and Soil 230, 77-86.

Babu, M.S.U and Puttaiah, E.T., 2013. Greenhouse gas emissions from agriculture sector and potential for carbon sequestration in Tungabhadra river basin, India. International Journal of Basic and Applied Science (2): 38-47.

Banger, K., Tian, H., Lu, C., 2012. Do nitrogen fertilizers stimulate or inhibit methane emissions from rice fields? Global Change Biology doi: 10.1111/j.1365-2486.2012.02762.x.

Banik, A., Sen, M., Sen, S.P., 1996. Effects of inorganic fertilizers and micronutrients on CH_4 production from wetland rice (*Oryza sativa* L). Biology and Fertility of Soils 21, 391-322.

Behera, A.K. 1998. Response of scented rice (*Oryza sativa*) to nitrogen under transplanted condition; Indian Journal of Agronomy 43(1): 64-67

van den Bergh, J.C.J.M., and Verbruggen, H., 1999. Spatial sustainability, trade and indicators: an evaluation of the 'ecological footprint'. Ecological Economics 29: 61-72.

Bodelier, P.L.E., Hahn, A.P., Arth, I.R., Frenzel, P., 2000a. Effects of ammonium-based fertilization on microbial processes involved in methane emissions from soils planted with rice. Biogeochemistry 51, 225-257.

Bodelier, P.L.E., Hahn, A.P., Arth, I.R., Frenzel, P., 2000b. Effects of ammonium-based fertilization on microbial processes involved in CH_4 emission from soils planted with rice. Biogeochemistry 51, 225-257.

Bodelier, P.L.E., Roslev, P., Henckel, T., Frenzel, P., 2000. Stimulation by ammonium-based fertilizers of CH_4 oxidations in soil around rice roots. Nature 403, 439-443.

Bodelier, P.L.E., Roslev, P., Henckel, T., Frenzel, P., 2000b. Stimulation by ammonium-based fertilizers of methane oxidation in soil around rice roots. Nature 403, 421-424.

Boling, A.A., Tuong, T.P., Suganda, H., Konboon, Y., Harnpichitvitaya, D., Bouman, B.A.M., Franco, D.T., 2008. The effect of toposequence position on soil properties, hydrology, and yield of rainfed lowland rice in Southeast Asia. Field Crop Research 106: 22-33.

Bouman, B.A.M and Tuong, T.P., 2001. Field water management to save water and increase its productivity in irrigated lowland rice. Agricultural Water Management 49 (1): 11-30.

Broadbent FE (1979). Mineralization of organic nitrogen in paddy soils. In: Nitrogen and Rice, International Rice Research Institute, Los Banos, Philippines 10(5):118.

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 and Soil 196, 7-14.

Cai, Z., Shan, Y., Xu, H., 2007. MINI-REVIEW: Effects of nitrogen fertilization on CH_4 emission from rice fields. Soil Science and Plant Nutrition 53, 353-361. Doi:10.1111/j.1747-0765.2007.00153.x.

Cai, Z.C., Tsuruta, H., Minami, K., 2000. Methane emission from rice fields in China: Measurements and influencing factors. Journal of Geophysical Research 105(D13), 17,231–17,242.

Casanova, D., Goudriaan, J., Catala Forner, M.M., and Withagen, J.C.M., 2002. Rice yield prediction from yield components and limiting factors. European Journal of Agronomy 17:41-61.

Cassman KG, Gines HC, Dizon M, Samson MI, Alcantara JM. 1996. Nitrogen-use efficiency in tropical lowland rice systems: contributions from indigenous and applied nitrogen. Field Crops Research 47:1-2.

Cassman KG, Peng S, Olk DC, Ladha JK, Reichardt W, Dobermann A, Singh U. 1998. Opportunities for increased nitrogen use efficiency from improved resource management in irrigated rice systems. Field Crops Res. 56:7-38.

Channabasavanna, A.S. and Setty, R.A. 1994. Response of broadcast rice (*Oryza sativa*) to level of nitrogen, phosphorus and potassium and time of N application; Indian Journal of Agronomy 39(3): 457-459

Chen, Y.H. and Prinn, R.G. 2006. Estimation of atmospheric methane emissions between 1996 and 2001 using a three-dimensional global chemical transport model. Journal of Geophysical Research 111, D10307, 1-25.

Chikere CB, Omoni VT and Chikere BO (2008). Distribution of potential nosocomial pathogens in a hospital environment. African Journal of Biotechnology 7: 3535-3539.

