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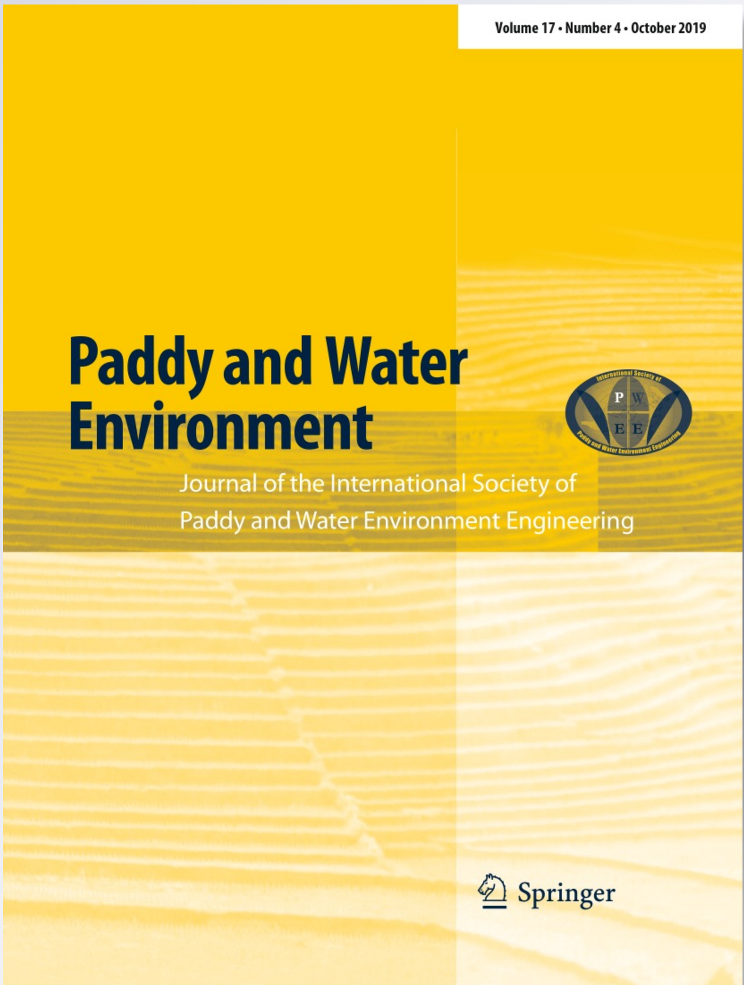

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ARTICLE

Emissions of nitrous oxide and methane from rice field after granulated urea application with nitrification inhibitors and zeolite under different water managements

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Abstract

A field experiment was carried out to determine the emissions of nitrous oxide (N_2O) and methane (CH_4) and yield of rice grains under water management of continuously flooded (CF) and non-continuously flooded (NCF) systems and to find out those were affected by both input of water managements in combination with urea granulated with nitrification inhibitors (neem and dicyandiamide) and zeolite. Urea combined with zeolite and nitrification inhibitors (NIs) reduced the emission of N_2O in both plots of CF and NCF compared with urea alone, while the release of CH_4 was induced, especially at CF plot. However, no differences existed in the emissions of N_2O and CH_4 between the types of urea granulated with zeolite and NIs and urea treatments in both water input managements. A paired comparison between CF and NCF plots revealed fewer emissions of N_2O and CH_4 in NCF plot with urea granulated with zeolite and neem treatments. Urea with zeolite and NIs did not have any effect on improving rice grain yield different from the effect of urea alone. The nitrogen use efficiency employed in this study had little effect on delayed oxidation of NH_4^+ in the soil of both plots of rice field. The study showed that the water management or practice of irrigation promises to reduce the emissions of N_2O and CH_4 compared to nitrogen use efficiency application.

Keywords Emission of N_2O and CH_4 · Nitrification inhibitors · Rice field · Water management

Introduction

Nitrous oxide (N_2O) and methane (CH_4) are greenhouse gases, which contribute to global warming by destroying or removing the troposphere and stratosphere of the ozone layer. The major source of CH_4 and N_2O is the agriculture sector, and their global warming potential (GWP) is 25 and 298 for CH_4 and N_2O, respectively, times more than that of carbon dioxide (CO_2) (IPCC 2007). Methane is a product of the final step of the anaerobic decomposition (methanogenesis) of organic matter in the soil, while N_2O is produced by nitrogen compound transformation mainly through nitrification and denitrification processes.

Generally, rice field requires an amount of standing water (flooded condition), especially during the early growth stage for optimal growth and yield. However, a flooded condition in the field results in an anaerobic condition that promotes both methanogenesis and denitrification (Le Mer and Roger 2001; Tate 2015). The majority of the past studies have revealed that the greater part of the emission of CH_4 in rice field occurs during the planting season when the field is flooded. However, appreciable emissions of N_2O and CH_4 have also been noticed after drainage at the end of the planting season (Wassmann et al. 2000; Inubushi et al. 2002).

