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Effect of Controlled Water Level on CH_4 and N_2O Emissions from Rice Fields in Indonesia

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Abstract Several options to reduce methane (CH_4) emission from rice fields have been reported including straw management, soil amended with $Fe(OH)_3$ and iron slag, encapsulated calcium carbide, and water management by drainage-flooding. In the present paper, field experiments were conducted to determine whether controlled water level below 3 cm and 6 cm might affect CH_4 and nitrous oxide (N_2O) emissions compared to local rice farmer practice (water level mostly above 6 cm but basically uncontrolled) in Maros area, South Sulawesi, Indonesia. CH_4 and N_2O fluxes were measured at one-week intervals throughout two cropping seasons using a closed chamber method. Grain yield was determined at the end of cultivation. The results showed that CH_4 emission in the 1st cultivation was reduced by 36.5% and 33.8% in the plots with 3 cm and 6 cm water levels, respectively, whereas, in the 2nd cultivation, it was reduced by 63.6% and 44.6%, compared to farmer practice plots. N_2O emission from paddy fields was not detected and tended to decrease in both cropping seasons. We concluded that controlled water level lower than that in farmer practice could significantly reduce CH_4 emission without affecting rice grain yield and N_2O emission.

Key words: CH_4 and N_2O emissions, Controlled water level, Indonesia, Rice field

Introduction

Global atmospheric concentrations of methane (CH_4) and nitrous oxide (N_2O) have increased due to natural and biological processes and also to anthropogenic activities. CH_4 concentration in the atmosphere has increased since the early 90s from about 1732 ppb to 1774 ppb in 2005, and that concentration has increased up to 40% since pre-industrial times, while global atmospheric concentration of N_2O has increased since pre-industrial times from about 270 ppb to 319 ppb in 2005 (IPCC, 2007).

CH_4 which is an important component of the global carbon cycle, contributes to enhanced greenhouse effect as well as N_2O (IPCC, 2007). Paddy cultivation is considered to be one of the main human related sources of CH_4, and it has been predicted that CH_4 emission from this cultivation will increase as production has increased by 65% since the end the 1990s from 460 Mt yr^{-1} to 760 Mt yr^{-1} in 2020 (Neue, 1997). CH_4 emission from paddy cultivation contributes to about 20 to 150 Tg CH_4 yr^{-1} to the global budget (Crutzen, 1995). Fumoto *et al.* (2008) also reported that the larger variation in the magnitude of CH_4 emission from that source could be attributed to soil properties (pH, redox potential, organic matter content, temperature, and clay) or agronomic conditions (rice cultivars and farming practices).

The magnitude of CH_4 emission from rice fields reflects the balance between methanogenesis and methanotrophy. CH_4 production is the final process in the anoxic microbial degradation pathway in paddy field soil, while, methane oxidation occurs at the anaerobic-aerobic interface with available oxygen (O_2) and CH_4 concentration. The amount of CH_4 actually emitted depends on both the production and oxidation of CH_4. Therefore, basic knowledge on the underlying processes is required when designing strategies to mitigate and control CH_4 emission from rice fields (Arth *et al.,* 1998; Bodegom *et al.,* 2001).

CH_4 is produced by a microbial community consisting of various fermenting microorganisms that degrade organic matter, and ultimately leading to the production of acetate, H_2 and CO_2. Most of the actual production of CH_4 is brought about by methanogenic archaea, which either convert acetate to CH_4 and CO_2 (acetoclastic methanogenesis) or convert H_2 plus CO_2 to CH_4 (hydrogenotrophic methanogenesis) (Conrad and Klose, 2006; Sakai *et al.,* 2008). Any CH_4 mitigation option used in paddy cultivation must sustain crop production. Several

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mitigation options have been reported and found to be capable of reducing CH_4 emission from paddy fields, including the use of nitrification and urease inhibitor, encapsulated calcium carbide and selected SO_4^{2-} compounds (Malla *et al.,* 2005), soil amended with Fe $(OH)_3$ and iron slag (Watanabe and Kimura, 1999; Furukawa and Inubushi, 2004), selected rice cultivars (Husin *et al.,* 1995; Bahl *et al.,* 1997), and water management by drainage-flooding (Sass *et al.,* 1992; Yagi *et al.,* 1996; Kreye *et al.,* 2007). However, these mitigations are sometimes not applicable in practice by local farmers because of some economic reasons (cost or labor), restriction of water supply (irrigated or rainfed) fields and effect on yield (Wassman *et al.,* 2000; Yagi *et al.,* 1997).

