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Assessing fertilizer N placement on CH_4 and N_2O emissions in irrigated rice systems

Maria Arlene A. Adviento-Borbe [a,*], Bruce Linquist [b]

[a] Delta Water Management Research Unit, U.S. Department of Agriculture — Agricultural Research Services, Jonesboro, AR 72401, USA
[b] Department of Plant Sciences, University of California, Davis, CA 95616, USA

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Improved N fertilizer management practices can increase rice yields and mitigate global warming potential (GWP). While banding N has been shown to have positive effects on yield and nitrogen use efficiency (NUE), there is little information on how it affects greenhouse gas (GHG) emissions from flooded rice systems. We tested the hypothesis that in continuously flooded rice systems where GWP is dominated by CH_4 emissions, deep placement of urea in bands would reduce CH_4 and N_2O emissions. Rice yields and GHG emissions were measured from three field experiments which had three treatments: (1) no N (N0), (2) urea broadcast (U-BR) on soil surface and (3) urea banded at 7.5 cm soil depth (U-BA). All urea was applied in a single application before flooding in preparation for planting at N rates of 143–150 kg N ha^{-1}. Throughout the rice growing season GHG emissions were measured using a vented flux chamber and gas chromatograph. Across all fields, N fertilizer application increased yield on average by 121%. Between the N placement methods, grain yields and NUE (37 kg grain kg^{-1}) were similar. Daily N_2O emissions were low to negative and did not differ among treatments. CH_4 emissions were the major source of GWP emissions and cumulative emissions ranged from 6.3 to 297 kg CH_4–C ha^{-1} $season^{-1}$ among fields. While in some cases fertilizer N increased CH_4 emissions, there was no effect of N placement on them.

1. Introduction

Rice is the largest single source of calories for over 3.7 B people and rice cultivation is the largest single use of land for food (GRISP, 2013). According to FAO projections, feeding a world population of 9 B in 2050 will require raising overall food production by 70% (FAO, 2009). Given the current world population and estimated projections, rice production needs to increase annually by 1.2–2.4% during the next decade to meet global demand (GRISP, 2013, Ray et al., 2013). However at the current rate of grain yield increase, supply will not meet the demand (Grassini et al., 2013) and thus, production systems need to be more productive while at the same time reducing negative environmental impacts.

Dobermann (2004) estimated that for each ton of grain yield produced, rice requires 15–20 kg N when all other factors for growing rice are not limiting. However, increasing N rates to achieve higher yields can also lead to higher N_2O emissions (Pittelkow et al., 2014). Recent results of meta-analysis of N fertilizer effects on GHG emissions showed that N fertilizer-induced N_2O emission factor during the rice growing season was 0.21% for continuously flooded fields and 0.40% for fields with drained periods (Linquist et al., 2012). A higher N_2O emission factor of 0.31% was reported by Akiyama et al. (2005) for both organically and synthetically fertilized rice fields under all water management practices. Likewise, addition of fertilizer N influences CH_4 emission through enhanced CH_4 oxidation, increased transport for CH_4 and more carbon substrate for CH_4 production (Schimel, 2000; Wassmann and Aulakh, 2000). Field studies report variable results on the effect of N fertilization on CH_4 emission however, based on a meta-analysis, Linquist et al. (2012) concluded that impacts of N fertilizer on growing season CH_4 emissions are N rate-dependent, where low to moderate N rates increased emissions and high N rates decreased emissions.

In the same review, Linquist et al. (2012) found that deep placement or banding of fertilizer N in continuously flooded rice systems reduced CH_4 emissions by 40% and increased N_2O emissions by 18%. Given that N_2O emissions are relatively low in rice systems, the large decrease in CH_4 emissions could potentially lead to a net reduction in GWP. The reason suggested for reduced CH_4 emissions was that deep-placed fertilizer N stimulates CH_4 oxidation through the concentration of N in localized areas. However, the amount of data available for this analysis was small suggesting the need for further study before conclusions could be drawn.

Deep placement of N can also lead to increased NUE because it minimizes N losses as the ammonium is protected from nitrification/denitrification in anaerobic soil layers (Savant and Stangel, 1990). While

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Abbreviations: GHG, greenhouse gas; GWP, global warming potential; GWP_Y, yield-scaled global warming potential; NUE, nitrogen use efficiency.

