Published June 25, 2014

Journal of Environmental Quality TECHNICAL REPORTS

ATMOSPHERIC POLLUTANTS AND TRACE GASES

Optimal Fertilizer Nitrogen Rates and Yield-Scaled Global Warming Potential in Drill Seeded Rice

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Drill seeded rice (*Oryza sativa* L.) is the dominant rice cultivation practice in the United States. Although drill seeded systems can lead to significant CH_4 and N_2O emissions due to anaerobic and aerobic soil conditions, the relationship between high-yielding management practices, particularly fertilizer N management, and total global warming potential (GWP) remains unclear. We conducted three field experiments in California and Arkansas to test the hypothesis that by optimizing grain yield through N management, the lowest yield-scaled global warming potential (GWP_Y = GWP Mg^{-1} grain) is achieved. Each growing season, urea was applied at rates ranging from 0 to 224 kg N ha^{-1} before the permanent flood. Emissions of CH_4 and N_2O were measured daily to weekly during growing seasons and fallow periods. Annual CH_4 emissions ranged from 9.3 to 193 kg CH_4–C ha^{-1} yr^{-1} across sites, and annual N_2O emissions averaged 1.3 kg N_2O–N ha^{-1} yr^{-1}. Relative to N_2O emissions, CH_4 dominated growing season (82%) and annual (68%) GWP. The impacts of fertilizer N rates on GHG fluxes were confined to the growing season, with increasing N rate having little effect on CH_4 emissions but contributing to greater N_2O emissions during nonflooded periods. The fallow period contributed between 7 and 39% of annual GWP across sites years. This finding illustrates the need to include fallow period measurements in annual emissions estimates. Growing season GWP_Y ranged from 130 to 686 kg CO_2 eq Mg^{-1} $season^{-1}$ across sites and years. Fertilizer N rate had no significant effect on GWP_Y; therefore, achieving the highest productivity is not at the cost of higher GWP_Y.

Rice is the staple food crop for more than 3 billion people and provides more calories than any other cereal for human consumption (FAO, 2012). Global demand for rice is projected to increase annually, and meeting this demand can be achieved through increasing rice yields from current levels to 80% of estimated yield potential (Cassman et al., 2002). Intensive rice cropping systems in areas with favorable resources can spare natural ecosystems from agricultural expansion but may also enhance greenhouse gas (GHG) emissions (CH_4, N_2O, and CO_2) (Tilman et al., 2001). Intensification of rice through efficient crop management practices to obtain higher yields with less use of agricultural inputs (i.e., fertilizer, land, water, energy, and labor), also known as ecological intensification, is one way to achieve global food security and lessen environmental degradation (Dobermann et al., 2008).

Recognizing that issues of food security and global climate change are interrelated, GHG emissions are increasingly assessed with respect to crop yield. Yield-scaled global warming potential (GWP_Y) (van Groenigen et al., 2010), also referred to as GHG intensity (Mosier et al., 2006), is a metric that can be used to identify efficient cropping systems that produce high grain yields with low GWP values. Recent results of a meta-analysis suggest that low yield–scaled N_2O emissions were obtained in intensive cropping systems managed at near yield potential with high N use efficiency and that significant N_2O emission increases were observed only when fertilizer N was applied in excess of crop demand (van Groenigen et al., 2010). Although N fertilizer has been shown to have direct impacts on yield and N_2O emissions, much less is known about its effects on CH_4 emissions. Because CH_4 emissions contribute the majority of GWP (89%) in rice systems (Linquist et al., 2012a), it is important to consider gases and their relationship to rice productivity when evaluating mitigation strategies and extrapolating emission estimates to regional and national scales.

J. Environ. Qual. 42:1623–1634 (2013)
doi:10.2134/jeq2013.05.0167
Received 1 May 2013.
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Abbreviations: EF, emission factor; GC, gas chromatograph; GHG, greenhouse gas; GWP, global warming potential; GWP_Y, yield-scaled global warming potential; masl, meters above sea level.