Mitigation strategies should only be developed if the source strength of a rice field is reliably identified and discriminated based on rice ecology, production systems and should be acceptable at the farm level. Hence, further studies to evaluate the mitigation options should focus on feasibility for local farmers, since climatic conditions and type of paddy field or cultivation practices differ among sites. Therefore, the option being should be selected according to the local or site conditions (Neue, 1997; Yagi *et al.,* 1997; Jumadi *et al.,* 2008; Hadi *et al.*, 2010).

The experimental rice field station in Maros area, south Sulawesi, Indonesia includes some part of intensive paddy cultivation area with an irrigation system that covers around 3500 hectares, where the water is supplied into the field by regulated-rotation irrigation implemented by the Irrigation Bureau of Maros local government. In this area, the conventional water management practice consists of avoiding drainage of the field except at the time fertilizer application and harvest, and of keeping the field continuously flooded or submerged in a range above 6 cm level as common practice of paddy cultivation. Hence, the mitigation options by intermittent or midseason drainage may not be suitable and it may be difficult to implement them in this area.

There are also constraints association with water demand in the surrounding area for drinking water and industry, which increases year by year, suggesting, that water use for paddy production system in this area is likely to decrease. Alternately, reducing the amount of water for field submerge below the level of farmer practice may save water and increase water productivity. However, this option should not exert any adverse effect on rice yield, and should be a potential strategy for reducing CH_4 emission without trade-off of another greenhouse gas, namely increase of N_2O emission.

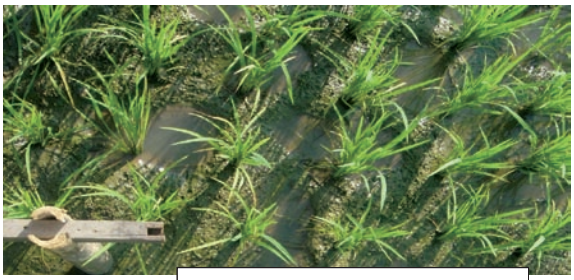
Field studies have been conducted to evaluate the reduction of CH_4 emission from a submerged rice field below the water level adopted in farmer practice and the effect on N_2O emission and rice yield in the tropics, particularly in Indonesia's rice fields. In the present paper, we proposed an option to suppress CH_4 and N_2O emissions by decreasing the water level of rice field in the farmer practices that would be suitable in Maros, Indonesia.

Materials and Methods

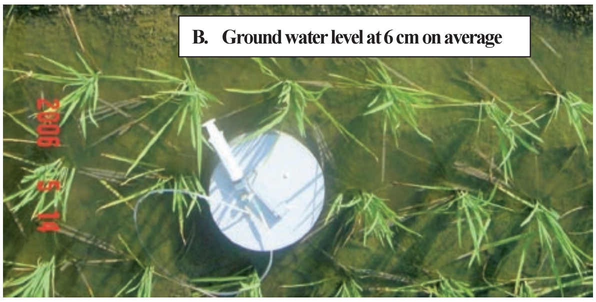
Field experiment, soil analysis and grain yield

The field experiment site was located in the Maros district, South Sulawesi province, Indonesia (5m asl.,05° 00.419' S 119° 31.219' E). The field experiment was conducted in a rice-growing area (6513 ha) irrigated by a dam in Bantimurung Maros. The average amount of rainfall was about 2464 mm and the mean monthly air temperature ranged from 21.5 to 35.2°C. In this area, rice is commonly grown twice a year, in the wet season (November to March) and dry season (April to August). The present studies were conducted in both seasons of rice cultivation in 2006-2007.

The experiments included three treatments namely daily highest water levels of 3 and 6 cm, and farmer practice (water level, mostly above 6 cm but basically uncontrolled). Water levels in the treatment plots were kept at 3 cm and 6 cm by pumping water out of the plots, if the water level exceeded those levels at least once a week. The average level of groundwater during the experiment is show in Fig. 1. If the water levels were below those



A. Ground water level at 3 cm on average



B. Ground water level at 6 cm on average

Fig. 1 Level of ground water in field during the experiment.

levels, water control was not implemented. After recording the water levels, gases were sampled and soil physicochemical properties such as soil Eh and temperature were measured weekly. The size of a treatment plot was 30 m^2 (5 m x 6 m) divided into three micro-plots of 10 m^2 (2 m x 5 m) as replications. The structure of the barrier plots, particularly in the 3 and 6 cm plots consisted of a mound with the insertion of a thin wood board as in the farmer practice plot. Water was introduced into the plots before the barrier was set up and without cultivation between the 1st and 2nd experiments. The field site and plot arrangement are shown in Fig. 2.