* Corresponding author.

E-mail addresses: Arlene.AdvientoBorbe@ars.usda.gov (M.A.A. Adviento-Borbe), balinquist@ucdavis.edu (B. Linquist).

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some studies find no effect of deep N placement or banding of N on grain yields (Suratno et al., 1998; Setyanto et al., 2000) many studies report grain yields and NUE increase compared to broadcast (Savant and Stangel, 1990; Schnier et al., 1993; Ingram et al., 1991; Linquist et al., 2009).

Realizing the variable results of N fertilizer management practices on GHG emissions and rice yield, it is difficult to assume that a strategy based exclusively on rates, source or method of application will promote both low N_2O and CH_4 emissions and higher yield because gas fluxes are largely influenced by fertilizer N, soil, crop and their interactions (Horwath, 2011; Chai et al., 2013) and mitigating one gas may lead to stimulating the other gas. Therefore, in field experiments we tested the hypothesis that N fertilizer banded below the soil surface would result in the lowest CH_4 and N_2O emissions and higher grain yield relative to N that is broadcasted on the soil surface.

2. Materials and methods

2.1. Field experiment

Three field trials were conducted on an experimental field located at the University of California near Davis, CA in 2012 (Field 1: 38.54 N; 121.81 W; elevation 20 m above sea level [masl]), a commercial farm near Marysville, CA in 2013 (Field 2: 39.22 N; 121.54 W; elevation 23 masl), and at the Rice Experiment Station of the California Cooperative Rice Research Foundation, Inc. near Biggs, CA in 2014 (Field 3: 39.46 N; 121.74 W; elevation 29 masl). Site details, including cropping history and previous crop residue management are reported in Table 1.

The experiments were set up as randomized complete block design with three to four replicates in plots of 5.5–55.7 m^2. Fertilizer N rates were 0, 150 kg N ha^{-1} (Fields 1 and 3) and 0, 143 kg N ha^{-1} (Field 2) (Table 2). The three fertilizer N treatment combinations used were: U-BR: urea N fertilizer broadcast on the soil surface, U-BA: urea N fertilizer placed in a row at 7.5 cm depth and 22.9 cm apart, and N0; no fertilizer N applied. At all sites, fertilizer N was applied as a single dose and either broadcast or deeply placed in a row right before permanently flooding the field in preparation for planting. Triple superphosphate (46 kg P ha^{-1}) and K_2SO_4 (22 kg K ha^{-1}) fertilizers were applied before seeding to ensure these nutrients were not limiting. After fertilizer addition and flooding, pre-germinated rice seeds (varieties Table 1) were sown at a rate of 123–168 kg seeds ha^{-1}. All three fields were continuously flooded with flood water maintained at 6–22 cm during the growing season until fields were drained about three to four weeks before harvest (Table 1).

2.2. CH_4 and N_2O flux measurements

Methane and N_2O fluxes were measured daily during N fertilization and drain events and weekly during the rest of growing season using a static vented flux chamber technique (Hutchinson and Livingston, 1993). Gas sampling occurred between 09:00 to 12:00 h and the sequence of gas measurements was randomized to avoid bias to changing air temperature.

Flux chambers consisted of a base (29.5 cm in diameter), an extension (15.3 to 80.6 cm throughout the growing season to accommodate plants), and a lid (7.6 cm tall) all made of polyvinyl chloride (PVC) pipe. The flux chamber base was placed 15 cm into the soil leaving approximately 8 cm above the soil surface. Two holes were made on upper sides of the base and four 11 cm diameter holes were drilled in the bottom of the chamber base in order to prevent restriction of water and root movement above and below the soil surface. The chamber lid had a vent tube to equalize pressure between the inside and outside of the chamber (Hutchinson and Mosier, 1981) and a fan to mix the headspace gas for one minute before sampling. Air temperature was measured by a thermocouple wire while floodwater height was measured manually by ruler and continuously using a water level sensor and logger (Global Water Inst., College Station, TX). At four equal time intervals within an hour of chamber closure, a 25 mL gas sample was taken from the enclosed flux chamber and immediately transferred into an evacuated 12-mL glass vial (Labco Ltd., Buckinghamshire, UK) with rubber septa double sealed with 100% silicon for leak-free storage prior to gas analysis. Concentrations of CH_4 and N_2O from the headspace gas samples were analyzed on a GC-2014 gas chromatograph (Shimadzu Scientific, Inst, Columbia, MD) with a ^{63}Ni electron capture detector (ECD) for N_2O concentrations and flame ionization detector (FID) for CH_4 concentrations. N_2O and CH_4 were separated by a stainless steel column packed with Hayesep D, 80/100 mesh at 75 °C isothermally. The ECD was set at 325 °C while FID was set at 250 °C. A 1 mL headspace gas was injected into the GC inlet port using an autosampler (Bandolero™, XYZTEK, Sacramento, CA).