The main reason for applying nitrogen fertilizer to rice crop is to boost the yield of rice grains. However, the nitrification–denitrification processes in the soil field lower the efficiency of nitrogen fertilizer (Datta and Adhya 2014;

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Akiyama et al. 2010). Nitrification inhibitors (NIs) are used to enhance nitrogen use efficiency (NUE) of the crop by preventing the oxidation of ammonium (NH_4^+) to nitrate (NO_3^-) in the soil (nitrification). Hence, more NH_4^+ is available to the crops and the less NO_3^- is found (Weiske et al. 2001; Trenkel 1997; Sharma and Prasad 1996). Because NH_4^+ and NO_3^- are, respectively, substrates for nitrification and denitrification and both can cause the emission of N_2O, the use of NIs can help to reduce the emission of N_2O from the agriculture sector.

The mechanism involved in nitrification inhibition is complex where NIs bind on membrane cell protein (ammonium monooxygenase) inclusive which are responsible for the oxidation of NH_4^+ to NO_3^- (Benckiser et al. 2013; McCarty 1999). Nitrification inhibitors (NIs) are added to soil such as nitrapyrin, DMPP (3, 4-dimethylpyrazole phosphate) and DCD (dicyandiamide) (Ruser and Schulz 2015). However, NIs are expensive and have limited availability, especially in Indonesia chemical market.

Effort has been made to increase the efficiency of nitrogen use by substituting chemical NIs with organic NIs such as karanj (*Pongamia glabra*) and neem (*Azadirachta indica*) which have properties that can hinder nitrification (Opoku et al. 2014; Prasad and Power 1995; Majumdar et al. 2000; Sharma and Prasad 1996). These organic NIs are cheaper and can be obtained more easily than chemical NIs in Indonesia. Neem seeds contain bioactive compounds known as tetranortriterpenoids; among them are azadirachtin, nimbin, or certain unsaturated fats that can act as NIs (substrate for AMO); therefore, it can hinder oxidation of NH_4^+ and boost the efficiency of nitrogen fertilizer, e.g., ammonium sulfate or urea (Sharma and Prasad 1996; Mohanty et al. 2008; Abbasi et al. 2011).

Another way of increasing the efficiency of nitrogen use is by using polymer materials such as polyolefin, polyethylene, and zeolite minerals to slow down the release of fertilizer in the soil, (Jumadi et al. 2008; Ahmed et al. 2008; Akiyama et al. 2013). Zeolites are aluminosilicate minerals which occur naturally and have a three-dimensional structure hollow and aisle. Therefore, it has sufficient surface area for binding nitrogen (Kithome et al. 1998). Numerous studies have shown that zeolite can be used to reduce ammonia volatilization due to its high cation exchange capacity (CEC) and great affinity for NH_4^+ (Ferguson and Pepper 1987; Ahmed et al. 2008); therefore, it is capable of increasing the growth and yield of a variety of crops due to its effect on either increasing the efficiency of nitrogen use or reducing NH_4^+ toxicity (Huang and Petrovic 1994; Tarkalson and Ippolito 2011).

Majumdar et al. (2000) came up with a suggestion that NIs may not be optimally efficient in a flooded rice field due to the fact that the soil system is under anaerobic condition, which suppresses nitrification. However, NIs might perform better in irrigated rice system if the field is drained periodically (non-continuously flooded), especially in sandy or sandy loam soils which have a porosity that makes it possible for the soil to be in fully or partially aerobic condition (Majumdar 2005). Additionally, when the water levels are being maintained in the rice field, there is a need for frequent irrigation done with fresh water to bring a large amount of dissolved oxygen and the soil will remain partially aerobic for some time, even after being flooded, thereby making the NIs function effectively.

In the flooded rice system, the final drainage contributed to the emissions of 5–14% and 0–82% of total seasonal CH_4 and N_2O, respectively. In rice field, N_2O emission depends on the presence of waterlogging, soil Eh, and the amount of nitrogen input applied (Cai et al. 1997; Jumadi et al. 2012). Several studies have also indicated that change in environmental factor and management activities in rice field such as re-watering without meeting an oxide condition completely would contribute peak of N_2O and CO_2 emission (Beare et al. 2009; Aguilera et al. 2013). Aquilera et al. (2013) pointed out that a large amount of N_2O fluxes in Mediterranean cropping system occurred following rainfall or irrigation activities, especially when the soil was previously dried. Therefore, considering the environment and management system in rice cropping, the idea of using NIs in rice field can be justified.

The rice field in Maros area, South Sulawesi, comprises an irrigation system that covers about 3500 ha, and water is supplied to the field using regulated-rotation irrigation that is managed by the Irrigation Bureau of Maros district government. The rice farmers in Maros Area often irrigate the field prior to fertilizer application or many weeks before the harvest. After fertilizer application, the field is continuously kept flooded or submerged above 6 cm level (Jumadi et al. 2012). Therefore, the mitigation option of intermittently draining the field below soil saturation level may not be appropriate and may be difficult to implement in this area. Also, there is an increasing demand for water all year round in the surrounding area for industrial purpose, household use, and drinking water, and water used for paddy production system in this area is bound to decrease. The reduction in the amount of water table during planting at the level below farmer usual practice might be one of the solutions for saving water for other purposes. However, this option does not have any different effect on rice grain yield, and also it is a potential strategy for reducing the emission of CH_4 without increasing N_2O emission.