Irrigated rice is unique from most other crops because it is grown under flooded conditions, and rice plants serve as pathways for gas release to the environment (Nouchi et al., 1990). Flooded rice fields lead to conditions favorable for CH_4 production, and, with the total harvested area of rice representing 14% of Earth's cropland, rice cultivation is the largest terrestrial source of CH_4 (Smith et al., 2007). Through its direct and indirect effects on methanogenesis and methanotrophy processes that lead to net CH_4 emissions, fertilizer N can contribute to variations in CH_4 fluxes (Schimel, 2000). It has been reported that the addition of fertilizer N can lead to an increase in CH_4 emissions (Shang et al., 2011; Singh et al., 1996) or a decrease in CH_4 emissions (Xie et al., 2010; Yao et al., 2012) or that it can have no effect on CH_4 emissions (Cai et al., 2007; Schütz et al., 1989). However, in a recent meta-analysis, Linquist et al. (2012b) found that the effect of N is largely rate dependent, with low to moderate N rates increasing CH_4 emissions and excessive N rates reducing CH_4 emissions. Regarding N_2O, emissions are largely determined by water and N management practices. High N_2O emissions have been reported in fields with introduced aeration events (e.g., intermittent irrigation or midseason drainage periods) (Zou et al., 2005) or with excessive amounts of fertilizer N (Cai et al., 1997). The application of mineral N increases substrate for nitrification and denitrification processes, the major drivers of N_2O production (Dobbie et al., 1999). Therefore, lowering anthropogenic emissions of N_2O and CH_4 while maintaining rice yields through efficient fertilizer N management remains a challenge for rice production.

A majority of field studies evaluating CH_4 and N_2O emissions from rice systems have quantified emissions only during the growing season. Growing-season GHG emissions are commonly reported to compare differences among mitigation strategies or to further understand the effects of crop management factors on CH_4 and N_2O emissions (e.g., Schütz et al., 1989; Yang et al., 2012). However, annual GHG emissions are often necessary to fully evaluate a production cycle. For example, multiple crops can be grown within the same rice field each year (i.e., the rice–wheat rotation in India) with different GHG emissions occurring under each crop (Linquist et al., 2012a). Moreover, large N_2O emissions can occur from rice fields during the nonflooded fallow period due to moist soil conditions brought about by precipitation (Zheng et al., 2000). Hence, the lack of available data on GHG emissions during the fallow period may lead to underestimation of annual emissions and/or different interpretation of results when emissions are evaluated on a growing season basis compared with an annual basis.

Rice is produced on 1.46 million ha in the United States (FAO, 2012), with drill seeded rice occupying 64% of this area (NASS, 2012; Hill et al., 1991). Drill seeding requires that rice be planted in a row (similar to maize), and the crop is established through rainfall or flush irrigation. After establishment (about 3–5 wk after planting), the field is permanently flooded until drainage before harvest. Drill seeding is promoted as a mitigation option for wet-seeded rice (where fields are flooded from planting until drainage before harvest) because it has the potential to reduce CH_4 emissions when compared with fields that are flooded before seeding and remain flooded throughout the plant growth period (Pathak et al., 2013). However, the longer aerobic period during crop establishment may increase N_2O emissions (Cai et al., 1997) and lead to higher GWP values. Although there has been considerable research on CH_4 emissions from drill seeded rice in the United States (e.g., Lindau, 1994; Sass et al., 1992), there has been no measurement of N_2O from these systems to adequately assess GWP. Here, we tested the hypothesis that the lowest GWP_Y would be achieved at optimal N rate, which we define as the minimum amount of N required for maximum yield. The specific objectives of this study were (i) to quantify CH_4 and N_2O emissions from drill seeded rice fields fertilized at different N rates and (ii) to determine annual GHG emissions during the growing season and the fallow period.

Materials and Methods

Field Experiment

Field experiments were conducted on two commercial rice farms near Robbins, CA (CA1: 38.90 N; 121.73 W; elevation 7 m above sea level [masl]; CA2: 39.01 N, 121.70 W; elevation 11 masl), and on an experimental field (AR) at the University of Arkansas Rice Research & Extension Center near Stuttgart, AR (34.45 N, 91.40 W; elevation 62 masl). Experiments occurred during 2010–2011, 2011–2012, and 2011–2012 at CA1, CA2, and AR, respectively. Before field experiments, rice straw was incorporated after the previous harvest without winter flooding in CA1, whereas rice straw residues in CA2 and AR were cut and left on the surface with and without winter flooding, respectively. Soil properties were determined from samples taken in April 2010 and 2011 from the 0- to 0.15-m soil layer (Table 1).

