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Evaluation of fertilizer and water management effect on rice performance and greenhouse gas intensity in different seasonal weather of tropical climate

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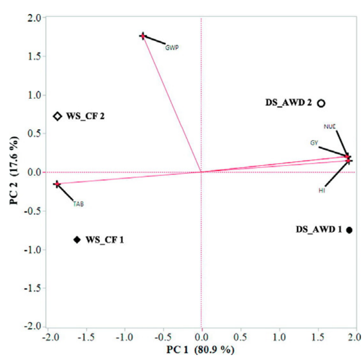
HIGHLIGHTS

- Cattle manure combined with urea fertilizer enhanced global warming potential under continuous flooding;
- $CaSiO_3$ application increased global warming potential despite reduction in N_2O emission under alternate wetting and drying;
- Utilizing urea was an optimal N to sustain rice production and minimize global warming potential in tropical climate;
- Alternate wetting and drying was effective in reducing global warming potential in double cropping rice system.

GRAPHICAL ABSTRACT



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ABSTRACT

Intensively double cropping rice increases greenhouse gas (GHG) emission in tropical countries, and hence, finding better management practices is imperative for reducing global warming potential (GWP), while sustaining rice yield. This study demonstrated an efficient fertilizer and water management practice targeting seasonal weather conditions effects on rice productivity, nitrogen use efficiency (NUE), GWP, and GHG intensity (GHGI). Two-season experiments were conducted with two pot-scale experiments using urea and urea + cattle manure (CM) under continuous flooding (CF) during the wet season (2013WS), and urea with/without $CaSiO_3$ application under alternate wetting and drying (AWD) during the dry season (2014DS). In 2013WS, 120 kg N ha^{-1} of urea fertilizer resulted in lower CH_4 emission and similar rice production compared to urea + CM. In 2014DS, $CaSiO_3$ application showed no difference in yields and led to significant reduction of N_2O emission, but increased CH_4 emission and GWP. Due to significant increases in GHG emissions in urea + CM and $CaSiO_3$ application, we compared a seasonal difference in a local rice cultivation to test two water management practices. CF was adopted during 2013WS while AWD was adopted during 2014DS. Greater grain yields and yield components and NUE were obtained in 2014DS than in 2013WS. Furthermore, higher grain yields contributed to similar values of GHGI although GWP of cumulative GHG emissions was increased in 2014DS. Thus, utilizing urea only application under AWD is a preferred practice to minimize GWP without yield decline for double cropping rice in tropical countries.

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1. Introduction

Increased greenhouse gas (GHG) emissions have increased the global warming potential (GWP) in all regions of the world, resulting in elevated global average temperature near the surface of the Earth. Methane (CH_4) and nitrous oxide (N_2O) are two important greenhouse gases in agricultural soils that cause chemical changes in the atmosphere. Irrigated rice fields have the potential to emit both CH_4 and N_2O simultaneously, but the magnitude of these emissions depends on agricultural management systems (Linquist et al., 2012). Paddy field and irrigated lowland rice cultivation systems significantly affect the emissions of CH_4 and N_2O (Cai et al., 1997; Yao et al., 2012). Linquist et al. (2012) estimated that the aggregate emission of CH_4 and N_2O in rice production systems was approximately four times higher than that of either upland wheat or maize systems.

Agricultural practices have the potential to mitigate GHG emissions. The most effective management practices to mitigate GHG emission for irrigated rice paddies, particularly to reduce CH_4 emissions, are water management practices during the rice-growing season (Trost et al., 2013; Yan et al., 2005). Appropriate water management strategies can substantially decrease GHG emissions (Feng et al., 2013). The most effective practices include midseason drainage and intermittent irrigation, which aims to improve rice growth by controlling surplus tillering and supplying rice roots with molecular oxygen (O_2) to prevent sulfide toxicity (Kanno et al., 1997). Another practice is alternate wetting and drying (AWD), which conserves water and reduces GHG emissions in rice cultivation while maintaining yields; AWD was developed by the International Rice Research Institute (IRRI) (Bouman et al., 2007). The AWD practice in Southeast Asia was adopted in rice cultivation during the dry season (DS) instead of the wet season (WS) because of water shortage in a rice–rice double cropping system. WS rainfall is typically sufficient to sustain rice crops, whereas additional irrigation is required for viable rice crops in the DS. The DS generally produces higher emissions than the WS due to high plant biomass (Sass et al., 1990; Ziska et al., 1998). However, lower emissions during the DS were also reported (Corton et al., 2000). Both rice-growing seasons can be significant sources of CH_4 and N_2O depending on fertilizer and water management practices. Significant CH_4 emissions may occur under continuously flooded soils, whereas N_2O emissions result if soils are alternately wet and dry (Bronson et al., 1997). Thus, the estimated GHG budget exhibited large spatio–temporal variations (Chakraborty et al., 2006).

Many studies have reported the effect of N fertilization on rice production and its relation to GHG emissions (Cai et al., 2007; Ku et al., 2016). In general, N fertilization can increase whole rice biomass productivity while resulting in vigorous growth in arenchyma, tiller number, and root biomass as well as releasing increased amount of labile carbon and CO_2 during the productive stages (Wassmann et al., 2000a). Under submerged paddy soils, CH_4 is produced from the soil due to the anaerobic condition of the soil. In theory, CH_4 has three different emission pathways to the atmosphere: diffusion through the water layer, ebullition (i.e. bubbling), and transport through the arenchyma of rice plants. Nitrous oxide is produced by ammonia-oxidizing bacteria and archaea via nitrification and denitrification processes in the soil (Santoro et al., 2011). The emissions of N_2O depend on the presence of water logging, soil Eh, and the amount and timing of the application of N sources (Cai et al., 1997; Zou et al., 2005). Under submerged paddy soils, N_2O emissions are normally inhibited due to an anaerobic condition by low soil Eh and most N gas is released as N_2 (Hou et al., 2000; Mosier et al., 1990). Under AWD, the soil microbial processes of nitrification and denitrification enhance N_2O emissions (Khalil et al., 2004; Wang et al., 2011). Nitrous oxide has higher global warming potential than CH_4, thus its emission from paddy soils should be controlled. Improving the efficiency and effectiveness of crop N use can potentially reduce N_2O emission by reducing the potential for elevated residual NO_3-N in the soil profile (Dobermann, 2007; Snyder and Bruulsema, 2007).