Dang, V.Q., Schreinemachers, P., Berger, T., Vui, D.K. and Hieu, D.T., 2008. Agricultural statistics of two subcatchments in Yen Chau district, Son La province, Vietnam 2007, The Upland Program SFB 564

Das, K., Baruah, K.K., 2008. A comparison of growth and photosynthetic characteristics of two improved rice cultivars on CH_4 emission from rain-fed agro-ecosystem of Northeast India. Agriculture, Ecosystem and Environment 124, 105-113.

Dercon, G., Deckers, J., Poese, J., Govers, G., Sanchez, H., Ramirez, M., Vanegas, R., Tacuri, E. and Loaiza, G., 2006. Spatial variability in crop response under contour hedgerow systems in the Andres region of

Ecuador. Soil and Tillage Research 86(1):15-26.

Dobermann A, Dawe D, Roetter RP, Cassman KG., 2000. Reversal of rice yield decline in a long-term continuous cropping experiment. Agronomy Journal 92:633-643.

Dong, H.B., Yao, Z.S., Zheng, X.H., 2011. Effect of ammonium-based, non-sulfate fertilizers on CH_4 emissions from a paddy field with a typical Chinese water management regime. Atmospheric Environment 45, 1095-1101.

Dung, N.V., Vien, T.D., Lam, N.T., Tuong, T.M., Cadish, G., 2008. Analysis of the sustainability within the composite swidden agroecosystem in Northern Vietnam. 1. Partial nutrient balance and recovery times of upland fields. Agriculture Ecosystem and Environment 128(1-2): 37-51.

Eshett, E.T., Omueti, J.A.I., Juo, A.S.R., 1989. Soil properties and mineralogy in relation to land use on a sedimentary toposequence in South-Eastern Nigeria. Journal of Agricultural Science 112: 377-386.

FAO, 2010. Selected indicators of food and agricultural development in the Asia-Pacific region, 1999-2009. RAP publication.

FAO, undated. Available at (http://www.fao.org/docrep/017/i3084e/i3084e18.pdf)

FAOSTAT. 2012. (available at: www.faostat.fao.org/)

Fageria, N.K., Slaton, N.A., Baligar, V.C. and Donald, L.S., 2003. Nutrient management for improving lowland rice productivity and sustainability, Advances in Agronomy. Academic Press, pp. 63-152

Freney, J.R., Trevitt, A.C.F., Muirhead, W.A., Denmead, O.T., Simpson, J. R., Obcemea, W.N., 1988. Effect of water depth on ammonia loss from lowland rice. Fertility Research 16, 97-107.

Gao, P., Pasternack, G.B., Bali, K.M., Wallender, W.W., 2007. Suspended-sediment transport in an intensively cultivated watershed in Southeastern California. Catena. 69(3): 239-252.

Gee, G.W., Bauder, J.W., 1986. Particle-size Analysis. In: A. Klute (Editor), Methods of Soil Analysis. Part 1. 2nd ed. Agronomy 9, 383-399.

General Statistics Office of Vietnam, 2008. http://www.gso.gov.vn

General Statistics Office of Vietnam, 2010.http://www.gso.gov.vn.

Gogoi, N., Baruah, K., Gogoi, B., Gupta, P.K., 2008. Methane emission from two different rice ecosystems (Ahu and Sali) at lower Brahmaputra valley zone of North East India. Apply Ecology and Environmental Research 6(3), 99-112.

Gon, H.A.D.V., Bodegom, P.M.V., Wassmann, R., Lantin, R.S., Metra-Corton, T.M., 2001. Sulfate-containing amendments to reduce CH_4 emissions from rice fields: Mechanisms, effectiveness and costs. Mitigation and Adaptation Strategies for Global Change 6, 71-89.

van der Gon, H., Kropff, M.J., van Breemen, N. et al., 2002. Optimizing grain yields reduces CH_4 emissions from rice paddy fields. Proceedings of the National Academy of Sciences of the United States of America, 99, 12021–12024.

Goto, E., Y. Miyamori, S. Hasegawa and O. Inatus. 2004. Reduction effects of accelerating rice straw decomposition and water management on methane emission for paddy fields in a cold district. Japanese Journal of Soil Science and Plant Nutrition 75:191-201 (in Japanese with English abstract).

Hadi, A., Inubushi, K., Yagi, K., 2010. Effect of water management on greenhouse gas emissions and microbial properties of paddy soils in Japan and Indonesia. Paddy Water Environ. 8, 319-324.