The aims of this study are to determine the rate of reduction in CH_4 and N_2O emissions from the water regime level of continuously flooded field which is adopted by farmers and non-continuously flooded system and also to determine whether the grain yield of rice is affected by both water regimes in combination with urea granulated with NIs (neem cake and DCD) and natural slow release (zeolite).

Materials and methods

The field experiment, soil analysis, and grain yield

The site of the field experiment was Indonesian Cereals Research Institute (ICERI), Maros District of South Sulawesi Province, Indonesia (4°59′2.8″S 119°34′36.9″E). Studies were carried out at the end of wet seasons of rice cultivation in the year 2015. In the course of the field experiment, average rainfall amount was about 232 mm and the mean monthly air temperature was in the range of 22.5–35.2 °C. The soil at the experimental site belonged to the class of Typic Haplusterts (USA. Department of Agriculture Natural Resources Conservation Service, Soil Survey Staff (1998), which was classified as alluvial soil type (Subardja et al. 2014). The texture of field soil was 8% sand, 54% silt, and 38% clay which belongs to texture classified as silt clay loam. The soil pH (H_2O) was 6.7, total carbon content 20.5 g–C kg^{-1}, total N content 2.1 g–N kg^{-1} dry soil, and C/N ratio 9.76, CEC of 28.15 cmolc/kg, P_2O_5 of 79.60 μg–P g^{-1}. In early growth stage of rice, the water table was kept constantly at 7–8 cm until 25 DAT for both plots of continuously flooded (CF) and non-continuously flooded (NCF). Then, it slowly dried to 0 cm (soil water-saturated condition) to 39 DAT at NCF for 3 weeks and irrigated again to 2 cm before flowering time, while in CF plot the