A silicate fertilizer such as $CaSiO_3$ was shown to be one of the promising strategies to mitigate GHG emission from rice cultivation (Ali et al., 2008). It is a byproduct of the steel industry and contains high amounts of active iron and free iron oxides, acting as an oxidizing agent that controls CH_4 emissions in submerged paddy soils. Slag-type silicate fertilizer used as soil amendment, along with nitrogenous fertilizer in rice cultivation, significantly decreased seasonal CH_4 flux by 16–20% and increased rice productivity by 13–18% in Korean wetland paddy soils (Ali et al., 2008). In the upland rice paddy soils of Bangladesh, the same type of silica fertilizer with urea application decreased total seasonal CH_4 flux by 12–21% and increased rice grain yield by 5–18% (Ali et al., 2012). However, information on the effect of a silicate fertilizer on N_2O emissions is limited, and further study is needed to evaluate the effect of this fertilizer through evaluating N use efficiency.

In tropical countries, most farmers have applied animal manure or the combination of manure and synthetic N fertilizer as sources of N to produce rice yield. However, animal manure application may cause significant CH_4 emissions, especially under continuous flooding in the WS. Although AWD irrigation in the DS due to water scarcity has been recommended to suppress CH_4 emission, it has the risk of increasing N_2O emission mainly due to the use of synthetic N fertilizer. Current fertilizer and water management practices are focused on sustaining rice production while reducing GHG emissions. However, seasonal weather differences between the WS and DS are not taken into account and few studies have examined the effect of these seasonal differences. Our research examined fertilizer and water management effects on rice production, nitrogen use efficiency, and GHG emissions in a wet and dry season. A conceptual framework is provided (Fig. 1). The specific objectives of this study were to 1) determine an optimal N application based on rice production and GHG emissions, 2) elucidate the role of silicate in rice production and GWP of CH_4 and N_2O emissions under AWD irrigation, and 3) propose an efficient fertilizer and water management practice that takes in account seasonal weather effects on reducing GWP without reducing yield in a double cropping rice system.

2. Materials and methods

2.1. Experimental design

Two-season pot-scale experiments were consecutively conducted in a screen house at the IRRI during the wet season (WS), from May 29 to October 3, 2013 for experiment 1 (2013WS) and during the dry season (DS), December 20, 2013 to April 22, 2014 for experiment 2 (2014DS). Based on local field and climate conditions in Philippines, 2013WS was conducted with continuous flooding (CF) water management method during the WS since rainfall was sufficient to supply water for rice production. However, alternate wetting and drying (AWD) water management was applied for 2014DS because of water scarcity during the DS (Fig. 2a and b).

A polyethylene pail with a height of 700 mm, inner diameter of 530 mm, and capacity volume of 138 L was used as a pot and chamber. This experimental setup was adopted from the design of Furukawa et al. (2007) but modified to meet the requirements of the current experiment. The modified pot consists of a water-filled channel fitted at the top of the pot circumference to prevent the diffusion of gas after the chamber is closed. The chamber includes an ordinary thermometer and a vented silicon tube, which was fitted permanently at a quarter position in the head space and sealed with silicon septum for gas sampling. From the tillering stage of rice plants, a chamber extension made of opaque polyvinyl chloride (PVC) with a height of 200 mm and inner radius of 530 mm was prepared to accommodate rice growth during gas sampling. The outer surfaces of the pots and the gas-collection chambers were covered with aluminum foil to prevent an increase in temperature from sunlight.

Paddy soil, classified as *Andaqueptic Haplaquoll* (Raymundo et al., 1989), was collected from a plow layer in an IRRI experimental field

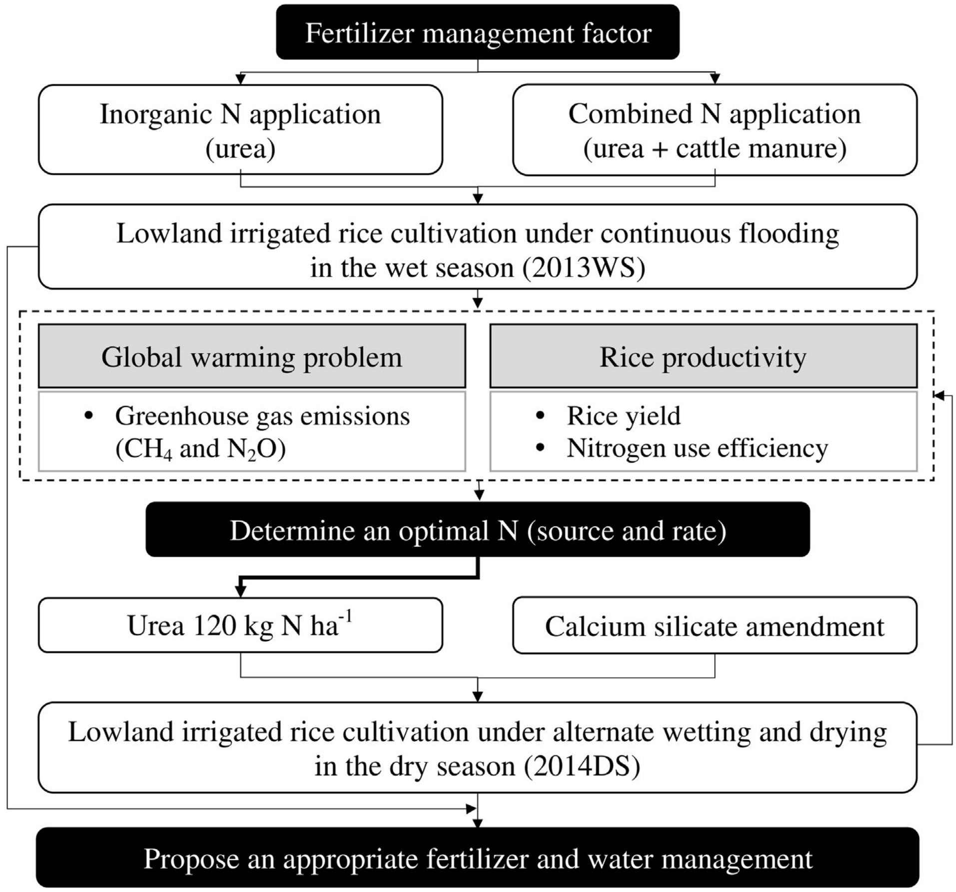

Fig. 1. A conceptual framework of this study.