Fluxes of N_2O and CH_4 were estimated from the linear increase of gas concentration over time based on $r^2 \geq 0.90$ (Liu et al., 2010; Shang et al., 2011) while providing the maximum available flux data in the analysis of gas emissions. Gas concentrations were converted to mass per unit volume (g N_2O or CH_4 L^{-1}) using the Ideal Gas Law at chamber air temperature measured during each sampling event and 0.101 MPa. Fluxes of N_2O and CH_4 were computed as:

$$F = \frac{\Delta C}{\Delta t} \times \frac{V}{A} \times \propto \qquad (1)$$

where F is gas flux rate for N_2O/CH_4 (g N_2O–N/CH_4–C ha^{-1} d^{-1}), $\Delta C / \Delta t$ denotes the increase or decrease of gas concentration in the chamber (g L^{-1} d^{-1}), V is the chamber volume (L), A is the enclosed surface area (ha), and $\propto$ is a conversion coefficient for elemental N and C (28/44 for N_2O; 12/16 for CH_4). Gas fluxes which failed linearity test were not included in the data analysis and accounted for <2% of the total data set, while gas fluxes that failed significance and detection tests were set to zero flux. A complete discussion of chamber flux method is described in Adviento-Borbe et al. (2013).

Table 1
Crop management details and fertilizer N rates in the three study fields.

Management	Field 1	Field 2	Field 3
Cropping history	Dominated by weeds prior to field trial	Continuous irrigated rice	Continuous irrigated rice
Previous fallow management	Fallow for four years	Winter flooded (for two months) with rice straw incorporated	Winter flooded with rice straw incorporated
Tillage	Spring plowing with disk, 0.15 m, rolled	Fall plowing with disk, 0.15 m deep; Spring plowing with disk, 0.15 m, rolled	Fall plowing with disk, 0.15 m deep; Spring plowing with disk, 0.15 m, rolled
Irrigation	Flooded; 0.01–0.22 m permanent water depth	Flooded; 0.02–0.22 m permanent water depth	Flooded; 0.02–0.19 m permanent water depth
Variety	M104	M206	M206
Planting date	18 May 2012	9 May 2013	28 May 2014
Seeding/Seed rate	Broadcast/157 kg ha^{-1}	Broadcast/123 kg ha^{-1}	Broadcast/168 kg ha^{-1}
Drain date in preparation for harvest	1 to 15 Oct. 2012	11 Sep. to 1 Oct. 2013	16 Sep. to 8 Oct. 2014
N rates, kg N ha^{-1}	0 and 150	0 and 143	0 and 150

Table 2
Soil classification and characteristics of the three study fields.

		Field 1	Field 2	Field 3
Soil classification		Fine, montmorillonitic, thermic Typic Chromoxererts	Fine-loamy, mixed, active, thermic, Aquic Haploxerepts	Fine, smectitic, thermic, Xeric Epiaquerts and Duraquerts
Soil type		Capay silty clay	Trainer loam	Equon-Neerdobe clay
Soil texture[a]	g kg^{-1}			
Sand		60	300	230
Silt		470	420	300
Clay		530	280	470
Chemical properties[a]				
pH		6.6	5.46	4.80
Electrical conductivity	dS m^{-1}		0.17	0.19
Cation exchange capacity	cmol kg^{-1}	35.5	24.7	33.8
Total organic C	g kg^{-1}	15.9	13.7	12.6
Total N	g kg^{-1}	0.80	1.1	0.77

[a] Soil properties represent 0 to 0.15 m soil depth.