Land preparation followed the practices of local farmers to allow a better analysis of the data on a regional scale. The plant residues from previous paddy cultivation were homogeneously incorporated into the experimental plots. Twenty five day-old rice seedlings (*Oryza sativa*, var Cigulis, a common rice variety cultivated in Indonesia) were transplanted at a rate of 3-4 seedlings per hill with a 25 cm x 25 cm spacing into the field. Fertilizer applied consisted of NPK (10:10:10) 100 kg ha^{-1} season^{-1} as basal fertilizer, urea 300 kg ha^{-1} season^{-1}, ammonium sulphate (ZA) 50 kg ha^{-1} season^{-1}, super phosphate (SP36) 50 kg ha^{-1} season^{-1} and chopped (<5 cm) rice straw 4 Mg ha^{-1} season^{-1}.

Grain yield from individual replicates was determined at the end of cultivation. The cultivation schedule is shown in Table 1. The soil at the experimental site was classified as Typic Haplusterts (U.S. Soil Taxonomy, 1998), which was characterized as alluvial soil type (Center for Soil and Agroclimate Research, Indonesia, 2000). Soil samples were taken from each micro-plot either before transplanting or after plowing (December 5, 2006) at a depth of 0 –15 cm (plowed layer) and sieved under

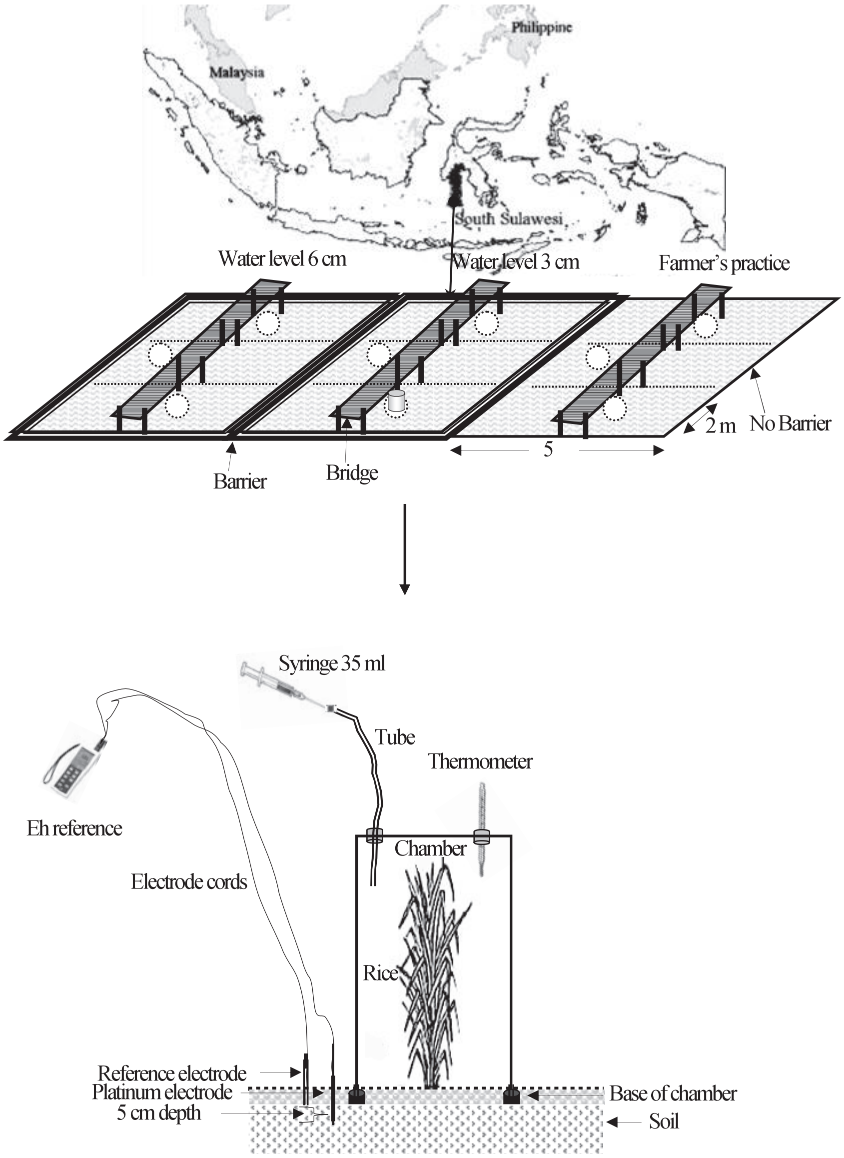


Fig. 2 Field site and arrangement of the plots in the field experiment.