Haefele, S.M. and Konboon, Y., 2009. Nutrient management for rainfed lowland rice in northeast Thailand. Field Crops Research 114(3): 374-385.

Haefele, S.M. and Wopereis, M.C.S., 2005. Spatial variability of indigenous supplies for N, P and K and its impact on fertilizer strategies for irrigated rice in West Africa. Plant ad Soil 270(1): 57-72.

Hatcho, N., Ochi, S. and Matsuno, Y., 2010. The evolution of irrigation development in monsoon Asia and historical lessons. Irrigation and Drainage 59(1):4-16

Holzapfel, P.A., Conrad R Seiler, W., 1986. Effects of vegetation on the emission of methane from submerged paddy soil. Plant Soil 92, 223-233.

Holzapfel-Pschorn, A., Seiler, W., 1986. Methane emissions during a cultivation period from an Italian rice paddy. Journal of Geophysical Research 91, 11803–11814.

Homma, K., Horie, T., Shiraiwa, T., Supapoj, N., Matsumoto, N., Kabaki, N., 2003. Toposequential variation in soil fertility and rice productivity of rainfed lowland paddy fields in mini-watershed (Nong) in Northeast Thailand. Plant Prod. Sci. 6: 147-153.

Hori, K., Inubushi, K., Matsusmoto, S., Wada, H., 1990. Competition for acetic acid between CH_4 formation and sulfate reduction in paddy soil. Japanese Journal of Soil Science and Plant Nutrition 61, 572-578.

Hori, K., Inubushi, K., Matusmoto, S., Wada, H., 1993. Competition for hydrogen between CH_4 formation and sulfate reduction in paddy soil. Japanese Journal of Soil Science and Plant Nutrition 64, 363-367.

Hseu, Z.Y., Chen, Z.S., 2001. Quantifying soil hydromorphology of a rice-growing ultisol toposequence in Taiwan. Soil Science Society of American Journal 65: 270-278.

Huang, Y., Wang, H., Huang, H., Feng, Z.W., Yang, Z.H., Luo, Y.C., 2005. Characteristics of CH_4 emission from wetland rice-duck complex ecosystem. Agriculture, Ecosystem and Environment 105, 181–193.

Husson, O., Hanhart, K., Phung, M. T. and Bouma, J. 2000. Water management for rice cultivation on acid sulphate soils in the Plain of Reeds, Vietnam. Agricultural Water management 46, 91-109.

Husson, O., Verburg, P. H., Phung, M. T. and Van Mensvoort, M. E. F. 2000. Spatial variability of acid sulphate soils in the Plain of Reeds, Mekong Delta, Vietnam. Geoderma 97, 1-19.

IPCC: Summary for Policymakers. In: Climate Change, 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, N.Y., USA.

IRRI . 2006. Bringing hope, improving lives: Strategic Plan 2007–2015. Manila .61 p.

IRRI. 2008. World rice statistics.

Inubushi, K., Cheng, W.G., Aonuma, S. et al., 2003. Effects of free-air CO_2 enrichment (FACE) on CH_4

emission from a rice paddy field. Global Change Biol. 9, 1458–1464.

Jacobson, M.Z., 2005. Atmospheric Pollution; History, Science and Regulation. Cambridge University Press, New York.

Jean, L.M., 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.

Kanno, T., Miura, Y., Tsuruta, H. and Minami, K., 1997. Methane emission from rice paddy fields in all of Japanese prefecture. Nutrient Cycling in Agroecosystems 49: 147-151.

Kaushik, D., Baruah, K.K., 2008. A comparison of growth and photosynthetic characteristics of two improved rice cultivars on methane emission from rainfed agroecosystem of northeast India. Agriculture Ecosystem and Environment 124:105-113.

Khalil, M.A.K., Shearer, M.J., Rasmussen, R.A., Xu, L., Liu, J.L., 2008. Methane and nitrous oxide emissions from subtropical rice agriculture in China. Journal of Geophysical Research 113, G00A05, doi:10.1029/2007JG000462.

Kimura SD, Mu Z, Toma Y and Hatano R (2010) Eco-balance analysis of land use combinations to minimize environmental impacts and maximize farm income in northern Japan. Sustain Sci. 5, 19-27

Kimura, M., 1992. Methane emission from paddy soils in Japan and Thailand. In: Batjes, N.H., Bridges, E.M. (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 mid-summer drainage: pot experiment. Environmental Science 4, 265-271.