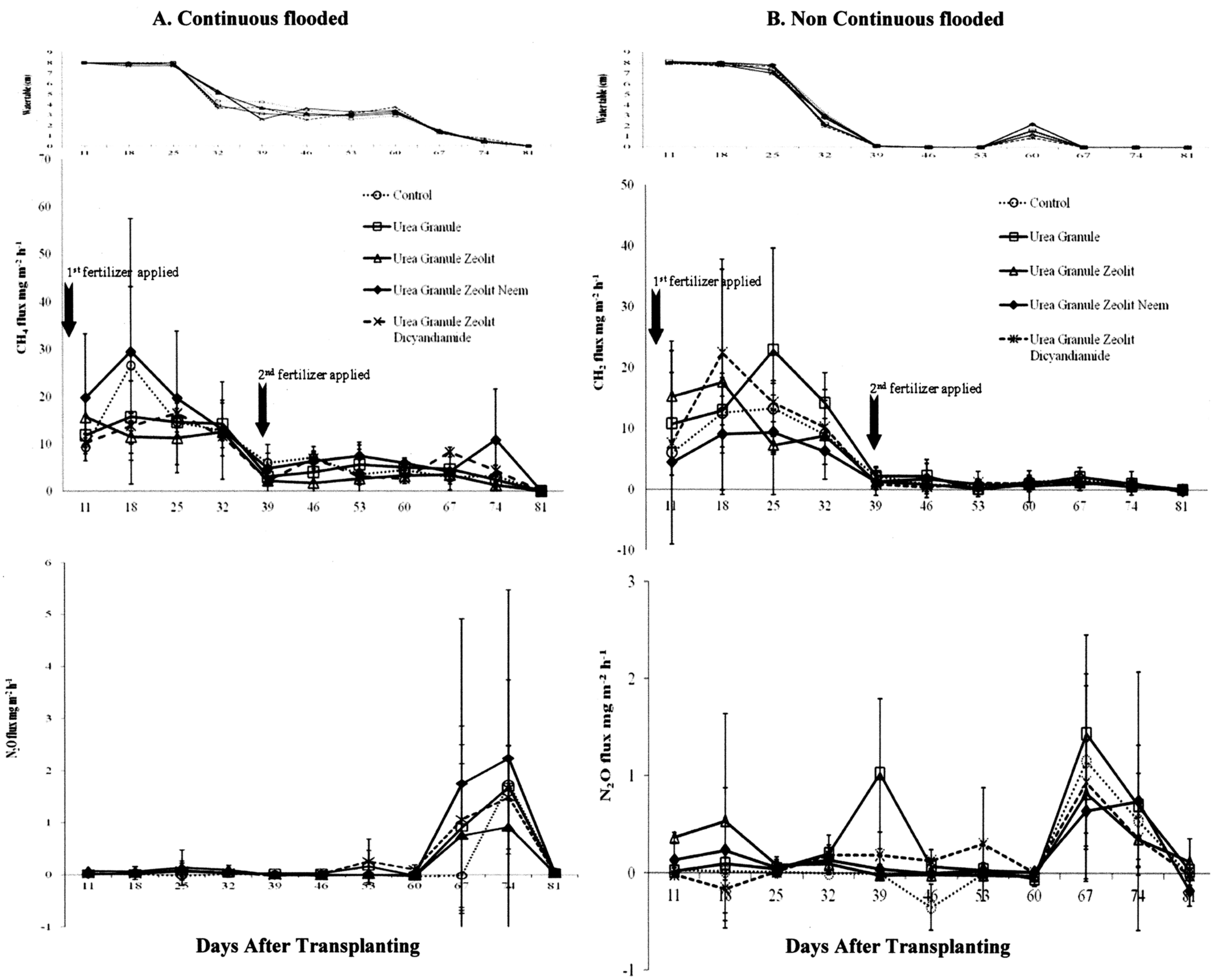

Fig. 1 **a** Change in water table height, N_2O and CH_4 fluxes in a continuously flooded rice field; **b** change in water table height, N_2O and CH_4 fluxes in a non-continuously flooded rice field, during rice cropping season (March 13, 2015, to August 5, 2015). At each sampling time for each soil, vertical bars indicate ± standard deviations. Means are not significantly different at ($P < 0.05$) by Tukey HSD test

water table was maintained at 3–4 cm during maturing stage growth and drained before harvesting time (Fig. 1).

Soil samples were obtained from triplicate plots at 0–15 cm depth and sieved through a 2.00-mm sieve for the analysis of soil properties and for the purpose of incubation experiment (Foster 1995). The pH (H_2O 1:5) and total carbon and nitrogen were measured using electrode and combustion and Kjeldahl methods, respectively (Page et al. 1982). Extractable phosphorus (phosphorus pentoxide, P_2O_5) was determined using the Bray method as the basis (Bray and Kurtz 1945), while the cation exchange capacity (CEC) was determined by using the method of Burt (2004). The analysis of soil textures and moisture was performed by using a hygrometer method (Bouyoucos 1962) and oven-drying method (Foster 1995).

Temperature and precipitation data were collected from the Meteorological and Geophysical Bureau of Maros District. The practices of local farmers were followed in land preparation to give room for a better analysis of the data on a district scale. The variety of rice paddy planting was similarly incorporated as the experimental plots. Transplanting of 21-day-old rice seedlings (*Oryza sativa*, var Ciherang, a commonly cultivated rice variety in South Sulawesi) was done at a rate of 3–4 seedlings hill^{-1} with "Jajar Legowo" system (2:1) of rice space row planting. The system transplanting consists of two rows and interspaces with rows of empty 1 per line [20 cm (between row) × 10 cm (line side) × 40 cm (empty row)]. Paddy transplanting system "Jajar Legowo" has been used by the farmer because of the easy application of fertilizer and pesticides, the benefits of sunlight exposure which allows farmers to plant of more seedlings, hence resulting in a high yield of rice.

The experiments involved two plots of water management or regimes input. The first plot was continuous flooding (CF, 8–2 cm depth of water) which was maintained on the soil surface until 20 days before the paddy was harvested. The second plot was non-continuous flooding (NCF) which used 8–2 cm water level since the early growth stage 0 day after transplanting (DAT) to 25 DAT and the soil was kept flooded for 2–3 weeks until it became saturated (0 cm) with water. Soil saturation was done twice at 25–43 DAT and 67 DAT, and then the soil was drained until the harvest time. The continuous flooding planting is commonly practiced in regulated and semi-regulated irrigation areas in South Sulawesi.

Each plot under the different water managements (CF and NCF) was implemented in an area of about 150 m^2 which was divided by microplot measurements in a size of 10 m^2 (2.5 m wide × 4.0 m length). Plastic sheets were used to cover the inner side borders of the plots to 30 cm soil depth to avoid water being transported horizontally between plots and outside field plots. The barrier plots' structure, especially in NCF plots also involved a mound has an aluminum sheet plate inserted to 35 cm soil depth to hinder diffusion of water between in/outside plots and outer field experiments. This barrier structure was appropriate for the easy management of the freshwater flow in or out of the plot of NCF.

Three replicates of five urea fertilizers with and without nitrification inhibitor (NIs) and zeolite treatments were set out in a completely randomized design of each plot of water regimes (CF and NCF) treatments beginning from March 13, 2015, and ending on August 5, 2015. The fertilizers were granulated and used on each plot of the water regimes field, namely:

1. Control (C: no addition of nitrogen).
2. Urea granule (UG: nitrogen content of 45%).
3. Urea granule with zeolite [UGZ: zeolite is, of course, natural zeolite from local mine that used natural slow release and mixed with urea at a rate of 10% (w/w)].
4. Urea with zeolite and neem [UGZN: zeolite and neem cake were mixed with urea at a rate of 10% and 5% (w/w), respectively].
5. Urea with zeolite and dicyandiamide (UGZD: zeolite and DCD were mixed with urea at a rate of 10% and 5% (w/w), respectively)].

The granulation was carried out using inclined pan granulator methods (Hoeung et al. 2011). The total rate of nitrogen applied in each treatment was 150 kg–N ha^{-1}, and the application was done in two splits time (75 + 75) on April 12, 2015, and May 13, 2015. Basal application of triple superphosphate and KCl at the rates of 100 kg h^{-1} was given to all plots including control as basal dose. The rate of fertilizers and timing application followed the practices of local farmers.