station (Plot No. 208). The soil samples were prepared following the procedure of IRRI prior to filling each pot to a depth of 500 mm (Pleysier, 1990). A PVC water-level tube (600 mm high and 63.5 mm inner radius) was inserted into the sand layer beneath the 500-mm-deep soil layer along the central axis of the pot to monitor the water level. The chemical and physical properties of the soil in each experiment are shown in Table 1.

2.2. Management of fertilizer application, water irrigation, and rice cultivation

Urea (46% N) and cattle manure (CM) were used as sources of nitrogen (N) for 2013WS. The N rates of urea and its combination with CM were 120 kg N ha^{-1}. The combination ratio of urea and CM was 1:1 (urea:CM = 60:60 kg N ha^{-1}). CM was collected from the animal farm station of the Animal Science Cluster at the University of the Philippines Los Baños, air-dried for one month, and sieved before application with mesh of 10 mm. The prepared soil samples were mixed with CM one day before transplanting. For 2014DS, calcium silicate ($CaSiO_3$, Si 24%) was used as a source of Si, and the amount of $CaSiO_3$ (224.5 kg ha^{-1}) was determined based on the recommended rate for tropical rice paddy soils (Dobermann and FairHurst, 2002). Urea was split into three applications and applied on −1, 29, and 60 days after transplanting (DAT) for 2013WS, and on −1, 32, and 54 DAT for 2014DS, respectively. Prior to transplanting on −1 day, CM and $CaSiO_3$ were applied in each experiment (Table 2). Both experimental layouts were a randomized complete block design with four replications.

Water management practices for 2013WS and 2014DS were continuously flooded (CF) and alternating wetting and drying (AWD), respectively. The condition of surface water during the rice growing seasons is shown in Fig. 2b. The experimental conditions during the two different seasons were identical and comparable except the flooding treatment used to represent local farming practices. In 2013WS, irrigation was applied two to three times per week until 104 DAT. 50 mm of water was maintained above the soil surface in the flooded pots throughout the rice-growing period. In 2014DS, irrigation was carried out once or twice a week from 36 DAT to 100 DAT when the water table inside the tube was at a depth of ≤150 mm below the soil surface. Irrigation in both seasons was stopped before the physiological maturity stage and the harvest was conducted at 108 DAT.

The rice cultivar was used for the experiments. PSB Rc-18 (*Oryza sativa* L.) (a popular variety among Filipino farmers) is a medium maturing variety (123 days to maturity and tillering capacity of 15 productive tillers $plant^{-1}$) (Cruz et al., 2005). An unfertilized wet bed was used for the seed bed (100 g seeds me-2) to prepare 15 day old seedlings. Transplanting was performed with 3 seedlings $hill^{-1}$ and 4 hills pot^{-1} for the experiments in 2013WS and 2014DS.

2.3. Agronomic measurements and analysis of nitrogen use efficiency

Rice grain yield and yield components (weight of 1000 grains, the number of panicles $hill^{-1}$, total spikelets $panicle^{-1}$, and % filled spikelets) were measured after harvest. Grain yield and total aboveground biomass were obtained after oven drying the samples at 70 °C for three days.

Total N was measured for both soil and plants, which were sampled after harvest. Soil samples were collected from a depth of 0 mm to 150 mm in each treatment. The samples were air dried, ground, and sieved (2 mm) prior to analysis. The aboveground biomass of rice was divided into grains, leaves, and stems and dried in an oven at 70 °C for three days. Each part was ground separately by a mechanical grinder

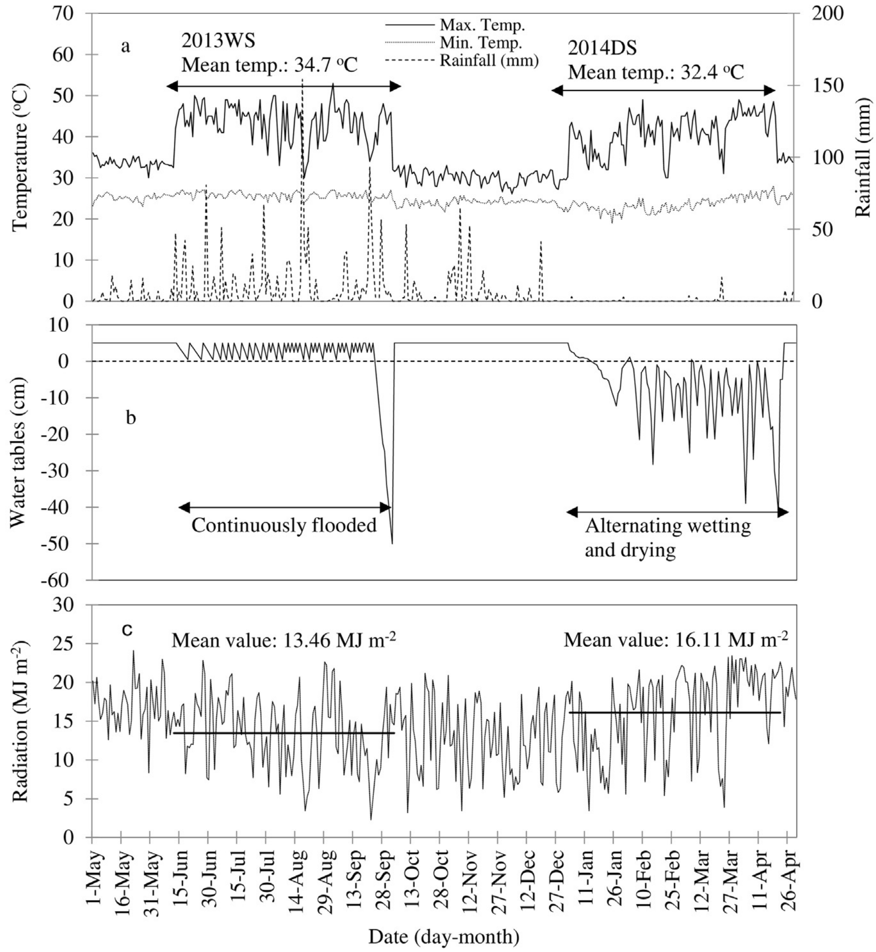

Fig. 2. Observed daily maximum and minimum temperature, amount of rainfall, water tables, and mean values of radiation during the wet season (2013WS) and dry season (2014DS).