Table 1 Cultivation schedule

	1st cultivation (May – August 2006)	2nd cultivation (December 2006 – March 2007)
Plowing		
1st	April 10, 2006	November 20, 2006
2nd	April 25, 2006	December 4, 2006
Transplanting	April 27, 2006	December 7, 2006
Fertilizer application		
Rice straw	April 20, 2006	November 28 , 2006
Basal	April 27, 2006	December 7, 2006
1st	May 5, 2006	December 14, 2006
2nd	May 18, 2006	December 29, 2006
Weeding		
1st	May 23, 2006	January 5, 2007
2nd	June 20, 2006	February 2, 2007
Harvest	July 30, 2006	March 4, 2007

moist conditions through a 2 mm mesh sieve and stored at 4°C until analysis.

The soil pH (H_2O) was 7.22, EC, 0.17 dS m^{-1}, total carbon content 22.5 g-C kg^{-1}, total N content 2.30 g-N kg^{-1} dry soil, and C/N ratio 9.78, measured using electrode and a C/N analyzer (MT 700, Yanaco, Kyoto, Japan), respectively. The soil redox potential (Eh) in each plot was measured with an ORP meter (HM-21P, TOA Japan) equipped with reference and platinum electrodes where the platinum was dipped into the soil to a 5 cm depth 3 days before gas measurements or starting from May 11, 2006 and December 14, 2006 in the dry season and rainy season, respectively, until the end of cultivation (Table 1).

The water table levels of the plots were monitored with a standard scale meter. The Eh and water table level were recorded on the same date as gas sampling. The data on daily precipitation and temperature during the experiments were collected from the Meteorological and Geophysical Bureau of Maros, South Sulawesi, Indonesia.

Greenhouse gas flux measurements

Methane (CH_4) and nitrous oxide (N_2O) fluxes were measured at one-week intervals throughout the cropping season using a closed chamber (inner dia.37 cm; height 50 cm and 110 cm) (Fig. 2). The gas samples were taken from the chamber after 0, 15, and 30 minutes using disposable syringes and then immediately transferred to evacuated air glass vials (25 ml) with butyl rubber stoppers. Gas sampling was triplicated for each treatment between 10:00 a.m and 14:00 p.m. Gas samples in the glass vials were analyzed in the Laboratory of Soil Science, Chiba University, Matsudo Japan within 3 weeks after sampling. The concentrations of CH_4 and N_2O in the samples were quantified using gas chromatographs (Shimadzu, GC 14B, Kyoto, Japan) equipped with a flame ionization detector (FID) and an electron capture detector (ECD), respectively. CH_4 and N_2O fluxes were calculated from the linear change in gaseous concentrations in the chamber over time (Jumadi *et al.,* 2008).

Cumulative CH_4 and N_2O fluxes per season from the field were obtained by integration of gaseous fluxes during the cropping season. Analyses were performed in triplicate and means and standard deviations were calculated. The percentage of reduction of CH_4 emitted from the fields with different water levels was calculated using the following equation in which CH_4 reduction (%) $=(A - B)/A \times 100$, where A is the cumulative CH_4 emission in the farmer plot, B is the cumulative CH_4 emission in the 3 cm or 6 cm level plots. Means and standard deviations of the data were calculated. Means were compared and subjected to the Bonferroni's modified LSD multiple-range test ($P< 0.05$) using SPSS software (Ver.11.0 for windows, SPSS Inc., Chicago, USA).

Results and Discussion

CH_4 and N_2O emission rates from the rice field as affected by the controlled water level have been studied in Maros, Indonesia during two cultivation seasons (1st cultivation = dry season and 2nd cultivation = wet season). The seasonal soil Eh value, precipitation, water level and greenhouse gas (CH_4 and N_2O) fluxes during the two cultivations are shown in Fig. 3. Seasonal soil Eh value fluctuated during the measurements ranging from -230 to 240 mV in both seasons, although the Eh value showed different patterns in each cultivation period (Fig. 3A). In the early period of the 1st cultivation,