Following the recording of the water levels, sampling of gases was done on a weekly basis. Grain yield of each replicate was found at the end of cultivation (Jumadi et al. 2012). The water table levels (cm) were measured using a standard scale meter and put on record on the same date as gas sampling.

Greenhouse gas fluxes, measurements of NH_4^+, and NO_3^- concentrations

Nitrous oxide (N_2O) and methane (CH_4) fluxes were determined at 1-week intervals at 9:00 a.m. and 14:00 p.m. throughout the planting season using a closed chambers technique with two sizes of chamber (inner diam. 55 cm: height 50 cm) and (inner diam. 55 cm: height 150 cm) over the whole growth stage. The chambers consisted of acrylic glass material, an assembled thermometer, and electric fan. The base of the chamber (galvanized steel: inner diam. 55 cm) was made to go about 7–10 cm into the soil and left in each plot field in the course of the experiment. Samples of the gas were obtained from the chamber after 0 and 30 min using disposable syringes 50 ml and then transferred immediately to evacuated air glass vials (25 ml) with butyl rubber stoppers. The concentrations of CH_4 and N_2O in the samples were determined using gas chromatography (Shimadzu, GC 14B) equipped with a flame ionization detector (FID) and an electron capture detector (ECD), respectively.

The fluxes of N_2O and CH_4 were determined using the change in the concentration of N_2O and CH_4 over the time, after accounting for diffusion constraints. Cumulative fluxes of CH_4 and N_2O from the paddy field per season were obtained by integrating gaseous fluxes in the course of the cropping season. Analyses were carried out in triplicate, and means and standard deviations were determined.

The percent reduction of CH_4 emitted from the fields with different water levels was calculated using the following equation:

$$CH_4 \text{ reduction } (\%) = (A - B)/A \times 100$$

where A is the cumulative CH_4 emission in the continuously flooded and B is the cumulative CH_4 emission in non-continuously flooded.

The percentage reduction of N_2O emitted from the fields with different water levels was found using the following equation:

$$N_2O \text{ reduction } (\%) = (C - D)/C \times 100$$

where C is the cumulative N_2O emission in the continuously flooded and D is the cumulative N_2O emission in non-continuously flooded.

Soil samples were obtained from each plot, nitrogenous fertilizer, and control treatments at 0–15 cm depth to analyze NH_4^+ and NO_3^- soil contents at five sequence times [11, 24, 38, 52, and 66 days after transplanting (DAT)] during a planting season. Five grams of fresh soil samples on an oven dry basis was weighed into 50-ml plastic bottle with a screw cap, and soils were immediately extracted with 25 ml of 2 M KCl (1:5) solution by shaking for 30 min on a reciprocal shaker and filtered by filter paper (Advantec No. 6). The amounts of NH_4^+ and NO_3^- were analyzed by nitroprusside (Anderson and Ingram 1989) and hydrazine reduction (Hayashi et al. 1997) methods, respectively.

The same means and standard deviations of the data were found. Means were compared and subjected to the Tukey HSD test ($P < 0.05$) using SPSS software (version 21.0 for windows, SPSS Inc., Chicago, USA).

Results

Soil properties, greenhouse gas fluxes, nitrogen change, and grain yield

In the area of the field experiment, rice is commonly planted twice a year in the wet season. The first rice was planted usually at early October to February and the second planted at the end of the wet season which lasts from March to July. The highest CH_4 emission for urea with zeolite and neem (UZN) at CF plot occurred at 18 DAT or 10 days after the first fertilizer application. Then, CH_4 emissions in CF plot gradually decreased until 39 DAT and it constantly emitted up to 10 mg–C m^{-2} h^{-1} until 81 DAT (Fig. 1a), whereas, in a plot of NCF, CH_4 emission also occurred at 11 DAT, peaked at 18 DAT and 25 DAT for UGZD and UG, respectively, and then slowly decreased until 39 DAT. The CH_4 emission was virtually negligible from 39 DAT until 81 DAT in NCF plot (Fig. 1b). The cumulative of CH_4 emissions in a season was not dramatically different from what obtained with other treatments. But, when pair comparison of both plots and all nitrogenous and control treatments was undertaken, the resulting CH_4 emission of UGZN treatment in both plots of CF (245.2 kg–C ha^{-1} $season^{-1}$) and NCF (60.4 kg–C ha^{-1} $season^{-1}$) was different. The total or cumulative of CH_4 emissions in NCF plot was almost a half lower than that in CF plot. Therefore, a clear difference in CH_4 emission was determined between CF and NCF plots, with the highest reduction of 75.3% from applying UGZN followed by UGZ, C, UZD, and UG of 59.7%, 47.7%, 31.0%, and 25.3%, respectively (Table 1).

In CF plot, the fluxes of N_2O just began to show up 53 DAT and the highest peak at 74 DAT of 2.1 mg–N m^{-2} h^{-1} for UG treatment, while in NCF plot it appeared at 11 DAT and fluctuated until 60 DAT. The highest peak of N_2O emission in NCF plot was noticed at 67 DAT for all nitrogenous treatments, including treatment of control (Fig. 1b). In a season period, the cumulative N_2O emissions were decreasing such that CF > NCF plots. But, their differences were also not significant (Table 1).