2.3. Measurements of ancillary variables

Prior to each field experiment, soil samples were taken from 0 to 0.15 m soil layer (Table 2). At physiological maturity, rice in a 1 m^2 area within each treatment was harvested at 1 to 2 cm above the soil surface, separated into grain and straw components, and dried at 60 °C to a constant weight. Grain yield was adjusted to 140 g kg^{-1} water content. Air temperature and rainfall data were obtained from weather stations located 5 to 59 km from study sites.

2.4. Data analysis

All data were subjected to normality tests using the Shapiro–Wilk approach and data that failed normal distributions were log-transformed ($P = 0.000$–0.224). Greenhouse gas emissions due to N fertilizer treatments and site as main effects and blocking and block × N fertilizer treatments as random effects were analyzed using PROC MIXED and the model was fitted using the restricted maximum likelihood procedure to estimate the means and standard errors for each combination (SAS, 2010). Analysis of repeated measures was performed using autoregressive order 1 covariance to determine if means and differences of daily gas emissions changed with measurement date. One-way analysis of variance on cumulative gas emissions, crop yield and NUE among N fertilizer treatments per site was also analyzed using PROC MIXED and means of N fertilizer treatments were compared using adjusted Tukey test at $P < 0.05$ (SAS, 2010).

Global warming potential (GWP) of N_2O and CH_4 was calculated in mass of CO_2 equivalents (kg CO_2 eq ha^{-1}) over a 100-year time horizon. A radiative forcing potential relative to CO_2 of 296 was used for N_2O and 25 for CH_4 (Houghton et al., 2001). Yield-scaled global warming potential (GWP_Y) expressed as GWP per unit mass of rice grain (kg CO_2 eq Mg $grain^{-1}$) was computed by taking the ratio of GWP (kg CO_2 eq ha^{-1}) and grain yield (Mg ha^{-1}). Cumulative seasonal CH_4 and N_2O emissions were determined using linear interpolation which included flux measurement period from tillage to harvest at each field. Unfertilized and N fertilized treatment plots were used to estimate NUE (kg kg^{-1}). Nitrogen use efficiency was computed from the grain yield increase per unit of fertilizer N added (Dobermann and Fairhurst, 2000).

3. Results

3.1. Climate

In all fields, mean daily air temperature ranged from 12.4 to 32.8 °C during the rice growing period with the warmest mean air temperature measured in Field 3 (Fig. 1). Total annual rainfall was 138 to 466 mm (3 years) and 91% occurred during the non-growing period.

3.2. Grain yield, crop biomass and nitrogen use efficiency

Without N fertilizer, grain yields ranged from 2.9 to 11.6 Mg ha^{-1} with Field 2 having yields >9 Mg ha^{-1} (Fig. 2). In all fertilized N treatments, grain yield (Fig. 2) and crop biomass (data not shown) increased on average by 121% and 138% relative to N0 treatment, respectively. Across all fields, banding and broadcasting N fertilizer increased grain yield by 152% and 91%, respectively, relative to fields without N fertilizer; however, differences in grain yield between U-BA and U-BR were not significant ($P = 0.207$–0.661) (Fig. 2). Likewise, NUE ranged from 10 to 56 kg grain kg^{-1} N applied and averaged 21% higher in U-BA treatments than in U-BR treatments in all fields but differences were not significant (Table 3).

3.3. N_2O emissions

Daily N_2O emissions were near zero during the flooded period but low emissions were detected when fields were dried in the spring and following drainage in preparation for harvest in all sites and treatments (Fig. 1). Daily N_2O emissions ranged from −6.78 to 5.60 g N_2O–N ha^{-1} d^{-1} with mean emissions of −0.44 g N_2O–N ha^{-1} d^{-1} ($P =$ 0.336–0.930) across sites and treatments. Cumulative N_2O emissions were negligible and ranged from −0.1 to 0.01 g N_2O–N ha^{-1} $season^{-1}$ and emissions were similar in all N treatment combinations ($P = 0.297$–0.541) (Table 3).