Kimura, S.D. and Hatano, R., 2007: An eco-balance approach to the evaluation of historical changes in nitrogen loads at a regional scale. Agricultural Systems 94, 165–176

King, A.P., Evatt, K.J., Six, J., Poch, R.M., Rolston, D.E., Hopmans, J.W., 2009. Annual carbon and nitrogen loadings for a furrow-irrigated field. Agricultural Water Management 96: 925-930.

Kumar, K. and Rao, K.V.P. 1992. Nitrogen and phosphorous requirements of upland rice in Manipur. Oryza; 29:306-309

Kyuma, K., 2004. Paddy soil science. University Press, Trans Pacific Press, Kyoto.

Lam, N.T., Patanothai, A., Limpinuntana, V., Vityakon, P., 2005. Land-use sustainability of composite swiddening in the uplands of Northern Vietnam: nutrient balances of swidden fields during the cropping period and changes of soil nutrients over the swidden cycle. International Journal of Agricultural Sustainability 3 (1): 1-12.

Lennartz, B., Horn, R., Duttmann, R., Gerke, H.H., Tippkötter, R., Eickhorst, T., Janssen, I., Janssen, M., Rüth, B., Sander, T., Shi, X., Sumfleth, K., Taubner, H., Zhang, B., 2009. Ecological safe management of terraced rice paddy landscapes. Soil and Tillage Research 102 (2), 179–192.

Lenzen, M., and Murray, S., 2003. The Ecological Footprint – Issues and Trends. ISA Research paper 01-03, University of Sydney.

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 and Tillage Research 113, 77-81.

Lin, K., Xiang, Y., Jiang, D., Hu, Q., Li, Z., Du, D., Tao, Z., 2000. Methane emission flux from paddy fields and its control in Hubei (in Chinese). Agro-environmental Protection 19, 257–270.

Liou, R.M., Huang, S.N., Lin, C.W., 2003. Methane emission from fields with differences in nitrogen fertilizers and rice varieties in Taiwan paddy soils. Chemosphere 50, 237-246.

Liu, X., Zhao, K., Xu, J., Zhang, M., Si, B. and Wang, F., 2008. Spatial variability of soil organic matter and nutrients in paddy fields at various scales in southeast China. Environmental Geology, 53(5): 1139-1147.

Lu, Y., Wassmann, R., Neue, H.U., Huang, C., 1999. Impact of phosphorus supply on root exudation, aerenchyma formation and CH_4 emission of rice plants. Biogeochemistry 47, 203-218.

Machado, S., Bynum, E.D., Archer, T.L., Lascano, R.J., et al., 2000. Spatial and temporal variability of corn grain yield: Site specific relationships of biotic and abiotic factors. Precision Agriculture 2: 359-376.

Manzanilla, D.O., Paris, T.R., Vergara, G.V., Ismail, A.M., Pandey, S., Labios, R.V., Tatlonghari, G.T., Acda, R.D., Chi, T.T.N/. Duoangsila, K., Siliphouthone, I., Manikmas, M.O.A. & Mackill, D.J., 2011. Submergence risks and farmers' preferences: Implications for breeding Sub1 rice in Southeast Asia. Agricultural Systems, 104: 335–347

Maruyama, T., Hashimoto, I., Murashima, K. and Takimoto, H., 2008. Evaluation of N and P mass balance in paddy rice culture along Kahokugata Lake, Japan, to assess potential lake pollution. Paddy and Water Environment 6(4):355-362.

Matsuda, M., 2009. Dynamic of rice production development in Myanmar: Growth Centers, Technological Changes, and Driving Forces. Tropical Agricultural and Development 53(1): 14-27, 2009

Matsumoto, J., Minamiyama, Y., Akahori, S. and Takahashi, K., 2002. Suppression of methane emission from paddy field supplemented with organic matter. Japanese Journal of Soil Science and Plant Nutrition 73:315-318 (in Japanese with English abstract)

Minami, K., 1994. Methane from rice production. Fertilizer Research 37, 167-179.

Minami, K., Neue, H.U., 1994. Rice paddies as a CH_4 source. Climate Change 27, 13-26.

Minamikawa, K., Sakai, N., Yagi, K., 2006. Methane emission from paddy fields and its mitigation options on a field scale. Microbes Environment 21(3), 135-147.

Mingzhou, Q., Jackson, R.H., Zhongjin, Y., Jackon, M.W., Bo, S., 2007. The effects of sediment-laden waters on irrigated lands along the lower Yellow River in China. Journal of Environmental Management 85(4): 858-865.