The two CA field experiments (CA1 and CA2) were planted to rice cultivar Koshihikari (a specialty short grain variety), and the AR rice field was planted to CLXL 745 (a hybrid rice variety). All fields were laid out in a randomized complete block design with four or five fertilizer N rates replicated three times in plots at least 24 m^2 in size. Nitrogen rates ranged from 0 to 200 kg N ha^{-1} at the CA sites and 0 to 224 kg N ha^{-1} in AR (Table 2). The treatment of 100 kg N ha^{-1} represents the typical N rate used in California for Koshihikari. The recommended N rate for CLXL 745 used in AR is 168 kg N ha^{-1}. At all sites, N fertilizer was applied as a single dose of urea and broadcast on the soil surface just before permanently flooding the field.

In early to mid-May, rice was drill seeded at all locations. Triple superphosphate (44–46 kg P ha^{-1}, depending on location) and K_2SO_4 (24–29 kg K ha^{-1}, depending on location) were applied at planting to ensure that P and K did not limit crop growth (Table 2). Immediately after planting, fields were flushed with water two to three times to germinate seeds and establish the rice crop. A permanent flood was applied when rice reached the three- to four-leaf stage (after approximately 30 d), and water was maintained between 8.5 and 14 cm during the rest of the growing season until a month before harvest, at which time fields were drained. After harvest, rice straw was retained in the field at all locations. At CA1, rice straw was incorporated into the soil, whereas at CA2 and AR, straw remained on the soil surface. The CA2 field was flooded from 7 Oct. 2011 to 31 Jan. 2012 to promote rice straw decomposition (Linquist et al., 2006), whereas CA1 and AR fields remained unflooded during the winter fallow period (Table 2).

Greenhouse Gas Flux Measurements

Methane and N_2O fluxes were measured daily to weekly during the entire year (with the exception of 2–3 wk in December) using

Table 1. General soil classification and characteristics of the three study sites.

Soil parameters	Study sites†		
	CA1	CA2	AR
Soil classification	fine, smectitic, thermic, Xeric Endoaquerts	fine, smectitic, thermic, Typic Argixerolls	fine, smectitic, thermic, Typic Albaqualfs
Soil type	Clear lake clay	Marcum clay loam	Dewitt silt loam
Soil texture,‡ g kg^{-1}			
Sand	100	300	130
Silt	310	430	690
Clay	590	280	180
Chemical properties†			
pH	6.10	5.46	6.19
Electrical conductivity, dS m^{-1}	0.59	0.17	0.57
CEC,§ cmol kg^{-1}	54.8	24.7	11.5
Total organic C, g kg^{-1}	13.4	13.7	6.76
Total N, g kg^{-1}	1.4	1.1	0.71
Extractable Olsen P, mg kg^{-1}	20.9	21.2	13.7
Exchangeable K, mg kg^{-1}	236	163	198

† Field experiments were conducted on two commercial rice farms near Robbins, CA (CA1: 38.90 N; 121.73 W; elevation 7 m; CA2: 39.01 N, 121.70 W; elevation 11 m), and on an experimental field (AR) at the University of Arkansas Rice Research & Extension Center near Stuttgart, AR (34.45 N, 91.40 W; elevation 62 m).

‡ Soil properties represent 0- to 0.15-m soil depth.

§ Cation exchange capacity.

a static vented chamber technique (Hutchinson and Livingston, 1993). Intensive gas sampling occurred at 1- to 3-d intervals after N fertilization and during field flooding and drainage events; these measurements continued until fluxes reached ambient levels. Gas fluxes were determined on 90, 80, and 56 occasions in CA1, CA2, and AR, respectively. Gas sampling occurred between 0900 to 1200 h, and the sequence of gas measurements in the N trial plots was randomized to avoid bias due to changing air temperature. On two occasions (14 June and 17 Aug. 2010 in CA1), gas fluxes were measured at 3-h intervals over a 24-h period, with no significant diurnal changes in CH_4 and N_2O fluxes being observed (data not shown).