and mixed to obtain a subsample for the analysis. The total N of the soil and rice plants was quantified using the Kjeldahl method. Each sample was analyzed in triplicate (Bremner et al., 1996). The partial factor productivity of applied N (PFP_N) and internal N efficiency (IE_N) (Yang et al., 2016) was determined using the following equations:

$$PFP_N = \frac{\text{grain yield in N application pot (g)}}{\text{N rate (g)}}$$

$$IE_N = \frac{\text{grain yield (g)}}{\text{N uptake of plant (g)}}$$

2.4. Measurement of CH_4 and N_2O

The gas flux in the pot experiment was measured using the closed chamber method of Hutchinson and Mosier (1981). Gas sampling was conducted in the morning (0730 to 1100) every week under CF and two to three times a week under AWD using a 50-mL plastic syringe at 5, 10, and 15 min (2013WS) and 2, 17, and 32 min (2014DS) after closing the chamber. The samples were immediately analyzed in the laboratory by gas chromatograph (SRI 8610C, Sri Instrument) equipped with a flame ionization detector and an electron capture detector to measure the concentrations of CH_4 and N_2O, respectively. Methane and N_2O fluxes were estimated with the equation (Rolston, 1986).

$$F = \rho \times (V/A) \times (\Delta c/\Delta t) \times [273/(273 + T)] \times (P/760) \times 60 \times 24$$

where F is the flux (in mg CH_4 m^{-2} day^{-1} and mg N_2O m^{-2} day^{-1}),
ρ is the gas density ($\rho CH_4 = 0.714$ kg CH_4 m^{-3} and $\rho N_2O = 1.964$ kg N_2O m^{-3} at 273 K and 760 mm Hg),
V is the volume of the chamber (in m^3),
A is the cross-sectional area of the chamber (in m^2),
Δc/Δt is the change in gas concentration inside the chamber as a function of time ($\Delta 10^{-6}$ m^3 m^{-3} min^{-1}),
T is the air temperature inside the chamber (in °C),
273 is a correction factor between C and K, and
P is the air pressure (in mm Hg).

The daily data of gas emissions were calculated by linear interpolation between the observed values of gas concentrations (Katayanagi

Table 1
Selected physical and chemical properties of soils used in the pot experiments.

Experimental season	pH	EC	CEC	Total nitrogen	Total organic carbon	Clay	Sand	Silt
	(1:1)	(dS m^{-1})	($cmol_c$ kg^{-1})	(%)	(%)	(%)	(%)	(%)
2013WS	6.6	0.97	36.0	0.11	1.24	41	24	35
2014DS	6.4	0.42	37.1	0.11	1.16	40	26	33

Table 2
Detailed treatments of nitrogen and silicate fertilizer application and water management practice for the wet season of 2013 (2013WS) and dry season of 2014 (2014DS).

Experimental season	Treatment	Water management	Amount of nitrogen and silicate fertilizer application[a]	
			(kg N ha^{-1})	(kg $CaSiO_3$ ha^{-1})
2013WS	WS_CF 1	Continuously flooded (CF)	120	0
	WS_CF 2		120 (60 + 60)[b]	0
2014DS	DS_AWD 1	Alternating wetting and drying (AWD)	123.5	0
	DS_AWD 2		123.5	224.7

[a] The amount of nitrogen and silicate fertilizer was recommended from IRRI nutrient manager for each season of rice plants (available at http://webapps.irri.org/ph/rcm/).
[b] Urea and cattle manure were combined at the ratio of 1:1.

et al., 2012) and summed up to estimate the GWP in CO_2 terms by multiplying observed values by 34 and 298 (Myhre et al., 2013).

The value of P was assumed to be 760 mm Hg in the current study. Before measuring the gas samples, the standard retention interval was calibrated every two weeks using standard gas curves ($R^2 > 0.99$) at 0, 0.05, 0.1, 0.5, and 1 ppm (parts per million) of N_2O and 0, 3, 5, 7, and 10 ppm of CH_4.

2.5. Statistical analysis

One-way ANOVA was computed using the STAR V. 2.0.1 computer program, whereas the differences between means were determined using the least significant difference at $p < 0.05$. Multiple regression analysis was conducted using the JMP pro V.12.1.0 for the principal component analysis (PCA) in order to interpret the effect of each treatment on rice productivity and global warming potential. Factor loading, eigenvector, eigenvalue, cumulative proportion, and principal component (PC) score were obtained through this analysis.