The changing pattern of NH_4^+ and NO_3^- from plots CF and NCF with the application of urea with zeolite and nitrification inhibitors (NIs) is shown in Fig. 2. The concentration of NH_4^+ was almost completely transformed into NO_3^- and/or plant uptake at 11 DAT and 38 DAT in plots of NCF and CF, respectively. In CF plot, at 24–52 DAT the concentration of NO_3^- was found to be substantially larger at UGZD than other treatments, whereas, in NCF plot,

Table 1 Total emissions of CH_4 and N_2O (kg–C ha^{-1} season^{-1}) and dry weight of grain rice [kg/plot (8 m^2)] in rice cropping season^{-1}

Treatments	Total (kg–C ha^{-1} season^{-1}) and reduction (%) in CH_4 emission			Total (kg–N ha^{-2} season^{-1}) and reduction (%) in N_2O emission			Dry weight of grain yield rice [kg/plot (8 m^2)]	
	CF	NCF	Reduction	CF	NCF	Reduction	CF	NCF
Control	141.7^a ± 69.6	74.1^a ± 27.0	47.7	2.9^a ± 3.0	2.0^a ± 2.1	31.0	4.30^a	3.72^a
Urea granule	137.7^a ± 24.6	102.8^a ± 29.2	25.3	7.2^a ± 2.7	5.9^a ± 4.4	18.0	5.99^b	5.06^b
Urea granule–zeolite	229.6^a ± 240.7	92.3^a ± 66.8	59.7	3.4^a ± 2.6	3.3^a ± 2.9	2.9	5.90^b	4.85^b
Urea granule–zeolite–neem	245.2^a ± 107.0	60.4^a ± 4.3	75.3	7.0^a ± 4.0	3.0^a ± 2.9	57.0	6.03^b	4.70^b
Urea granule–zeolite–dicyandiamide	147.7^a ± 61.9	101.1^a ± 54.3	31.0	4.7^a ± 2.6	3.2^a ± 1.8	31.9	6.11^b	5.36^b

Symbol ± indicates standard deviation. Means followed by the same letter are not significantly different at ($P < 0.05$) by Tukey HSD test