Flux chambers were composed of a base, an extension, and a lid made of polyvinyl chloride pipe. The chamber bases were installed and left in place during the entire year except during tillage events. The chamber base was 29.5 cm in diameter and 22.9 cm in height, and the chamber lid was 7.6 cm tall and closed on top with a polyvinyl chloride sheet. To provide a solid foundation, chambers were placed 15 cm into the soil, leaving approximately 8 cm above the soil surface. Two holes were drilled on the upper sides of the base, and four 11-cm-diameter holes were drilled in the bottom of the chamber base to prevent restriction of water and root movement above and below the soil surface. The chamber was equipped with a vent tube to equalize pressure between the inside

Table 2. Crop management and fertilizer nitrogen rates at the three study sites.

Management	Study sites†		
	CA1	CA2	AR
Previous cropping management	rice straw incorporated and drained during fallow period	winter flooded (for 4 mo) with rice straw applied on surface	drained during fallow period
Tillage	fall plowing with disk, 0.15 m deep; spring plowing with disk, 0.15 m, rolled	spring plowing with disk, 0.15 m, rolled	spring plowing with disk, 0.1 m and harrowed with a triple-k implement, rolled
Irrigation	flush flooding three times in early growing season; 0.01–0.28 m permanent water depth	flush flooding three times in early growing season; 0.02–0.18 m permanent water depth	flush flooding two times in early growing season; 0.02–0.15 m permanent water depth
Harvest and straw residue	combine for grain removal; rice straw was cut and incorporated, 0.15 m deep	combine for grain removal; rice straw was cut and left on the soil surface	combine for grain removal; rice straw was cut and left on the soil surface
Winter flooding	drained	flooded (7 Oct. 2011–31 Jan. 2012), 0.03–0.28 m water depth	drained
Varieties	Koshihikari	Koshihikari	CLXL745
Planting date	6 May 2010	3 May 2011	17 May 2011
Seeding/seed rate	drill seeding/70 kg ha^{-1}	drill seeding/70 kg ha^{-1}	drill seeding/28 kg ha^{-1}
Drain period before harvest	27 Sept.–18 Oct. 2010	20–30 Sept. 2011	12–22 Sept. 2010
Annual N application, kg N ha^{-1}	0, 50, 100, 150, and 200	0, 50, 100, 150, and 200	0, 112, 168, and 224
Annual P application, kg P ha^{-1}	24	24	29
Annual K application, kg K ha^{-1}	46	46	44

† Field experiments were conducted on two commercial rice farms near Robbins, CA (CA1: 38.90 N; 121.73 W; elevation 7 m; CA2: 39.01 N, 121.70 W; elevation 11 m), and on an experimental field (AR) at the University of Arkansas Rice Research & Extension Center near Stuttgart, AR (34.45 N, 91.40 W; elevation 62 m).

and outside of the chamber (Hutchinson and Mosier, 1981). A fan was used to mix the headspace gas for 1 min before sampling. Air temperature was measured by a thermocouple wire. The height of the chamber extensions increased from 15.3 to 80.6 cm during the course of the cropping season to accommodate the growing rice plants within the flux chamber.

For sampling the gas in the chamber headspace, a 25-mL gas sample was immediately transferred into evacuated 12-mL glass vials (Labco Ltd.) with rubber septa double sealed with 100% silicon for leak-free storage before gas analysis. Gas samples were taken from the chamber at three to four equal time intervals (21 and 30 min) within an hour of chamber closure. Before permanent flooding of fields, gas sampling occurred initially in control plots without fertilizer addition and subsequently in all treatments when N fertilizer was applied.

The headspace gas samples were analyzed on a GC-2014 gas chromatograph (GC) (Shimadzu Scientific) with a ^{63}Ni electron capture detector for N_2O concentrations and flame ionization detector for CH_4 concentrations. Nitrous oxide and CH_4 were separated by a stainless steel column packed with Hayesep D, 80/100 mesh at 75°C isothermally. The electron capture detector was set at 325°C, and the flame ionization detector was set at 250°C. The detection limits of the GC instrument were 0.3 pg s^{-1} N_2O and 2.2 pg s^{-1} CH_4. The GC was calibrated using standard N_2O and CH_4 with accuracies certified at 95% (Airgas Inc.). Results of GC analyses were accepted when standard gas calibrations produced linear relationships between voltage output and gas concentration with $r^2 > 0.996$. Quality assurances of N_2O and CH_4 concentrations generated by the GC were monitored by inserting standard gas check samples between every 10 unknown samples and were measured within 95% accuracy of the known concentration.