3.4. CH_4 emissions

The lowest CH_4 fluxes were in Field 1 and the highest in Field 2 (Fig. 1). Among N treatments, daily CH_4 emissions were similar in Fields 1 and 2 ($P = 0.451$) but in Field 3 the N0 treatment had lower CH_4 emissions particularly during the latter half of the growing season ($P =$ 0.009) than treatments that received fertilizer N. Across all fields, CH_4 emissions spiked during the first few days following the final drain, in the case of Field 3 these fluxes were the highest recorded during the growing season (Fig. 1). Total seasonal CH_4 emissions were highest in Field 2 (266 kg CH_4–C ha^{-1} $season^{-1}$) and lowest in Field 1 (32 kg CH_4–C ha^{-1} $season^{-1}$). Total CH_4 emissions during drainage period before harvest ranged from 2 to 10% of total seasonal CH_4 emissions. Daily CH_4 emissions between the two fertilizer placement methods were comparable for all sampling dates and there was no significant difference in total seasonal CH_4 emissions between them (Fig. 1 and Table 3).

3.5. Global warming potential

Methane emissions accounted for 99 to 100% of the total seasonal GWP and the magnitude of GWP increased in the order Field 2 > Field

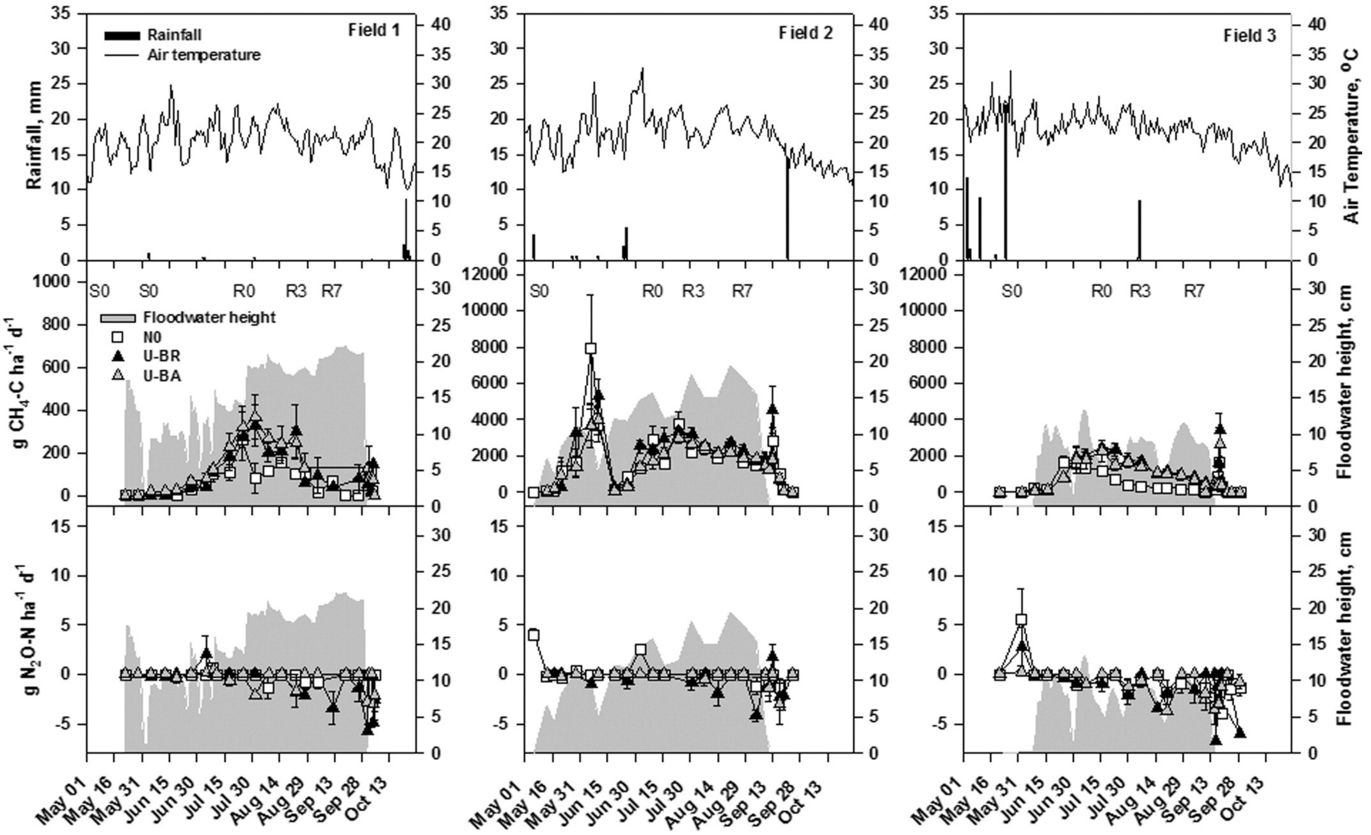

Fig. 1. Methane and N_2O emissions, floodwater height, rainfall and air temperature in the different N fertilizer treatments during 2012–2014 growing season. N0, U-BR and U-BA treatments correspond to no fertilizer N applied, urea N fertilizer surface applied, and urea N fertilizer deeply applied in row, respectively. S0, R0, R3 and R7 correspond to seeding, panicle initiation, heading and physiological maturity growth stages, respectively.

3 > Field 1. In general, yields were higher and GWP lower in the U-BA treatments (although these differences were not significant in either case); this resulted in non-significant differences in GWP_Y (Table 3).

4. Discussion

Among the three fields, Field 1 had the lowest total CH_4 emissions (<14 kg CH_4–C ha^{-1} $season^{-1}$) while Field 2 had the highest total seasonal CH_4 emissions (231 kg CH_4–C ha^{-1} $season^{-1}$) (Table 3). Linquist et al. (2012) reported that on average rice systems emit 100 kg CH_4 ha^{-1} $season^{-1}$; however there is tremendous variability around this estimate. Field 1 had particularly