Miraza Hasanuzaman, K.U., Ahamed, N.M., Rahmatullah, N., Akhter, K.N., and Rahman, M.L., 2010. Plant growth characters and productivity of wetland rice (*Oryza sativa* L.) as affected by application of different manures. Emirates Journal of Food and Agriculture, 22(1): 46-58.

Mitra, S., Aulakh, M.S., Wassmann, R., Olk, D.C., 2005. Triggering of methane production in rice soils by root exudates: effects of soil properties and crop management. Soil Science Society of American Journal 69, 563-570.

Mitra, S., Jain, M.C., Kumar, S., Bandyopadhyay, S.K. and Kalra, N., 1999. Effect of rice cultivars on methane emission. Agriculture, Ecosystems & Environment 73, 177– 83

Mitra, S., Wassmann, R., Jain, M.C., Pathak, H., 2002. Properties of rice soils affecting CH_4 production potential: 1. Temporal patterns and diagnostic procedures. Nutrient Cycling in Agroecosystems 64, 169-182.

Mochizuki, A., Homma, K., Horie, T., Shiraiwa, T., Watatsu, E., Supapoj, N., Thongthai, C., 2006. Increased productivity of rainfed lowland rice by incorporation of pond sediments in Northeast Thailand. Field Crop Research 96: 422-427.

Moormann, F.R., Veldkamp, W.J., Ballaux, J.C., 1977. The growth of rice on a toposequence- a methodology. Plant and Soil 48(3): 565-580.

Moritsuka N., Yanai J., Umeda M., Kosaki T., 2004. Spatial relationships among different forms of soil nutrients in a paddy field, Soil Science and Plant Nutrition, 50:4, 565-573

Mulla, D.J., Mc Bratney, A.B., 2000. Soil Spatial Variability. In: M E Sumner (Ed.), *Handbook of Soil Science*. CRC Press, Boca Raton

Mulla, D.J., Bhatti, A.U., Hammond, M.W. & Benson, J.A., 1992. A comparison of winter wheat yield and quality under uniform versus spatially variable fertilizer management. Agriculture, *Ecosystems & Environment* 38: 301-311

Mulugeta Seyoum, 2000. Utake and respone of rice (*Oryza sativa* L.) to nitrogen and phosphorus fertilization under rain fed lowland condition of the Fogera Plain of Ethiopia; Indian Journal of Fertilizer; 1(1): 47-51.

Murayama, N., 1979. The importance of nitrogen for rice production. In: Nitrogen and Rice. International Rice Research Institute, Los Banos, Philippines p. 5-23.

Mutert, E. & Fairhurst, T.H., 2002. Developments in rice production in Southeast Asia. Better Crops International, 15

Neue, H.U. and R.L. Sass., 1994. The budget of methane from rice fields. IGACtivities Newsletter 12: 3–11.

Okamoto I., 2004. Agricultural Marketing Reform and Rural Economy in Myanmar: The Successful Side of Reform; Paper presented at the Parallel Session II, "Reform in Agriculture-Country experiences from Asia", GDN the 5th Conference, 28th, January 2004, New Delhi, India;

Okamoto, I., 2001. Marketing liberalization of agricultural products and development of marketing system in rural area: A case study on green gram production area in Myanmar. Monthly Journal of the Institute of Developing Economic (Azia keizai) 42: 2-36.

Oo, A.Z., Kimura, S.D., Win, K.T., Huu, N.X., Nguyen, L., Cadisch, G., 2012. Effect of toposequence position on soil properties and crop yield of paddy rice in Northern Mountainous Region, Vietnam. Journal of Integrated Field Science, 9: 59-65.

Oo, A.Z., Nguyen, L., Win, K.T., Cadisch, G., Bellingrath-Kimura, S.D., 2013. Toposequential variation in methane emissions from double-cropping paddy rice in Northwest Vietnam. Geoderma 209-210, 41-49.

Overview of rice in Southeast Asia, 2004. "Asian Farmers Fight for Survival and Control of the Rice Industry". AFA and AsiaDHRRA Issue Paper. Vol. 1 No. 1. December 2004.

Palis, R.K., Aye Swe and Kyaw Shinn, 1989. Comparative performance of one work animal, a team of two work animals and an 8.5 HP power tiller in preparation of lowland rice field, Myanmar. Journal of Agricultural Science, Vol. 1, No. 2, pp. 79-84.