Fluxes of N_2O and CH_4 were estimated from the linear increase of gas concentration over time. 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 (g N_2O–N ha^{-1} d^{-1}) and CH_4 (g 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, 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 flux calculations were accepted based on $r^2 \geq 0.90$, similar to Shang et al. (2011), while providing the maximum available flux data in the analysis of gas emissions. Gas fluxes for which r^2 was below 0.90 but passed the detection tests were not included in the analysis and accounted for only 3.5% of the total data set (126/3611 flux measurements), whereas fluxes that failed detection tests were set to zero flux. Gas emissions before permanent flooding from control plots without N addition were used to calculate cumulative seasonal GHG emissions in N-fertilized plots. To determine annual emissions, N_2O and CH_4 interpolations at each site covered the measurement period from tillage (16 Apr. [CA1], 3 May [CA2], 17 May [AR]) to spring tillage of the following year (28 Mar.—9 Apr.). Growing season emissions refer to the period from the first tillage event each spring until harvest; the remainder of the year represents fallow emissions. Fertilizer-induced N_2O emission factor (EF_{N_2O}) was calculated as follows:

$$EF_{N_2O}=\left[\frac{(N_2O_{NF}-N_2O_{N0})}{N\ input}\right]100 \qquad [2]$$

where N_2O_{NF} is total N_2O emission from N fertilizer rate treatment (kg N_2O–N ha^{-1} yr^{-1}), N_2O_{N0} is the total N_2O emission from zero N fertilizer treatment (kg N_2O–N ha^{-1} yr^{-1}), and N input is the corresponding fertilizer N rate applied (kg N ha^{-1} yr^{-1}).

Measurements of Soil Ancillary Variables and Grain Yield

Air temperature and rainfall data were obtained from the automatic weather stations located about 0.3 (AR) and 50 km (CA) from the study sites.

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 mass. Grain yield was adjusted to 140 g kg^{-1} water content.

Data Analysis

Before variance component analysis, all data were subjected to normality tests using the Shapiro-Wilk approach, and data that failed normal distributions were log transformed (P = 0.001–0.459). To determine differences in GHG emissions among N rate treatments during each significant gas emission–related event (i.e., growing period, drain events, and fallow), SAS programs for randomized complete block design were used with least significant difference tests at $P < 0.05$ (SAS, 2003). Gas emissions due to main effects such as N fertilizer rate, site, blocking, and block × N fertilizer rate as random effect 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, 2003). 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.

The GWP of N_2O and CH_4 was calculated in mass of CO_2 equivalents (kg CO_2 eq ha^{-1}) over a 100-yr time horizon. Radiative forcing potentials relative to CO_2 of 298 and 25 were used for N_2O and CH_4, respectively (Houghton et al., 2001). Yield-scaled GWP (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}). Two-way ANOVA was used to evaluate treatment differences per field on annual and seasonal global warming potentials (SAS, 2003).

Results

Climate

In California, mean air temperature during the growing season was 20.5 and 10°C during the fallow period, and mean annual rainfall was 351 mm, with 81% of the rain occurring during the fallow period (average of 2 yr) (Fig. 1). Mean growing season air temperature in AR was 26.6 and 11.6°C during the