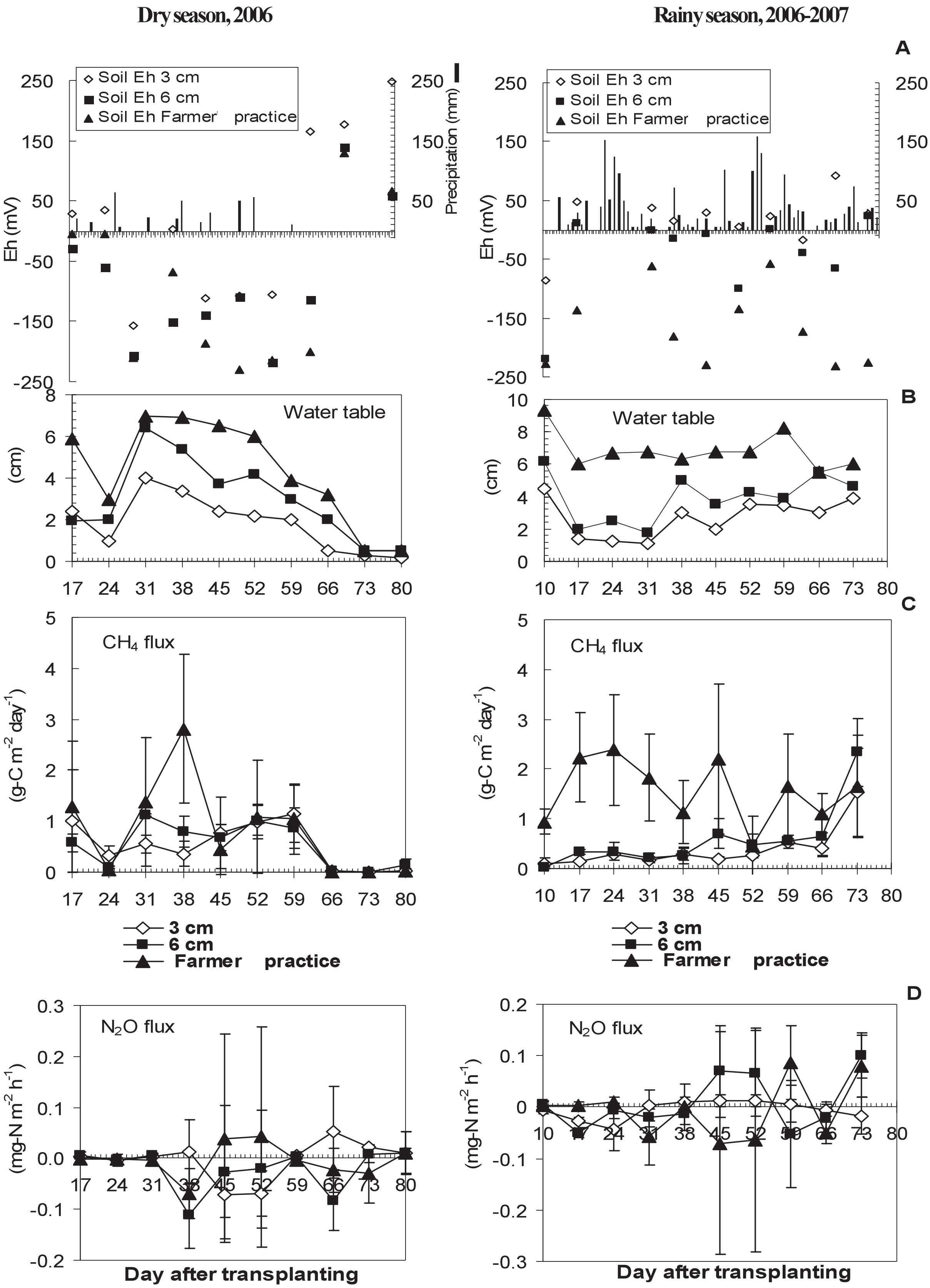


Fig. 3 Measurements of CH_4 and N_2O during a one-year period and effect of controlled water level and soil condition.

Eh in the 3 cm plot showed a positive value of 29 mV at 16 days after transplanting (DAT), while in other plots the values were negative, namely -4 mV in the 6 cm plot and -29 mV in the farmer practice plot (FP).

These values did not change appreciably until 30 DAT when the Eh value dropped to -158, - 206 and -210 in the 3 cmand 6 cm FP plots, respectively, and then shifted to positive values in the last period of cultivation. However, in the 2nd cultivation, the values of soil Eh in the 3 and 6 cm water level plots fluctuated, while in the FP plots, the Eh value remained negative until the end of the cultivation period. Soil Eh value was higher in 3 cm water level plot, compared to the 6 cm and FP water level plots. Intensity of precipitation in the 1st cultivation season was lower than in the 2nd cultivation (Fig. 3A). Frequent rainfall in the 2nd cultivation gradually increased the flooding intensity, particularly in FP plot (Fig. 3B). Hence, the precipitation intensity was correlated with the level of water in the field.

The water level in the 1st cultivation was in the water level of treatments designed, particularly at 3 cm and 6 cm plots except at 24 DAT when the fields were drained before the second application of fertilizer. Because of the high intensity of rainfall in the 2nd cultivation, the water level of the 3 cm plot had exceeded the level because the time when water was pumped out from the experimental plot was neglected such as the midnight raining time. However generally, the water level in the plot did not exceed to the limit of treatment.