Pansak, W., Hilger, T.H., Dercon, G., Kongkaew, T., Cadisch, G., 2008. Changes in the relationship between soil erosion and N loss pathways after establishing soil conservation systems in uplands of Northeast Thailand. Agriculture Ecosystem and Environment 128: 167–176.

Poch, R.M., Hopmans. J.W., Six, J.W., Rolston, D.E., Mclntyre, J.L., 2006. Considerations of a field-scale soil carbon budget for furrow irrigation. Agriculture Ecosystem and Environment 113(1-4): 391-398.

Posner, J.L., Crawford, E.W., 1992. Improving fertilizer recommendations for subsistence farmers in West Africa: the use of agro-economic analysis of on-farm trials. Fertility Research 32: 333-342.

Prakongkep, N., Suddhiprakarn, A., Kheoruenromne, I., Smirk, M. and Gilkes, R.J., 2008. The geochemistry of Thai paddy soils. Geoderma, 144 (1-2): 310-324.

Rambo, A.T., 1998. The composite swiddening agroecosystem of the Tay Ethnic Minority of the Northwestern Mountains of Vietnam. In: Land Degradation and Agricultural Sustainability: Case Studies from Southeast and East Asia, ed. by A. Patanothai. KhonKaen, Thailand: Regional Secretariat, the Southeast Asian Universities Agroecosystem Network.

Rasul, G., Thapa, G.B., 2003. Sustainability analysis of ecological and conventional agricultural systems in Bangladesh. World Development 31(10): 1721-1741

Reiner, W., Milkha, S.A., 2000. The role of rice plants in regulating mechanisms of methane missions. Biology and Fertility of Soils 31, 20-29. doi:10.1007/s003740050619

Rüth, B., Lennartz, B., 2008. Spatial variability of soil properties and rice yield along two catenas in Southeast China. Pedosphere 18: 409-420.

Salahuddin, K.M., Chowhdury, S.H., Munira, S., Islam, M.M., Parvin, S., 2009. Response of nitrogen and plant spacing of transplanted aman rice. Bangladesh. Journal of Agricultural Research 34(2): 279-285.

Sass, R.L., Fisher Jr., F.M., Andrews, J.A., 2002. Spatial variability in CH_4 emissions from a Texas rice field with some general implications. Global Biogeochemical Cycles 16(1), 1015, doi:10.1029/ 2000GB001355.

Sass, R.L., Fisher, F.M., Harcombe, P.A. and Turner, F.T. 1990. Methane production and emission in a Texas rice field. Global Biogeochemical Cycles (4): 47-68.

Sass, R.L., Fisher, F.M., Turner, F.T., Jund, M.F., 1991. Methane emission from rice fields as influenced by solar radiation, temperature, and straw incorporation. Global Biogeochemical Cycles 5, 335–350.

Schimel, J., 2000. Global change: rice, microbes and methane. Nature 403, 375-377.

Schmitter, P (2011). Carbon and nitrogen redistribution across the landscape and its influence on paddy rice production in Northwest Vietnam. Ph.D thesis.

Schmitter P, Dercon G, Hilger T, Thi Le Ha T, HuuThanh N, Lam N, DucVien T, Cadisch G (2010). Sediment induced soil spatial variation in paddy fields of Northwest Vietnam. Geodama 155: 298-307.

Schmitter P, Dercon G, Hilger T, Hertel M, Treffner J, Lam N, Duc Vien T, Cadisch G (2011). Linking spatio-temporal variation of crop response with sediment deposition along paddy rice terraces. Agriculture Ecosystems and Environment 140: 34-45.

Schmitter, P., Frohlich, H. L., Dercon, G., Hilger, T., Huu Thanh, N., Lam, N. T., Vien, T. D., Cadisch, G., 2012. Redistribution of carbon and nitrogen through irrigation in intensively cultivated tropical mountainous watersheds. Biogeochemistry 109, 133-150.

Schmitter, P., Frohlich, H.L., Dercon, G., Hilger, T., Huu Thanh, N., Lam, N.T., Vien, T.D., Cadisch, G., 2012. Redistribution of carbon and nitrogen through irrigation in intensively cultivated tropical mountainous watersheds. Biogeochemistry 109, 133–150

Schultz, M.K., Biegalski, S.R., Inn, K.G.W., Yu, L., Burnett, W.C., Thomas, J.L.W., Smith, G.E., 1999. Optimizing the removal of carbon phases in soils and sediments for sequential chemical extractions by coulometer. Journal of Environmental Monitoring 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 CH_4 emission rates from an Italian rice paddy, Journal of Geophysical Research 194, 16405–16416.