low values but they are similar to those reported by Simmonds et al. (2015) who measured GHG emissions from the same field and year but from a different experiment and location within the field. Low values are likely the result of this field having been in a weedy fallow for the previous four years with no flooding. Therefore, there was minimal residues and methanogen populations may have been low (Conrad and Klose, 2006; Eusufzai et al., 2010). In contrast, Fields 2 and 3 had been in rice the previous season and during the previous winter fallow both fields had rice straw incorporated into the soil and the field was flooded (Table 1).

Nitrous oxide fluxes were near zero throughout the rice growing season including the post drainage event resulting in low to negative cumulative emissions (Table 3). Our results differ from other studies which often reported significant N_2O emissions in flooded rice systems. For example, Pittelkow et al. (2013) reported growing season N_2O emissions under optimal N rates between 0.2 and 0.4 kg N_2O–N ha^{-1}. These emissions are usually not present during the flooded period but occur at the beginning of the season before the field is flooded and at the end of the season when the field is drained in preparation for harvest. With the exception of Field 2, post-drain N_2O emissions were not observed as is commonly observed as the soil dries at the end of the season (Adviento-Borbe et al., 2015) (Fig. 1). This may be because the N rates used in this study were not excessive as Pittelkow et al. (2014) reported that the highest N_2O emissions are observed when N is applied in excess.

4.1. Fertilizer N addition affects CH_4 and N_2O emissions

Application of fertilizer N increased CH_4 emissions compared to the N0 treatment only in Field 3 (Table 3). Nitrogen can influence CH_4 emissions by increasing or decreasing CH_4 consumption, production and

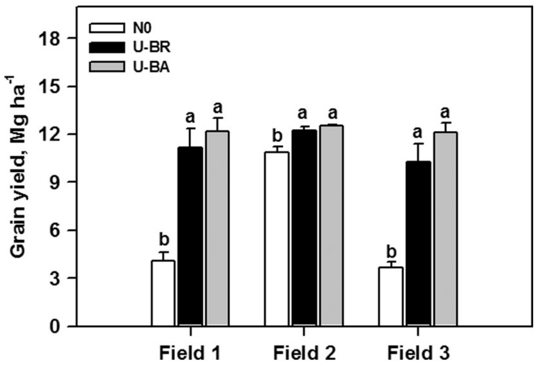

Fig. 2. Average grain yields in the different N fertilizer treatments and three fields. N0, U-BR and U-BA correspond to no fertilizer N applied, urea N fertilizer surface applied, and urea N fertilizer deeply applied in row treatments, respectively. Grain yields within each field followed by the same letter are not significantly different at $P < 0.05$.