The seasonal variations of CH_4 emission from the paddy field during the two cultivation periods are shown in Fig. 3C. The paddy field acted as a source of CH_4 during the observation periods. However, the controlled water levels of the paddy field exerted a significant effect on the reduction of CH_4 emission, compared to the water level in the farmer practice. CH_4 flux was higher when the level of water increased in the paddy field experiment in both cultivations. In the 1st cultivation (May 14, 2006 or 17 DAT), CH_4 fluxes monitored were 1.0, 0.6 and 1.3 g-C m^{-2} day^{-1} in the 3 cm, 6 cm and FP plots, respectively, and then they decreased at 24 DAT when the water level in the field decreased due to the field drainage before the 2nd fertilizer application. In the FP plot, the CH_4 flux peaked with a value of 2.8 g-C m^{-2} day^{-1} on June 4, 2006 or at 38 DAT, and then decreased to the values recorded in the other plots at 45 DAT.

In the 2nd cultivation, the CH_4 flux emission was larger in the FP plot than in the other plots until harvest. The CH_4 flux from the FP plot was consistently higher than that of other plots, except at the end of measurements at 73 DAT. The CH_4 flux in the FP plot rose sharply from 10 DAT and reached the highest recorded seasonal value at 24 DAT, and then fluctuated toward the end of cultivation. Meanwhile, CH_4 flux emissions in the other plots was lower compared to those in the FP plot.

Rates of CH_4 emission in the two cultivations were higher in the FP plot than in the other plots, and emission of CH_4 in the 2nd cultivation was higher than in the 1st cultivation. Seasonal average CH_4 emissions from the 3 cm, 6 cm and FP plots in the 1st cultivation were 330±64.5, 344±78 and 519±486 kg-C ha^{-1} $season^{-1}$, respectively. In the 2nd cultivation, the averages were 231±100, 351±32 and 635±71 kg-C ha^{-1} $season^{-1}$ for the 3 cm, 6 cm and FP plots, respectively. CH_4 emissions in the 1st cultivation decreased to 36.5% and 33.8% in the 3 cm and 6 cm plots, respectively compared to the FP plot, while, in the 2nd cultivation, the reduction values were 63.6% and 44.6% (Table 2). In the plots with a controlled 3 cm water level,

Table 2 Total CH_4 emission (kg-C ha^{-1} $season^{-1}$), N_2O emission (kg-N ha^{-1} $season^{-1}$), CH_4 emission reduction (%) throughout cultivation periods, and grain yield (ton ha^{-1})

Treatments	3 cm	6 cm	Farmer's practice
1st cultivation			
Total CH_4 emission	330±64	344±78	519±486
CH_4 emission reduction	36.5	33.8	-
Total N_2O emission	-0.4±0.5	0.1±0.2	-0.1±0.9
Grain yield	7.2±1.3	7.5±1.7	7.3±0.5
Average water level (cm)	1.8	3.0	4.3
2nd cultivation			
Total CH_4 emission	231±100	351±32	635±71
CH_4 emission reduction	63.6	44.6	-
Total N_2O emission	0.0±0.0	0.1±0.1	-0.1±0.8
Grain yield	7.0±0.5	6.0±0.6	6.5±0.6
Average water level (cm)	2.7	3.9	6.8

CH_4 emission was higher in the 1st cultivation than to in the 2nd cultivation, while, larger amounts of CH_4 were emitted from the FP and 6 cm plots in the 2nd cultivation. Therefore, the reduction of CH_4 emission among the treatments was larger in the 2nd cultivation than in the 1st cultivation in the FP plot compared to the controlled water level plots of 3 cm.

Several studies also suggested that methane emission in paddy fields could be reduced by water management (combination of irrigation and drainage) practices such as intermittent irrigation or midseason drainage. Most of these studies also showed that drainage practices applied during paddy cultivation periods, enable to significantly reduce CH_4 fluxes from paddy fields. This practice has been recommended as one of the effective options to mitigate CH_4 emission from paddy field without adverse effect on rice yield (Arth *et al.,* 1998; Sass *et al.,* 1992; Yagi *et al.,* 1996; Kimura *et al.,* 1991). Hence, a midseason drainage could reduce the seasonal methane emission rate to 50% and 80% by frequent aeration for 2-3 days at 3, 6, and 9 weeks after initial flooding in dry-seeded fields (Sass *et al.,* 1992).