Schütz, H., Seiler, W., Conrod, R., 1990. Influence of soil temperature on methane emission from rice paddy fields. Biogeochemistry 11: 77-95.

Shang, Q.Y., Yang, X.X., Gao, C.M., 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 Biology 17, 2196-2210.

Shoji K., Kawamura T., Horio, H., 2005. Variability of micro-elevation, yield, and protein content within a transplanted paddy field. Precision Agriculture, 6, 73–86, 2005

Siavoshi M., Nasiri A., Laware S. L., 2011. Effect of organic fertilizer on growth and yield components in rice (Oryza sativa L.). Journal of Agricultural Science. 3(3): 217-224

Singh R., van Dam, J.C. and Feddes, R.A., 2006. Water productivity analysis of irrigated crops in Sirsa district, India. Agricultural Water Management, 82(3): 253-278.

Singh, S., Kashyap, A.K., Singh, J.S., 1998. Methane flux in relation to growth and phenology of a high yielding rice variety as affected by fertilization. Plant and soil 201, 157-164.

Suryavanshi, P., Singh, Y.V., Prasanna, R., Bhatia, A., Shivay, Y.S., 2012. Pattern of methane emission and water productivity under different methods of rice crop establishment. Paddy Water Environment DOI 10.1007/s10333-012-0323-5.

Tachibana, T., Nguyen, T.M. and Otsuka, K., 2001. Agricultural intensification versus extensification: A case study of deforestation in the Northern-hill region of Vietnam. Journal of Environmental Economics and Management, 41(1): 44-69.

Thakur, R.B. 1993. Performance of summer rice (*Oryza sativa*) to varying levels of nitrogen; Indian Journal of Agronomy 38(2): 187-190.

Thitakamol, T., 2008, Influence of Distillery Slop on Methane Emission in Rice Paddies. Environment Asia 1(1), 46-50.

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 (CO_2) enrichment and soil warming experiments. Plant Soil DOI:10.10007/s11104-012-1356-7.

Trolldenier, G., 1995. Methanogenesis during rice growth as related to the water regime between crop seasons, Biology and Fertility of Soils 19, 84-86.

Tsubo, M., Basnayake, J., Fukai, S., Sihathep, V., Siyavong, P., Sipaseuth, Chanphengsay, M., 2006. Toposequential effects on water balance and productivity in rainfed lowland rice ecosystem in Southern Laos. Field Crops Research 97, 209-220

Tsubo, M., Fukai, S., Basnayake, J., To, P.T., Bouman, B., Harnpichitvitaya, D., 2007. Effects of soil clay content on water balance and productivity in rainfed lowland rice ecosystem in Northeast Thailand. Plant Production Science 10 (2): 232-241.

UNESCO (United Nations Educational, Scientific and Cultural Organization)., 1974. FAO/UNESCO Soil map of the world, 1:5,000,000 Vol. 1 Paris: UNESCO.

Vieira, S., Dechen, S., Gonzalez, A.P., 2010. Effect of long term no tillage on the spatial variability of soybean and maize in São Paulo, Brazil. World Congress of Soil Science, Soil Solutions for a Changing World. Published on DVD.

Vien, T.D., 2003. Culture, environment and farming systems in Vietnam`s northern mountainous region. Southeast Asian Studies, 41(2):180-205

Wackernagel M., and Rees W. 1996. Our Ecological footprint: Reducing Human Impact on the Earth, New Society Publishers, Gabriola island, B.C., Canada

Wackernagel, M, and Yount, J.D., 1998. The Ecological Footprint: An Indicator of Progress towards Regional Sustainability. Environmental Monitoring and Assessment 51:511-529.

Wackernagel, M., Schulz, N.B., Deumling, D., Linares, A.C., Jenkins, M., Kapos, V., Monfreda, C., Loh, J., yers, N., Norgaard, R. and Randers, J., 2002. Tracking the ecological overshoot of the human economy.

Proceedings of the National Academy of Science 99, 9266-9271.

Wang, B., Neue, H.U., Samonte, H.P., 1999. Factors controlling dial patterns of methane emission via rice, Nutrient Cycling in Agroecosystems 53: 219-225.

Wang, M.X., Li, J., 2002. CH_4 emission and oxidation in Chinese rice paddies. Nutrient Cycling in Agroecosystems 64, 43-55.