3. Results and discussion

3.1. Differences in yield performance and NUE between 2013WS and 2014DS

First experiment in 2013WS was conducted to determine the separate and combined effects of cattle manure (CM) and urea fertilizer on grain yield, nitrogen use efficiency (NUE), and greenhouse gas (GHG) emissions under continuously flooded (CF) water management (Ku et al., 2016). Based on the result of principal component analysis (PCA), the optimum N rate was determined to be 120 kg N ha^{-1} of urea and combination of urea with cattle manure (urea + CM = 60 + 60 kg N ha^{-1}), which indicated high rice productivity and NUE. However, there were no differences in rice production, yield component, and NUE between urea 120 kg N ha^{-1} (WS_CF 1) and urea + CM 120 kg N ha^{-1} (WS_CF 2) (Table 3). In the previous studies, Kang and Roh (2012) and Webb et al. (2013) studied available N of manure, which is the percentage of available N to be considered equivalent to the efficiency of manure N in the season of application. The average available N was in solid cattle manure approximately 30%. The N use efficiency (NUE) of mineral N fertilizer is approximately 60% by crop uptake. Then the N fertilizer replacement value (NFRV) of manure will be 50%. For reference, CM 60 kg ha^{-1} will become 30 kg ha^{-1} equivalent to urea. When 60 kg ha^{-1} urea is added to 30 kg ha^{-1} equivalent to urea of CM, the combination N has 90 kg ha^{-1} equivalency to urea. Therefore, no yield difference between combined application of urea and CM and sole urea application at the same N rate of 120 kg ha^{-1} was reasonable due to the practical application rate of N.

Followed by the N rate and source (120 kg urea-N ha^{-1}) determined by PCA analysis (Ku et al., 2016), two levels of $CaSiO_3$ application at 0 (DS_AWD 1) and 224.5 kg $CaSiO_3$ ha^{-1} (DS_AWD 2) were tested to evaluate the effect on rice productivity and NUE under alternating wetting and drying (AWD) water management in 2014DS. $CaSiO_3$ application had no significant difference on rice production, yield component, and NUE although rice plant in DS_AWD 2 treatment absorbed more SiO_2 content than in DS_AWD 1 treatment (Table 3). We could assume

Table 3
Rice production, yield component, nutrients uptake, nitrogen use efficiency (NUE), and total soil N after harvest in 2013WS and 2014DS.

Yield parameter	2013WS		2014DS	
	WS_CF 1	WS_CF 2	DS_AWD 1	DS_AWD 2
Rice production				
TAB (g pot^{-1})	665.4 ± 36.9a	639.1 ± 21.0a	519.0 ± 26.1b	545.6 ± 16.5b
GY (g pot^{-1})	236.9 ± 18.8b	232.2 ± 7.3b	281.7 ± 11.2a	287.9 ± 6.5a
HI (%)	35.6 ± 1.0c	36.4 ± 0.6c	54.1 ± 0.6a	52.8 ± 0.4a
Yield component				
PFS (%)	95.1 ± 0.7b	95.4 ± 0.7b	99.0 ± 0.0a	98.9 ± 0.1a
TGW (g)	15.8 ± 0.9b	15.6 ± 0.4b	18.3 ± 0.0a	18.0 ± 0.3a
Panicles hill^{-1} (no.)	32.1 ± 0.3c	30.8 ± 0.6d	35.4 ± 0.1b	38.6 ± 1.2a
Spikelets panicle^{-1} (no.)	118.4 ± 14.0a	121.2 ± 4.0a	109.2 ± 4.4ab	103.6 ± 0.2b
Nutrient uptake				
Total N (%)	0.88 ± 0.01a	0.87 ± 0.01a	0.86 ± 0.01a	0.86 ± 0.02a
Total SiO_2 (%)	–	–	13.0 ± 0.2b	13.7 ± 0.01a
Nitrogen use efficiency				
PFP_N (g g^{-1})	40.3 ± 3.2b	39.5 ± 1.2b	47.6 ± 1.9a	48.6 ± 1.1a
IE_N (g g^{-1})	40.5 ± 0.8b	41.7 ± 1.6b	63.1 ± 1.4a	59.6 ± 1.9a
Total soil N after harvest	0.13 ± 0.01b	0.14 ± 0.01a	0.12 ± 0.01c	0.12 ± 0.01c

Values are means ± SD for four replications. Different lowercase letters indicate significant differences for treatment at $p < 0.05$ by one-way ANOVA (LSD).
Note: WS_CF 1 = 120 kg urea-N ha^{-1}, WS_CF 2 = 60 kg urea-N + 60 kg manure-N ha^{-1}, DS_AWD 1 = 123.5 kg urea-N ha^{-1}, DS_AWD 2 = 123.5 kg urea-N ha^{-1} applied with 224.7 kg $CaSiO_3$ ha^{-1}, TAB = total aboveground biomass, GY = grain yield, HI = harvest index, PFS = percentage of filled spikelets, TGW = 1000-grain weight, PFP_N = Partial factor productivity of applied N: grain yield in N application pots (g)/N rate (g), and IE_N = internal N use efficiency: grain yield (g)/total cumulative plant N (g).

a critical level of SiO_2 content was absorbed by rice plant and was available in soil. Ma and Takahashi (2002) evaluated the Si requirement to increase rice yield with rice straw having < 11% SiO_2. There was no effect when rice straw had a SiO_2 content higher than 13% or when available SiO_2 content in the soil was higher than 130 mg kg^{-1}. Our data showed seemingly no effect of $CaSiO_3$ application on rice yield because there were 13% and 13.7% SiO_2 in aboveground biomass. Moreover, Yoshida (1975) reported that soil in IRRI experimental farm contains about 170 mg available SiO_2 kg^{-1} and he thus concluded that Si deficiency was not a constraint as this soil is fertile clay derived from young volcanic soils that tend to be rich in available Si. In addition, Si deficiency is not yet common in the intensively irrigated rice systems of tropical Asia (Dobermann and Fairhurst, 2000).