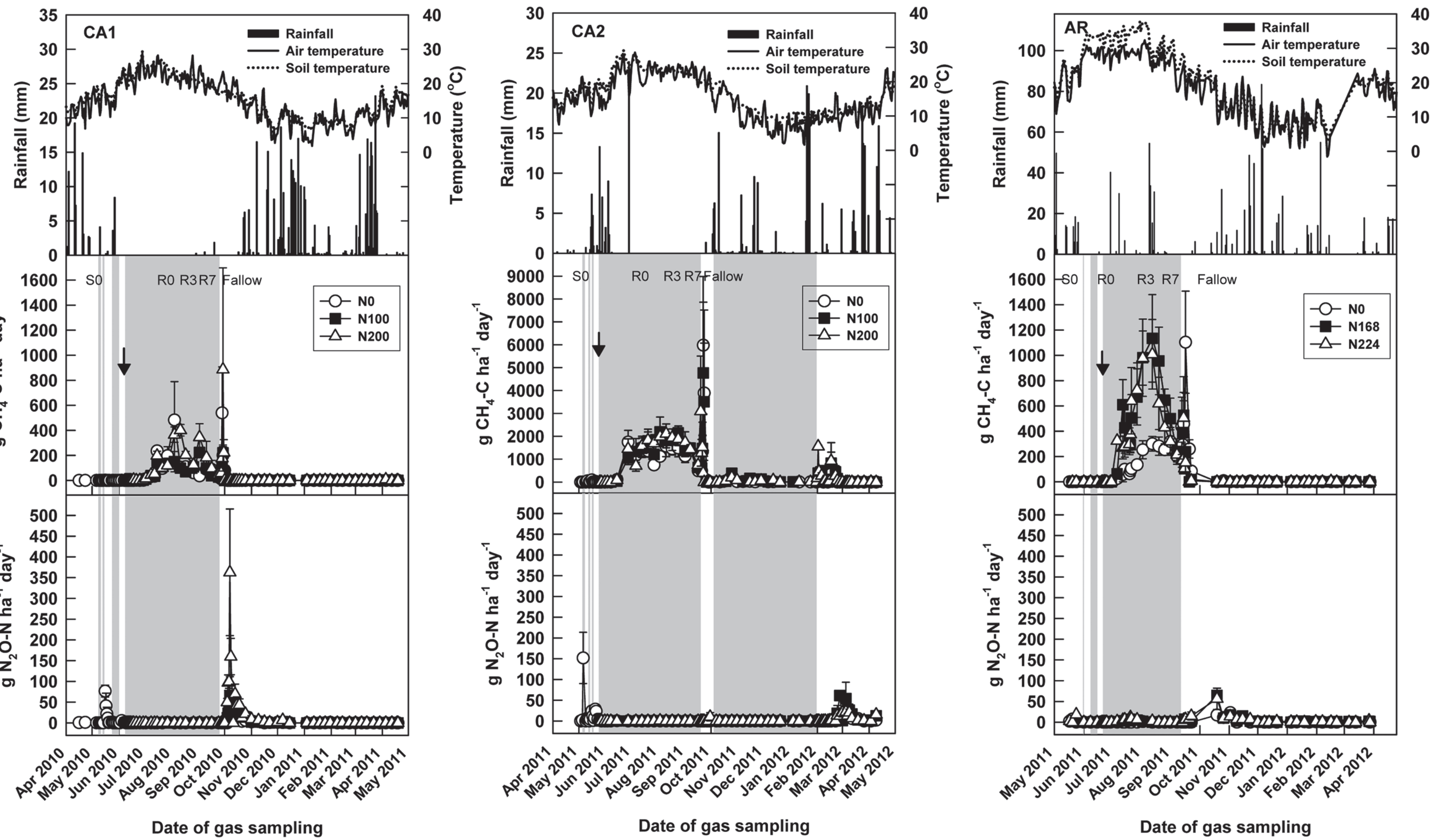

Fig. 1. Soil/air temperature, rainfall, methane, and N_2O emissions from drill seeded rice in CA1 and CA2 fertilized at 0, 100, and 200 kg N ha^{-1} and in AR field fertilized at 0, 168, and 224 kg N ha^{-1}. Arrow and shaded area locations indicate date of fertilizer N application and periods of flooded condition, respectively. S0, R0, R3, R7, and Fallow correspond to seeding, panicle initiation, heading, physiological maturity stages of rice, and fallow period, respectively. Field experiments were conducted on two commercial rice farms near Robbins, California (CA1: 38.90 N; 121.73 W; elevation 7 m; CA2: 39.01 N, 121.70 W; elevation 11 m) and on an experimental field (AR) at the University of Arkansas Rice Research & Extension Center near Stuttgart, Arkansas (34.45 N, 91.40 W; elevation 62 m).

fallow period. Total rainfall at the AR site was 866 mm, with 68% of the rain occurring during the fallow period.

Rice Yields and Nitrogen Response

Grain yields ranged from 3.8 to 6.0 Mg ha^{-1} without N fertilizer addition (Fig. 2). Fertilizer N rates required to reach maximum yields were 100 kg N ha^{-1} in both CA fields and 112 kg N ha^{-1} in AR. The addition of N fertilizer increased yields by 84% on average, with N rates above the optimum N rate leading to similar (CA1 and AR) or declining yields (CA2).