Table 3
Seasonal CH_4 and N_2O emissions and N use efficiency in the different N fertilizer treatments and study fields.

Site/N treatments	N Fertilizer placement	CH_4 emissions[a]		N_2O emissions[a]		Global warming potential[a]		Fertilizer-induced N_2O emissions	Nitrogen use efficiency[a]
						GWP	GWP_Y		
		kg CH_4–C ha^{-1} $season^{-1}$	kg CO_2 eq ha^{-1} $season^{-1}$	g N_2O–N ha^{-1} $season^{-1}$	kg CO_2 eq ha^{-1} $season^{-1}$	kg CO_2 eq ha^{-1} $season^{-1}$	kg CO_2 eq Mg^{-1} $season^{-1}$	%	kg grain kg^{-1} urea applied
Field 1									
N0	–	6.29a	210a	−0.014a	−6.6a	204a	46a		
U-BR	Broadcast	12.2a	409a	−0.050a	−23a	385a	33a	−0.02	47a
U-BA	Banded	13.6a	453a	−0.026a	−12a	440a	35a	−0.01	54a
Field 2									
N0	–	269a	8994a	0.010a	4.7a	8999a	824a		
U-BR	Broadcast	297a	9910a	−0.075a	−35a	9875a	808a	−0.06	9a
U-BA	Banded	231a	7711a	−0.013a	−6.0a	7705a	616a	−0.02	12a
Field 3									
N0	–	62.4b	2085b	−0.063a	−30a	2055b	574a		
U-BR	Broadcast	133a	4438a	−0.070a	−33a	4405a	449a	−0.01	44a
U-BA	Banded	115a	3834a	−0.107a	−50a	3784a	311a	−0.04	56a

[a] Gas emissions, global warming potential and nitrogen use efficiency within each field followed by the same letter are not significantly different at $P < 0.05$.

release at various levels of ecosystem (Schimel, 2000); however, Linquist et al. (2012) reported that the net effect of N fertilizer was that relative to zero N treatments, low to moderate N rates increase emissions and high N rates decrease emissions. Greater emissions at moderate N rates are likely due to increased plant growth resulting in a greater source of carbon for methanogens and more tillers for transport of CH_4 to the atmosphere (Wassmann and Aulakh, 2000). Therefore, since the fertilizer N rates in our study were typical of those used in California for optimal crop growth and grain yield (Linquist et al., 2006) the slight increase in CH_4 emissions with the addition of fertilizer N which we observed was expected; however it was only significant in Field 3 (Table 3).

Contrary to other field studies, application of N fertilizer had little to no effect on N_2O emissions. In various review papers (Akiyama et al., 2005; Linquist et al., 2012) authors have reported N fertilizer-induced N_2O emission factors in rice systems ranging from 0.21 to 0.40%. It is not clear why we found no fertilizer induced N_2O emissions but it may be partly attributed to a single fertilizer application at the beginning of the season and the fields remained flooded for the duration of the season. When fields are drained during the season N_2O emissions generally increase (Akiyama et al., 2005; Linquist et al., 2015). Moreover, the N rates used in our study were ≤150 kg N ha^{-1} which is sufficient to support optimal growth and development of rice (Adviento-Borbe et al., 2013; Pittelkow et al., 2013) but, not excessive which can promote high N_2O emissions (Pittelkow et al., 2014). That said, other studies have had similar conditions in terms of flooding and N rate but still reported positive cumulative N_2O emissions (Adviento-Borbe et al., 2013; Pittelkow et al., 2013; Simmonds et al., 2015).