Wassmann, R., Shangguan, X., Tőlg, M., Cheng, D., Wang, M., Papen, H., Rennenberg, H., Seiler, W., 1996. Spatial and seasonal distribution of organic amendments affecting methane emission from Chinese rice fields. Biology and Fertility of Soils 22, 191–195.

Wassmann, R., Wang, M.X., Shangguan, X.J., Xie, X.L., Shen, R.X., Wang, Y.S., Papen, H., Rennenberg, H., Seiler, W., 1993b. First records of a field experiment on fertilizer effects on methane emission from rice fields in Hunan-Province, (PR China). Geophysical Research Letter 20, 2071–2074.

Wendroth, O., Reuter, H. I., Kersebaum, K.C., 2003. Predicting yield of barley across a landscape: A state-space modeling approach. Journal of Hydrology 272: 250-263

Wezel, A., Steinmuller, N. and Friederichsen, J.R., 2002. Slope position effects on soil fertility and crop productivity and implications for soil conservation in upland northwest Vietnam. Agriculture, Ecosystems & Environment, 91(1-3):113-126

Wopereis MCS, Donovan C, Nebie B, Guindo D, N`Diaye MK. 1999. Soil fertility management in irrigated rice systems in the Sahel and Savanna regions of West Africa. I. Agronomic analysis. Field Crops Research 61:125-145

World Commission on Environment and Development, 1987. Our common future. Oxford University Press, Oxford; New York, pp 1–400

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 CH_4 emission from rice fields: multi-site field observations. Plant Soil 326, 393-401.

Xiong. Z.Q., Xing. G.X., Zhu, Z.L., 2007. Nitrous oxide and methane emissions as affected by water, soil and nitrogen. Pedosphere 17(2), 146-155.

Xu, H., Cai, Z., Jia, Z., 2002. Effect of soil water contents in the non-rice growth season on CH_4 emission during the following rice-growing period. Nutrient Cycling in Agroecosystems 64, 101-110.

Xu, H., Hosen, Y., 2010. Effect of soil water content and rice straw incorporation in the fallow season on CH_4 emissions during fallow and the following rice-cropping seasons. Plant and Soil 335,373-383.

Xu, Z., Zheng, X., Wang, Y., Han, S., Huang, Y., Zhu, J., Butterbach-Bahl, K., 2004. Effects of elevated CO_2 and N fertilization on CH_4 emission from paddy rice fields. Global Biogeochemical Cycles 18:GB3009. doi:10.1029/ 20044GB002233.

Yagi, K., Minami, K., 1990. Effects of organic matter application on CH_4 emission from some Japanese paddy fields. Soil Science and Plant Nutrition 36:599-610.

Yagi, K., Minami, K., Breitenbeck, G.A., Takayama, H., 1990. Emission and production of CH_4 from paddy fields. In: Transactions 14th International Congress of Soil Science, Kyoto II: 238-243.

Yagi, K., Tsuruta, H., Minami, K., 1997. Possible options for mitigating methane emissions from rice cultivation. Nutrient Cycling in Agroecosystems 49: 213-220.

Yamagishi, J., Nakamoto, T., Richner, W., 2003. Stability of spatial variability of wheat and maize biomass in a small field managed under two contrasting tillage systems over 3 years. Field Crops Research 81: 95-109.

Yamauchi, M., 1992. Growth of rice plants in soils of toposequence in Nigeria. Japanese Journal of Tropical Agriculture 36: 94-98.

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, S.S. and Chang, H.L. 1997. Effect of fertilizer application on methane emission/production in the paddy soils of Taiwan. Biology and Fertility of Soils 25:245-251.

Yang, S.S., Chang, H.L., 2001. Methane emission from paddy fields in Taiwan. Biology and Fertility of Soils 33, 157-165.

Yang, X., Shang, Q., 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. Agriculture, Ecosystems and Environment 137, 308-316.

Yunlong, C., & Smith, B., 1994. Sustainability in agriculture: a general review. Agriculture, Ecosystems & Environment, 49, 299–307.

Zhang, C.H., Wang, Z.M., Ju, W.M., Ren, C.Y., 2011. Spatial and temporal variability of soil C/N ration in Songnen Plain Maize Belt. Environmental Science, 32(5): 1407-1414

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 CO_2 enrichment on methane emissions from paddy rice fields. Global Change Biol. 12: 1717-1732

Zou, J., Huang, Y., Jiang, J., Zheng, X., Sass, R.L., 2005. A 3 year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effect of water regime, crop residue, and fertilizer application. Global Biogeochemical Cycles 19:GB2021.