Nitrous Oxide Emissions

The range of total annual N_2O emissions was similar in all fields, with emissions averaging 1.30 kg N_2O–N ha^{-1} yr^{-1} and ranging from 490 kg to 1915 g N_2O–N ha^{-1} yr^{-1} (Table 3). Nitrous oxide emissions varied depending on soil water status and the rate of N applied, with the highest emissions measured during nonflooded periods (Fig. 1). When fields were flooded, N_2O emissions were <14.3 g N_2O–N ha^{-1} d^{-1} and were usually nondetectable. Annual N_2O emissions in the 0N fertilizer treatment were 490, 854, and 833 g N_2O–N ha^{-1} yr^{-1} in AR, CA1, and CA2, respectively.

The relative amount of N_2O emissions during the growing and fallow seasons differed among fields. Averaged across N rates, growing season N_2O emissions represented 75, 36, and 10% of total emissions in CA1, CA2, and AR, respectively. The main emission events occurred during transition periods when the soil was moist as a result of rainfall or irrigation: spring tillage (AR), flush irrigation for crop establishment (CA1, CA2, and AR), after draining for harvest (CA1), and during early fall (AR) (Fig. 1).

In CA1 and AR, annual N_2O emissions significantly increased with increasing N input, but this effect was not observed in CA2 (Table 3). Although increasing fertilizer N rate resulted in higher N_2O emissions during the growing season, no significant effect of N fertilizer rate on N_2O emissions was observed during the winter fallow period (Table 3).

Averaged across all sites and N rates, the mean fertilizer-induced N_2O emission factor (EF) during the growing season was 0.22%. Whereas several N rates had no fertilizer-induced effect on N_2O emissions in CA2, the highest emission factor of 0.79% was observed at 150 kg N ha^{-1} in CA1. When emission factors were calculated based on annual N_2O emissions, the values ranged from 0.16 to 1.0%, with mean EFs across N rates at each site of 0.71, 0.58, and 0.36% for CA1, CA2, and AR, respectively (Table 3).

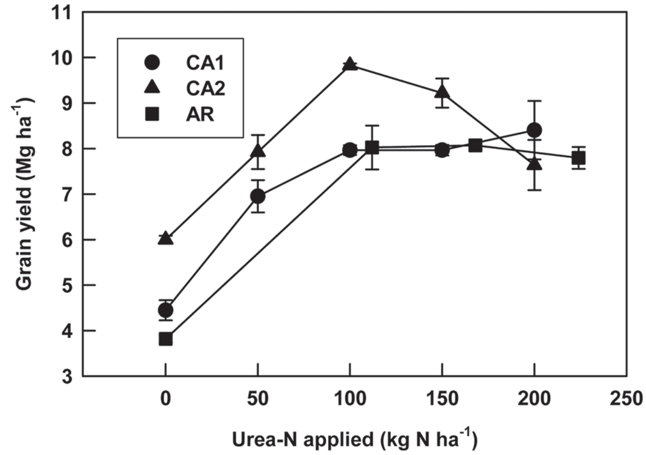

Fig. 2. Average grain yield at different fertilizer N rates in CA1, CA2, and AR. Vertical bars indicate standard errors of three replicates in each field. Field experiments were conducted on two commercial rice farms near Robbins, California (CA1: 38.90 N; 121.73 W; elevation 7 m; CA2: 39.01 N, 121.70 W; elevation 11 m) and on an experimental field (AR) at the University of Arkansas Rice Research & Extension Center near Stuttgart, Arkansas (34.45 N, 91.40 W; elevation 62 m).

Table 3. Estimated annual and seasonal greenhouse gas emissions and percent fertilizer-induced emissions at the three sites fertilized at various nitrogen rates.

Site†/N rate	Cumulative CH_4 emissions‡		Cumulative N_2O emissions‡		Fertilizer-induced emissions§
kg N ha^{-1}	kg CH_4–C ha^{-1}	kg CO_2 eq ha^{-1}	g N_2O–N ha^{-1}	kg CO_2 eq ha^{-1}	%
			Annual		
CA1					
0	13	429	490b	229b	
50	12	408	873b	409b	0.77
100	9.3	310	859b	402b	0.37
150	17	566	1978a	926a	0.99
200	19	644	1915a	896a	0.71
CA2					
0	140	4661	854	400	
50	164	5488	1119	624	0.53
100	176	5887	1881	881	1.03
150	193	6452	1438	673	0.39
200	166	5539	1627	762	0.39
AR					
0	20b	678b	833	390	
112	42a	1390a	1342	628	0.45
168	47a	1556a	1097	514	0.16
224	41a	1363a	1868	875	0.46

Table 3. Continued.