Typically, lowland rice in tropical weather is grown under CF condition regardless of the seasons, and the cultivated rice (PSB Rc 18) is one of the flood adapted varieties (Cruz et al., 2005). Recently developed AWD water management technology coping with saving irrigation water without yield reduction has been adopted for rice production in tropical climates. According to the results of 31 field experiments across Asia, almost 92% of the AWD irrigations resulted in yield reductions varying from negligible to 70% compared with the yield of the flooded conditions in the same season. The large variability in results was due to differences in the number of day of soil drying between irrigations and the soil and hydrological conditions (Bouman and Tuong, 2001). Thereafter, Bouman et al. (2007) developed "Safe" AWD technology. One of the key elements in the AWD technology is that during the rice growing period, irrigation water is applied whenever the perched water table falls to approximately 15 cm below the soil surface. The threshold of 15 cm will not cause any yield decline since the roots of the rice plants are still able to take up water from the perched groundwater and the almost saturated soil above the water table. Although we applied AWD water management only during 2014DS, differences in rice performance and NUE (PE_N and IE_N) between 2013WS and 2014DS were observed (Table 3). Data showed that 2014DS presented superior grain yield, yield component as well as harvest index, and NUE. Yang et al. (2016) pointed out three physiological mechanisms involved in increasing grain yield and water and N-use efficiencies under AWD irrigation in rice. First, AWD elevates abscisic acid levels in plants during the soil drying period, which can enhance the movement of photosynthetic assimilates towards developing seeds (Chen et al., 2016; Yang et al., 2002). Second, a "re-watering" effect increased the cytokinin levels in roots and leaves, root oxidation activities, and leaf photosynthetic rate in AWD. High cytokinin concentrations under AWD during grain setting and filling periods may help improve grain filling (Zhang et al., 2010). Third, a compensatory effect exists in AWD. Unlike CF water management, AWD water management can reduce the maximum number of tillers by 21%–23% and total leaf area by 14%, but the number of productive tillers and effective leaf area (leaf area of main stems and productive tillers) did not significantly differ between CF and AWD (Yang and Zhang, 2010). In the current study, 2014DS under AWD evidently increased the percentage of filled spikelets, 1000-grain weight, and panicles per hill. The improved yield component will reduce the amount of water used in producing unproductive tillers, which helps increase the total aboveground biomass. Furthermore, reduced redundant vegetative growth and increased carbon remobilization from vegetative tissues to kernels during grain filling can help increase the harvest index, which can improve grain yield (Yang and Zhang, 2010; Zhang et al., 2009). Wang et al. (2016) demonstrated that grain yield, water use efficiency, and NUE in rice are determined by irrigation regimes (e.g. alternate wetting and drying and continuous flooding) and their interaction with N rates. The study concluded that a synergistic water-N interaction can be achieved by AWD water management with a normal amount of N application. Further, the AWD exhibited a higher PFP_N and IE_N than CF, which was confirmed by Liu et al. (2013), Xue et al. (2013), and Chu et al. (2016). An additional considerable factor is the influence of solar radiation and temperature on biomass production, particularly grain yield (Islam and Morison, 1992). During the experimental periods, the average daily mean maximum and minimum temperature in the screen-house and the daily precipitation and average daily mean radiation values from the IRRI weather station were observed. The mean temperature values for 2013WS and 2014DS were 34.7 °C and 32.4 °C, respectively, and the mean radiation values were 13.46 MJ and 16.11 MJ m^{-2}, respectively (Fig. 2a and c). According to published results (Deng et al., 2015; Islam and Morison, 1992; Yoshida and Parao, 1976), a linear relation exists between grain yield and irradiance during the reproductive and ripening stages, whereas a negative correlation exists between grain yield and temperature as temperature increased. The rise in irradiance significantly improved grain yield by increasing panicle number, percentage filled grain, and 1000-grain weight, which consequently enlarged the harvest index, thus supporting the obtained results. Pan et al. (2017) observed that there was no significant interaction effect between water and N on the total N uptake and NUE over the two years in the same season, but grain yield in the first year was higher than in the later year probably due to greater solar radiation. Thus, a synergistic effect between AWD, solar radiation, and air temperature during 2014DS improved rice production and NUE.

3.2. CH_4 and N_2O emissions in response to GWP and GHGI

The evaluation of N fertilizer on the cumulative GHGs emission for 2013WS indicated that the combination of urea and cattle manure (WS_CF 2) enhanced CH_4 emissions as well as GWP under CF (Table 4). Similar result demonstrated that CM enhanced CH_4 emission over urea treatment as combined with urea at the same N rate (Ku et al., 2016). Dash et al. (2014) and Kim et al. (2014) supported the result that the labile C content, which is mainly released through microbial soil organic matter decomposition, can be increased by applying organic amendments, such as farmyard manure, crop residue, green manure, and animal manure, and hence increasing the CH_4 emission into the atmosphere.

As a promising strategy to mitigate CH_4 emissions, AWD water management was conducted during the rice production period in 2014DS. In Table 4, results indicated that $CaSiO_3$ application (DS_AWD 2) reduced N_2O emissions, while increased CH_4 emissions, as compared to urea alone (DS_AWD 1). In a previous study by Ku et al. (2017), there was a mechanism to explain the reverse trend of GHG emissions in the relation to use in rice plant. Silicon absorption by plants occurs as monosilicic acid (H_4SiO_4) which adsorbs or retains inorganic N (NH_4^+) weakly in soil solution (Matichenkov and Bocharnikova, 2001). At this absorption by rice plant, the NH_4^+ adsorbed in the surface area of H_4SiO_4 together or with other nutrients contributes to enhance rice growth through nutrient uptake mechanism (Meena et al., 2014). In general, N fertilization can increase whole rice biomass production, in addition to with Si fertilization in most rice cultivation. Si fertilization increases the number of panicles and grain yield sequentially. Vigorous growth in arenchyma, panicles number, and root biomass produced and released more labile carbon and CO_2 during the productive stages (especially the tillering and panicle initiation period), being produced CH_4 emission, as described by Wassmann et al. (2000b). Our result showed that the comparable total aboveground biomass and panicles number $hill^{-1}$ seemed to contribute to a reverse trend of higher CH_4 and lower N_2O emissions by $CaSiO_3$ application.

Between 2013WS and 2014DS, the pattern in CH_4 emissions differed (Fig. 3a and b). For 2013WS, the CH_4 emission gradually increased with rice growth. After split N application on −1, 29, and 60 days after transplanting, the tendency of CH_4 emission to increase was observed until 99 DAT when irrigation events were stopped for the physiological maturity of rice. However, for 2014DS, the CH_4 emissions initially increased, reached a peak at 35 DAT, decreased, and maintained at a lower level because of the anaerobic and aerobic cycles that occurred

Table 4
Effect of fertilizer and water management on cumulative CH_4 and N_2O emission in response to global warming potential and greenhouse gas intensity.