CF continuously flooded, *NCF* non-continuously flooded

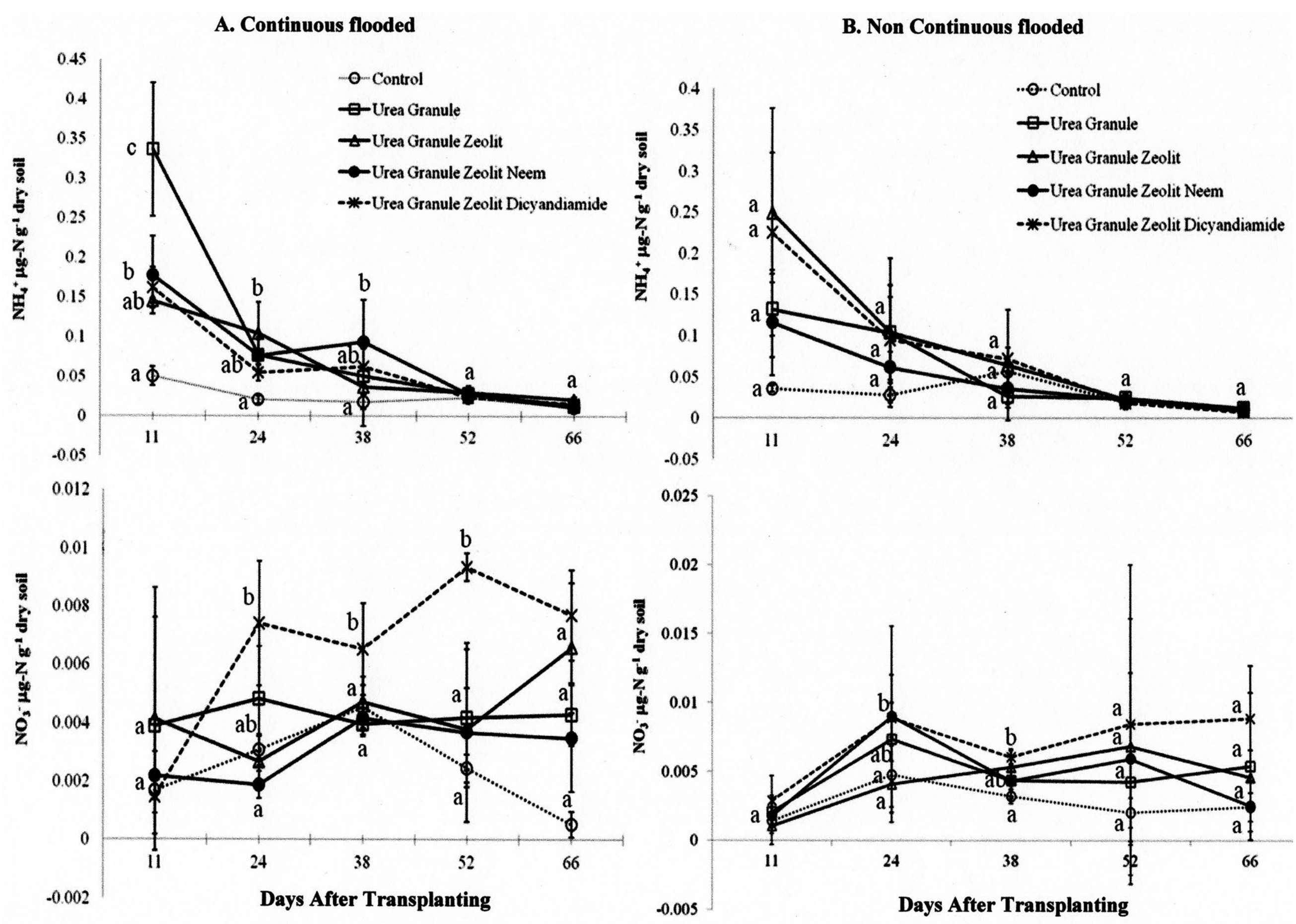

Fig. 2 **a** Change in NH_4^+ and NO_3^- soil field concentration in a continuously flooded rice field; **b** change in NH_4^+ and NO_3^- soil field concentration in non-continuously flooded rice field, during rice cropping season (March 13, 2015, to August 5, 2015). At each sampling time for each soil, vertical bars indicate ± standard deviations. Means followed by the same letter are not significantly different at ($P < 0.05$) by Tukey HSD test

NO_3^- was also high in UGZD treatments and significantly different at 24–38 DAT compared to other nitrogenous treatments ($P < 0.05$).

The grain yield of rice was better in plots of CF than that of NCF. However, in pair comparison with each other where urea with nitrification inhibitors (NIs) and zeolite treatments resulted in significantly higher grain yield than urea alone, however, they are significantly different from control for both soil water condition (CF and NCF) plots (Table 1).

Discussion

The application of nitrogen use efficiency (NUE), urea with nitrification inhibitors (NIs), and zeolite has no reduction effect on emissions of CH_4, and it seems that there is more emission than urea alone. The results also found that the emission of CH_4 was not significantly different among the type of NUE and urea in both water input managements. This indicates that combination of urea and nitrification inhibitors and zeolite in the rice field of continuously flooded (CF) plot and non-continuously flooded (NCF) had little or no effect on CH_4 emission during a period of rice cropping. However, a paired comparison of CF and NCF plot showed an appreciable difference of CH_4 emission at UGZN treatment and also lesser of the CH_4 emissions in NCF plot compared to CF plot. Therefore, the practice of water or irrigation management promised to reduce CH_4 emission compared to the application of nitrogen use efficiency. Other studies have come up with a suggestion that nitrogen fertilizer has a minimal effect on CH_4 emissions in flooded rice system (Dong et al. 2011; Xie et al. 2010; Datta and Adhya 2014). Additionally, the result of finding also agreed on by Linquist et al. (2012) on the basis of their metadata analysis showed that there is no effect of rate of nitrogen or NUE applications on CH_4 emission and also there was no relationship between DCD rate and CH_4 reduction. Singla and Inubushi (2015) also reported that increasing plant biomass content could also be probable main factor for not getting significant different of the total CH_4 emission in control and slag fertilizer treatments.

Schimel (2000) suggested that in flooded rice system, there is a complex interaction between nitrogen fertilizers and the CH_4 emission processes. Hence, it is difficult to pinpoint the underlying mechanisms contributing to the net effects on CH_4 emission. CH_4 and NH_4^+ have similar structure and substrate for methane monooxygenase bind or react with NH_4^+ instead of CH_4 (Linquist et al. 2012). Hence, the presence of NH_4^+ in the soil hinders the oxidation of CH_4. The concentrations of NH_4^+ in CF plots were observed simultaneously high until 38 DAT for all NUE amendments. Therefore, it is by direct or indirect mechanisms that the NH_4^+ inhibits CH_4 consumption where it is thought to occur in the field. Contrary, the NH_4^+ and NO_3^- concentration in NCF plot was already negligible at 11 DAT, which means it might be transformed by nitrification–denitrification or uptake by the plant. Furthermore, it is likely that nitrification occurs less in flooded field conditions and NH_4^+ in soil still remain regardless of whether NUE is applied or not.

Similar results by Yang et al. (2015) showed that the use of slow-release fertilizer in rice field showed more NH_4^+, NO_3^- and dissolve organic nitrogen losses in a plot of controlled irrigation (non-continuously flooded) than flooding irrigation in Taihu Lake region in China. Hence, we speculated that the type of NUE (urea granulated with nitrification inhibitors (NIs) and zeolite) used in this study has little effect on delayed oxidation of NH_4^+ in both plots of rice field soil, and assuming that the retardation of $NH4^+$ in soil is due to the anaerobic condition in the field soil, hence, a reasonably larger amount of CH_4 emission resulted from CF than from NCF (Table 1).