According to Yagi *et al.* (1996) in the Kanto area of Japan, short-term drainage practices in paddy fields reduced CH_4 emission by 42-45%, while in China, intermittent irrigation or constant moisture reduced the CH_4 emission rate by 20 – 50% (Cai *et al.,* 1997). In the present experiment, controlled water level up to 3 cm and 6 cm reduced CH_4 emission to an average of 50% and 39%, respectively. Mitigation strategies through intermittent drainage may not be easily adopted by the local farmers in Maros (experimental area), because the farmers prefer flooded conditions or constant submergence of the fields up to 6 cm during cultivation except at the time fertilizer application and before harvest, when the fields are allowed to dry or to be soaked. These water depth practices were also commonly used by local farmers in the irrigated area of Indonesia such as in the West Java provinces (Husin *et al.,* 1995; Lumbanraja *et al.,* 1998). The results of these studies showed that the emission of CH_4 from rice paddy fields was consistently lower by maintaining a water level to 3 cm compared to 6 cm and the water base-line in the local farmer practice in both dry and wet seasons without any adverse effect on rice production.

Rice grain yields tended to be higher in the 1st cultivation than in the 2nd cultivation in all the plots (Table 2). However, these differences were not statistically significant among the treatments in both cultivation seasons ($p<0.05$). The absence of yield losses under controlled water level compared to the FP plots was attributed to the relatively wet soil conditions. A study showed that rice growth was delayed when the rice plants were water-stressed at both vegetative and reproductive stages (Beldera *et al.,* 2004). However, in the current experiment, controlled water level did not affect the rice grain yield compared to the farmer practice, indicating that water stress did not occur in the controlled water plots when the lowest water level during rice growth was above 0.5 cm (Fig. 2B).

Controlled water level below 6 cm in this area of paddy cultivation is a promising option to mitigate the CH_4 emission without hampering the rice yield as well as to save water. However, these practices can not be easily adopted by the local farmers because they must determine whether the water level is above or below 6 cm and pump out water when the water level is exceeds 6 cm, once a week. Therefore, a more convenient method to monitor the water level by the farmers should be developed along with some incentives to the local government to save water in order to reduce the CH_4 flux. The CH_4 flux in rice fields can be readily predicted by using soil redox potential indices (Yagi *et al.,* 1997; Lumbanraja *et al.,* 1998). Soil Eh at a 5 cm depth was mostly monitored at negative values particularly in the FP plots to indicate that the redox potential in the subsurface soil layers of the field was low enough for active methanogenesis (Fumoto *et al.,* 2008; Yagi *et al.,* 1996). However, positive soil Eh values were also detected frequently in the 3 cm and 6 cm plots that possibly could induce CH_4 oxidation.

The decrease of the CH_4 emission in the 3 cm plot was probably due to the diffusion or presence of O_2 in the surface soil surrounding the rhizosphere which could provide aerobe microzones for CH_4 oxidizing bacteria. In addition, CH_4 may be released to the atmosphere through plant aerenchyma transport as it is estimated that roughly 98% of the CH_4 released was transported through the rice plant (Inubushi *et al.*, 1989; Tyler *et al.,* 1997). Methane oxidation potential is assumed to be uniform throughout the plough layer in aerobic soils but not necessarily in a flooded soil ecosystem that is mostly characterized by the presence of oxidized surface soil and oxidized rhizosphere (Jumadi *et al.,* 2008; Conrad *et al.,* 2002; Denier *et al.,* 1996; Inubushi *et al.,* 2002). Another study suggested that the CH_4 concentration decreased in the soil surface layers of an Italian flooded rice soil field below a 10 mm depth and a CH_4 oxidation site in the top layer at a depth of about at 2-4 mm (Conrad *et al.,* 1991). Results from various fresh water sediments indicated that O_2 penetration can occur at a depth of about 1-4 mm (Frenzel *et al.,* 1992). Significant methane oxidation also can occur only in the rhizosphere at microaerophilic sites, as well as at low acetate and high methane concentrations (Bodegom *et al.,* 2001). In the current experiment, measurements of the O_2 penetration depth and soil Eh at depths below 5 cm were not performed, therefore, it is difficult to determine whether CH_4 oxidation was caused by the availability of O_2 in the surface soil as well as at the rhizosphere site. However, the Eh value at the controlled water level was higher than that in the farmer practice, which suggest the presence of a large amount of oxygen that enhance the oxidation of CH_4.

CH_4 is emitted mostly through the vascular system of the rice plant, which also supplies O_2 to the roots and adjacent rhizosphere area. In wetland soil, CH_4 and O_2 are factors that influence CH_4 oxidation by methanotrophs (Bodegom *et al.,* 2001; Conrad and Arthl, 1996). The presence of O_2 in the soil is directly influenced by the soil water content and the capacity of the rice plant to transport O_2 from the atmosphere through foliage to the root region by diffusion (Henckel *et al.,* 2000). In addition, the presence of O_2 also enables various chemical and microbial oxidation processes to take place in the rhizosphere, such as ammonium (Arth *et al.,* 1998), sulfide (Wind and Conrad, 1995), and ferrous iron (Furukawa *et al.,* 2004; Kirk and Bajita, 1995).