Experimental season	Treatment	Cumulative CH_4 emission	Cumulative N_2O emission	GWP	GHGI
		(g m^{-2})	(g m^{-2})	(g CO_2 eq. m^{-2})	
2013WS	WS_CF 1	18.7 ± 0.5b	<d.l[†]	637.0 ± 34.2d	0.59 ± 0.04c
	WS_CF 2	23.1 ± 0.4a	<d.l	787.0 ± 28.1b	0.75 ± 0.04a
2014DS	DS_AWD 1	18.3 ± 0.2b	0.24 ± 0.01a	693.8 ± 20.0c	0.54 ± 0.03c
	DS_AWD 2	23.9 ± 0.6a	0.16 ± 0.01b	859.6 ± 38.1a	0.66 ± 0.03b

Values are means ± SD for four replications. Different lowercase letters indicate significant differences for treatment at $p < 0.05$ by one-way ANOVA (LSD).
Note: T1 = 120 kg urea-N ha^{-1}, T2 = 60 kg urea-N + 60 kg manure-N ha^{-1}, T3 = 123.5 kg urea-N ha^{-1}, T4 = 123.5 kg urea-N ha^{-1} applied with 224.7 kg $CaSiO_3$ ha^{-1}, GWP = global warming potential, and GHGI = greenhouse gas intensity.
† Under detection limit.

in soil. The variation in CH_4 emissions was attributed to the alternate water management practice. In paddy fields, CH_4 was inversely related to soil redox potential and was produced by methanogenic bacteria when the redox potentials are lower than −150 mV. Continuous flooding rice cultivation tends to decrease redox potential and provides a suitable environment for CH_4 production (Yagi et al., 1996). The changes in community structure and the metabolic activity of methanogenic archaea derived from AWD irrigation, which is associated with alternate anaerobic and aerobic cycling, influenced CH_4 emission under more oxidized conditions (WatanabeA, 2010). Several studies indicated that AWD is one of the most promising approaches to mitigate CH_4 emission (Li et al., 2002; Wassmann et al., 2000b; Yagi et al., 1997).

Two water management practices targeted for the WS and DS were adopted in the current study. Aside from CM and $CaSiO_3$ application, WS_CF 1 (2013WS) and DS_AWD 1 (2014DS) was only compared for evaluating GHG emissions, GWP, and GHGI (Table 4). No difference in CH_4 emissions was obtained, but DS_AWD 1 resulted in higher N_2O emission and GWP. The results could be attributed to the effect of rice growth and water management in relation to seasonal weather. Previous studies (Andales et al., 1994; Huang et al., 1997; Sass et al., 1990) evaluated seasonal assessment of rice growth on CH_4 emissions under CF water management. They concluded that higher rice biomass grown under higher solar radiation and lower air temperature enhanced CH_4 emissions during the DS than in the WS. If the experiment was conducted with both CF and AWD water managements during 2014DS, CF would increase CH_4 emission. Although CF was not applied during 2014DS, our data indicated that the effect of AWD on mitigating CH_4 emissions is probably significant. Moreover, higher grain yields would result in C sequestration instead of CH_4 emissions. van Der Gon et al. (2002) reported a negative correlation between grain yield and CH_4 emissions because of the availability of photosynthetic C as root exudates which is not used in seed production. The researchers summarized that the additional allocation of photosynthetic C to grains instead of roots may reduce CH_4 emissions. Meanwhile, N_2O emission was negligible because the concentrations were below the detection limit during 2013WS (Fig. 3c). In continuously flooded soil, the large amount of N_2O will be further reduced to N_2 before being emitted from the soil (Buresh et al., 2008). However, N_2O emissions can be observed only during 2014DS, which caused for partial peaks of N_2O emission, particularly at 4 to 5 days after the first and second N supplement at 32 DAT and 54 DAT. Thereafter, the peaks were immediately suppressed by re-irrigation events (Fig. 3d). Thus, N_2O emissions may increase when AWD is adopted. Smith and Patrick (1983) observed that alternate anaerobic and aerobic cycling considerably increased N_2O emission relative to that of constant aerobic and anaerobic conditions and net N_2O emission amplified with the duration of anaerobic and aerobic periods. Flessa and Beese (1995) also determined that N_2O emission peaked when waterlogged soil columns were drained to become