Generally, the applications of NUE promote the growth of rice and also enhance carbon supply for methanogenesis and provide a larger aerenchyma tissue for transport of CH_4 from the soil to the atmosphere. Inubushi et al. (1989) reported that more than 90% of the total CH_4 released from rice is diffusely transported through aerenchyma. Unfortunately, we did not observe the appearance of aerenchyma cell in this study, but the parameter growth of grain yield was significantly high at urea with and without nitrification inhibitors (NIs) and zeolite treatments compared to control (Table 1). In addition, based on morphological observation of rice growth at urea with and without nitrification inhibitors (NIs), zeolite treatments have larger and more tillers compared to control, and the enhancement also possibly allows a substantial pathway for CH_4 to be transported to the atmosphere.

The NUE treatments were applied to increase nitrogen use efficiency of rice and reduce nitrogen loses to environment, e.g., N_2O and NO_3^-. But, an addition of nitrification inhibitors and zeolite with urea did not gain any increased yield compared to urea alone. However, the rice grain yield on urea with and without NUE treatments was significantly higher than control. In addition, the grain yield in CF was higher than that in NCF; however, the paired comparison of CF and NCF plots resulted in no difference in grain yield ($P < 0.05$) (Table 1). This result is in contrary to other studies where nitrification inhibitors have enhanced the rice grain yield (Roy et al. 2006; Datta and Adhya 2014; Ma et al. 2007). However, this result is also in agreement with the discovery of Majumdar (2005) that plant nitrogen uptake and nitrogen recovery efficiency were not significant between urea and NUE (additional DCD and neem material) treatments in flooded rice field, and Yang et al. (2015) also reported no significant effect of irrigation management and controlled release fertilizer on rice grain yield. Several studies have pointed out that in rice field system, NUE is effective for improving nitrogen use efficiency in dry cropping system or the delay between nitrogen application and flooding (Barison and Uphoff 2011; Carreres et al. 2003).

Treatments of urea with nitrification inhibitors and zeolite were proposed and evaluated as one of the mitigation options for N_2O emission in this area; therefore, the focus was on the determination of nitrification after drainage. Urea with NIs and zeolite has a suppressive effect on N_2O emission from NCF plot compared to CF plot with the averages of inhibitions about 46.3% and 19.3% of NCF and CF, respectively. These quantities of reduction are also finding by Linquist et al. (2012) of 17–39% by using metadata analysis. Akiyama et al. (2010) also reported that nitrification inhibitor (DCD) reduced N_2O emission from rice field at averages 24% to 43%. The N_2O emission was less observed in CF plot before drainage that might at that time the soil might be in an anaerobic condition, as anticipated from CF plot, the anaerobic denitrification is considered to be the main process causes N_2O reduction. In denitrification, N_2O is used as an electron acceptor and transforms it to N_2 when NO_3^- content in the soil is very low (Audet et al. 2014). Indeed, it confirmed the concentration of NO_3^- in soil at flooding time around 0.003 μg–N g^{-1} (Fig. 2a). However, a larger portion of N_2O emission occurred following drainage started at 53 DAT to 81 DAT, which perhaps derived from nitrification–denitrification. In contrary, the emission of N_2O in NCF plot was fluctuated during measurement time. Unlike CH_4, the N_2O emission was variable across in NCF plot and urea with NIs and zeolite has a lower emission of N_2O compared to urea alone, but it was also not significantly different.

The averages amount of N_2O fluxes released from NCF plot was a half compared to CF plot. As a result, the total or cumulative of N_2O emission was more than CF plot, but this also is not significant to other treatments by pair comparative ($P < 0.05$). Similar by Kudo et al. (2016) reported that the cumulative emission indirect N_2O emission in continuously flooded treatment was approximately four times larger than in non-continuously flooded treatment (3.9 mg–N_2O m^{-2}), while Haque et al. (2017) found that intermittent drainage decreased the net ecosystem carbon budget by ca. 6–64% than CF under same rate of biomass. Other reports showed that application of NIs considerably lowered inhibition of N_2O emission in different types of soil and climate (Mohanty et al. 2009; Datta and Adhya 2014). Therefore, it seems that there was not a consistent effect of urea with NIs and zeolite under both water input managements in the rice field.

Conclusions

The use of NIs and zeolite tends to lower N_2O emission in both plots of CF and NCF compared to urea alone, while emissions of CH_4 were stimulated, especially at CF plot. But, there was no significant difference in the emissions of CH_4 and N_2O among the type of urea granulated with and without NIs and zeolite in both water managements. A paired comparison of CF and NCF plots showed a significant difference in the emission of CH_4 at UGZN treatment and also lesser CH_4 emissions in NCF plot compared to CF plot. The urea with NIs and zeolite used in this study has little effect on delayed oxidation of NH_4^+, with an assumption that the retardation of NH_4^+ in the soil is due to the anaerobic condition in the field soil. Hence, reasonably larger amount of CH_4 emission resulted from CF than from NCF. The effect of urea with nitrification inhibitors and zeolite at improving rice grain yield was also not different from urea granule alone. Therefore, the management of irrigation practice promises to reduce CH_4 and N_2O emissions compared to the application of urea with NIs and zeolite. The extra cost of its use needs to be considered, and more studies are suggested on these inhibitors and zeolite on different background properties of soil and rice varieties for more understanding of their influence on parameter growth and yield.

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