Methane oxidation can only be effective at low oxygen and low acetate concentrations and thus only at very specific micro-sites within a rice plant (Bodegom *et al.,* 2001). We suggested that a controlled water table at a 3 cm height in the field may create a microenvironment or microsite that suitable for methane oxidation by methanotrophs, unlike the other plots. Flooding of rice field up to a 3 cm water level may limit the presence of oxygen in the surrounding rhizosphere. Hence, the development of anaerobic conditions in soil where methanogens control CH_4 production. Therefore, CH_4 oxidation in the farmer practice plot was inhibited and methanogens were stimulated, resulting in a higher CH_4 concentration in the rhizosphere compared to the controlled water level plots, particularly during the rainy season.

It is also possible that CH_4 production was suppressed at 3 cm or 6 cm water levels compared to the FP practice due to the presence of O_2 in the soil that allowed the oxidation of reduced sulfur to sulfate and of ferrous iron to ferric iron. Sulfate and Fe (III) enhance the activity of sulfate-reducing and iron-reducing bacteria, respectively. These bacteria utilize acetate and H_2 more effectively than methanogens. Thus, the concentrations of H_2 and acetate, the most important methanogenic substrates decreased to values no longer thermodynamically suitable for CH_4 production. Therefore, we assumed that plot with controlled water tables at 3 cm or 6 cm offered more conducive conditions to allow the penetration of O_2 into the soil. As a result, other microbes using substrates for methanogenesis were stimulated and CH_4 oxidization in the rhizosphere zone was enhanced.

Seasonal patterns of N_2O fluxes from rice field experiments were different from those of CH_4 fluxes and varied among replications in each treatment (Fig. 3D). The N_2O fluxes tended to be lower than the ambient N_2O concentration. Cumulative N_2O values were negative and also the time course data showed that N_2Oemission in the paddy fields did not occur or even showed negative values for both seasons (Table 2 and Fig. 3D).

The amount of N_2O flux to the atmosphere from the 3 cm and 6 cm plots in the 1st cultivation was extremely low (0.002~0.006 mg-N m^{-2} h^{-1}) in the fields during the drainage time before fertilizer application and then the values became negative when the fields were under flooded conditions. In the 2nd cultivation, N_2O fluxes showed positive values during the early period of cultivation (0.003 ~ 0.007 mg-N m^{-2} h^{-1}), in the middle of cultivation (0.01 ~ 0.007 mg-N m^{-2} h^{-1}) and at the end of cultivation (0.1 mg-N m^{-2} h^{-1}). Rates of N_2O fluxes were lower in the wet season than in the dry season. The averages value of the N_2O flux between both the first and second cultivations were similar in the 6 cm plot and farmer practice plot, while in the 3 cm plot, the amount of N_2O flux was higher in the dry season than in the wet season.

Water management by intermittent drainage or midseason drainage is one option to reduce the CH_4 flux from paddy field. However, this practice also enhances the rate of N_2O flux from the field during the drainage period (Cai *et al.,* 1997). N_2O is produced in flooded paddy soils via nitrification of ammonium to nitrate and denitrification, and nitrate tends to accumulate in soils with an aerobic surface layer and under anaerobic condition, respectively (Arth *et al.,* 1998; Suratno *et al.,* 1998; Akiyama *et al.,* 2005). The main pathway of N_2O emission from paddy-soil system depends on the soil water status. Fluxes of N_2O were released by more than 80% to the atmosphere through the rice plant when the paddy field soil was flooded, while through the soil when the soil was not flooded (Yu *et al.*, 1997; Yan *et al.*, 2000). The field study also showed that N_2O emissions from all the plots were suppressed and it could be predicted that N_2O emission was almost in existent. Another field study in West Java in Indonesia showed that if the field was continuously flooded, a significant reduction of N_2O flux occurred compared to intermittent irrigation. This suggests that aerobic-anaerobic cycling triggers interchangeable nitrification of ammonia and denitrification of nitrate, enhancing the total amount of N_2O gas, while, under continuous flooding, these processes were limited (Suratno *et al.,* 1998).

Conclusions

The experiments showed that by maintaining flood water levels up to 3 cm and 6 cm N_2O emission was not stimulated, while CH_4 emission reduced without a decrease of grain yield of rice, compared to the farmer practice and the amount of water used could be saved, leading to the increase of water productivity. These results also suggested that controlled water level below that in farmer practice affected the availability of O_2 in the soil. However, additional field investigation and measurement should be performed to determine whether this mitigation option could be adopted by the local farmers.

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