4.2. N fertilizer placement on CH_4 and N_2O emissions

The practice of deep placement of fertilizer N is often recommended to reduce N losses and enhance NUE because fertilizer NH_4^+ is concentrated in the anaerobic soil layer which reduces the potential for nitrification/denitrification losses (Linquist et al., 2009). In a review, Linquist et al. (2012) reported that placement of N fertilizer in bands or as pellets below the soil surface reduced CH_4 emissions by 40% compared to broadcast on the surface. They proposed a couple of reasons for this. First, concentrating NH_4^+ into localized areas or bands has been shown to stimulate CH_4 oxidation by soil methanotrophs and reduce overall CH_4 emissions (Bodelier et al., 2000a, 2000b). Second, deep placement of N may promote rice root growth deeper in the soil where CH_4 production is greater (Krüger et al., 2001) and the increased oxygen availability in the rhizosphere would likely enhance CH_4 consumption in these layers and reduce overall emissions (Gilbert and Frenzel, 1998). However, in this study this effect was not observed as within each field the cumulative CH_4 emissions and daily fluxes were similar between the two N placement treatments.

While CH_4 emissions in the deep placement treatment tended to be lower in two fields (on average by 18%) this was not significant. To further explore the treatment effects we compared emissions between the N treatments during the first 45 days of the season. In these rice systems fertilizer N applied preplant is taken up by the plant within 45 days of planting (Pittelkow et al., 2013; Linquist et al., 2006). Therefore, the benefit of banding fertilizer on reducing CH_4 emissions (if N stimulates CH_4 oxidation as suggested by Bodelier et al. (2000a, 2000b)) should be observed during this period when N fertilizer is still in the soil. Our results showed no difference in CH_4 emissions between the two N placement treatments during this period of the season ($P = 0.285$–0.890) (data not shown). It is not clear why our results differ from those of others. In the only other two studies that have been conducted in continuously flooded rice systems that have examined the effects of fertilizer N placement on GHG emissions (Schütz et al., 1989; Setyanto et al., 2000) they reported an average 40% reduction in CH_4 emissions when N fertilizer was banded or deeply placed compared to surface applied applications (Linquist et al., 2012). In those studies the N fertilizer was placed deeper (20 cm deep — Schütz et al., 1989) or applied as a urea pellet (Setyanto et al., 2000). Pellets will concentrate N fertilizer even more than banding fertilizer, thus perhaps enhancing CH_4 oxidation. Given these conflicting results, we suggest further study to determine if there are opportunities for reduction of CH_4 emissions with fertilizer placement.

Despite the slight increase of N_2O flux rates during dry or drained periods; proportions of fertilizer induced N_2O emissions were negligible, indicating little to zero loss of N_2O for both N placement methods. Contrary to the study of Suratno et al. (1998), the practice of deep N placement increased NUE and had lower N losses than surface applied N. Also, nitrification/denitrification losses were minimized which is suspected to decrease N_2O emissions (Keerthisinghe et al., 1996; Khalil et al., 2009).

4.3. Fertilizer N placement on grain yield and global warming potential

Grain yields in N fertilized plots were within the optimal range reported for the region (Adviento-Borbe et al., 2013; Pittelkow et al., 2013). While the addition of urea fertilizer substantially increased grain yields across all fields, fertilizer placement methods had no direct effect on yield and NUE (Table 2). Among three fields, absolute values of NUE in Field 2 were lower compared to the rest of the fields because yields in the unfertilized treatment were close to the N fertilized treatments. The lack of yield response to fertilizer N placement in this study is likely due to N being applied at optimal rates, thus small increases in NUE between the two methods are not easily detected in this study.

Total seasonal GWP were dominated by CH_4 emissions in this study. Yield-scaled GWP emissions decreased in N fertilized treatments due to higher yields. Since grain yield and total seasonal CH_4 emissions were not strongly affected by fertilizer placement method, GWP_Y was similar in both N placement treatments (Table 3).

5. Summary

Our study evaluated the two N placement methods in flooded wet seeded rice systems. Applying urea-N fertilizer on the surface or banded below the soil surface had no effect on total seasonal CH_4 and N_2O emissions, daily fluxes, GWP or GWP_Y. These results are in contrast to a couple of other studies that have examined this and shown a reduction of CH_4 emissions due to concentrating N below the soil surface. Given this disparity of results, further research is needed to clarify if N placement can be a viable management strategy to reduce GWP and GWP_Y in flooded rice systems.

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