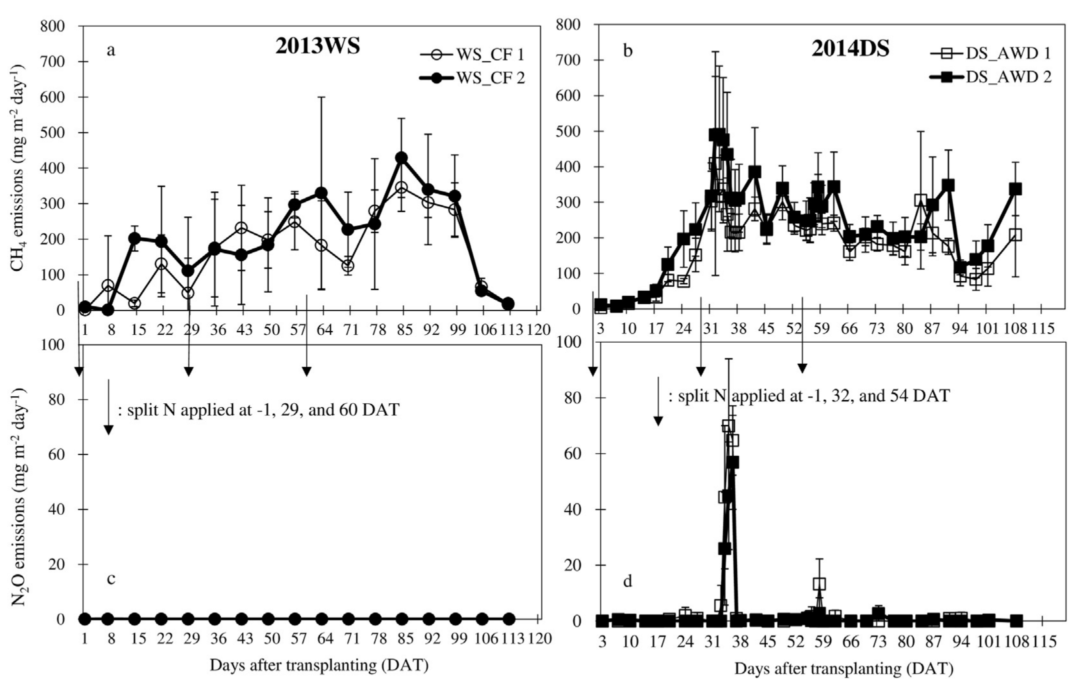

Fig. 3. CH_4 and N_2O emissions under different irrigation treatments in the pot experiment conducted during the wet season (CF) and dry season (AWD). Data are the averages (mean ± SD) for four replications. (Note: WS_CF 1 = 120 kg urea-N ha^{-1}; WS_CF 2 = 60 kg urea-N + 60 kg cattle manure-N ha^{-1}; DS_AWD 1 = 123.5 kg urea-N ha^{-1}; DS_AWD 2 = 123.5 kg urea-N ha^{-1} + 224.7 kg $CaSiO_3$ ha^{-1}).

well-aerated (water-filled pore space = 63%) and a small amount of N_2O was emitted during the waterlogging period.

In conclusion, CM (WS_CF 2) and $CaSiO_3$ (DS_AWD 2) application did not reduce GWP, as determined by the cumulative CH_4 and N_2O emissions. However, urea only treatments exhibited low GWPs at 637.0 g CO_2 eq. m^{-2} (WS_CF 1) followed by 693.8 g CO_2 eq. m^{-2} (DS_AWD 1). The values of GHGI between WS_CF 1 and DS_AWD 1 were determined by dividing GWP by rice yield. No difference in GHGI between them was observed because higher grain yields in DS_AWD 1 contributed to lower value of GHGI.

3.3. Determination of an appropriate fertilizer and water management practice by PCA analysis

Principal component analysis (PCA) was conducted to characterize the effect of each treatment in 2013WS and 2014DS. The factors being engaged for this analysis were HI, GY, NUE, TAB, and GWP, and the analysis was successful as the obtained eigenvalue was 0.9 as of the PC 2 and 98.5% of information was explained with the PC 1 and PC 2. The PC 1 was interpreted as rice productivity since GY, NUE, HI, and TAB were highly contributing factors. The PC 2, on the other hand, was interpreted as an environmental problem as GWP had a high eigenvector. Fig. 4 presents the scattered diagram of the obtained principal component scores, with PC 1 on the x-axis and PC 2 on the y-axis. The figure shows that the treatments with DS_AWD 1 and DS_AWD 2 are in the 2nd and 4th quadrant of the graph where the effect is considered to be high on rice productivity, in contrast with WS_CF 1 and WS_CF 2, while the treatments with WS_CF 1 and DS_AWD 1 are in the 3rd and 4th quadrant where the effect to the environment is considered to be low. Thus, the treatment with DS_AWD 1 in the 4th quadrant is an appropriate fertilizer and water management practice indicating relatively high rice productivity and low environmental effects.

4. Conclusion

Tropical climates allow for a double cropping rice system to be implemented during the wet season (WS) and dry season (DS). The intensively irrigated rice field increases global warming potential (GWP), resulting in elevated global average temperature near the surface of the Earth. Thus, an appropriate practice that sustains rice productivity and reduces GWP must be developed and implemented in rice cultivation in Southeast Asia. The current study evaluated the effect of fertilizer and water management on rice productivity, GWP, and greenhouse gas intensity (GHGI) in different seasonal weather conditions. During 2013WS, the combination of CM with urea fertilizer enhanced GWP more than urea alone under continuous flooding (CF). Although $CaSiO_3$ application led to reduction of N_2O emission, it also increased GWP under alternate wetting and drying (AWD) during 2014DS, as compared to the urea alone. Thus, utilizing urea fertilizer was an appropriate practice to maintain rice yield and prevent increase in GWP in the study. Moreover, alternative water management based on seasonal weather (CF in the WS vs AWD in the DS) did not exhibit differences in GHGI between the 2013WS and 2014DS.

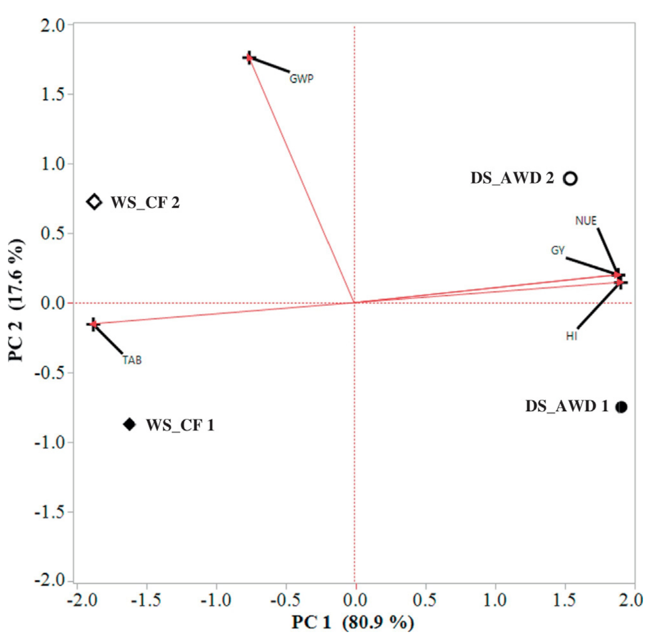

Fig. 4. Assessment of rice productivity (PC 1) and environmental problem (PC 2) on fertilizer and water management. (Each symbol indicated PCA scores in all treatments: WS_CF 1 = 120 kg urea-N ha^{-1}; WS_CF 2 = 60 kg urea-N + 60 kg cattle manure-N ha^{-1}; DS_AWD 1 = 123.5 kg urea-N ha^{-1}; DS_AWD 2 = 123.5 kg urea-N ha^{-1} + 224.7 kg $CaSiO_3$ ha^{-1}).

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