Site†/N rate	Cumulative CH_4 emissions‡		Cumulative N_2O emissions‡		Fertilizer-induced emissions§
kg N ha^{-1}	kg CH_4–C ha^{-1}	kg CO_2 eq ha^{-1}	g N_2O–N ha^{-1}	kg CO_2 eq ha^{-1}	%
			Growing season¶		
CA1					
0	13	429	351b	164b	
50	12	408	670b	314b	0.64
100	9.2	308	626b	293b	0.28
150	17	563	1538a	720a	0.79
200	19	642	1489a	697a	0.57
CA2					
0	134	4480	457	214	
50	148	4942	468	219	0.02
100	155	5163	455	213	0.00
150	183	6126	451	211	0.00
200	156	5208	478	224	0.01
AR					
0	19b	638b	28c	13c	
112	41a	1375a	69bc	33bc	0.04
168	46a	1550a	161b	76b	0.08
224	40a	1336a	336a	157a	0.14
			Fallow season#		
CA1					
0	0	0	139	65	
50	0	0	203	95	0.13
100	0.05	1.7	234	109	0.09
150	0.06	2.1	440	206	0.20
200	0.07	2.3	425	199	0.14
CA2					
0	5.4	181	397	186	
50	16	546	651	305	0.51
100	22	724	1427	668	1.03
150	9.8	327	987	462	0.39
200	9.9	330	1148	538	0.38
AR					
0	1.1	39	805	377	
112	0.44	15	1273	596	0.42
168	0.18	6	935	438	0.08
224	0.81	27	1532	717	0.33

† Field experiments were conducted on two commercial rice farms near Robbins, CA (CA1: 38.90 N; 121.73 W; elevation 7 m; CA2: 39.01 N, 121.70 W; elevation 11 m), and on an experimental field (AR) at the University of Arkansas Rice Research & Extension Center near Stuttgart, AR (34.45 N, 91.40 W; elevation 62 m).

‡ Within each CH_4 and N_2O seasonal, annual, site emissions and global warming potential followed by the same letter are not significantly different at $P < 0.05$.

§ The N_2O emission factor was calculated by dividing the total kg N_2O–N emitted minus background N_2O emissions per ha by total kg N applied per ha × 100.

¶ Growing season refers to the period from seeding to harvest of rice.

Fallow season refers to the period from harvest in the fall to spring cultivation.

Methane Emissions

Annual CH_4 emissions ranged from 9 to 193 kg CH_4–C ha^{-1} yr^{-1} (Table 3). At all sites, significant CH_4 fluxes were measured approximately 2 to 3 wk after fields were permanently flooded (Fig. 1). The highest CH_4 emissions occurred between panicle initiation and heading and decreased thereafter. Immediately after field drainage and before harvest, there was a large increase in CH_4 emissions. Total CH_4 emissions during this postdrainage event ranged from 3 to 18% of total annual CH_4 emissions.

During the winter fallow, CH_4 emissions remained low in all fields, with the highest emissions occurring in CA2, which was flooded during the winter months. Despite this site being flooded during the winter fallow period, 89% of annual CH_4 emissions occurred during the growing season. At CA1 and AR, CH_4 emissions during the growing season contributed >94% to the total annual CH_4 emissions.

Annual CH_4 emissions from treatments without N addition were 13, 140, and 20 kg CH_4–C ha^{-1} yr^{-1} in CA1, CA2, and AR, respectively (Table 3). Differences in growing season and annual

CH_4 emissions among N treatments were not significant with one exception; fertilizer N addition increased CH_4 emissions during the growing season in AR.

Global Warming Potential

Estimated GWP based on annual GHG emissions ranged from 658 to 7126 kg CO_2 eq ha^{-1} yr^{-1} (Table 4). There were significant effects of N fertilizer rate on GWP at CA1 and AR during the growing season but not during the fallow period. At CA2 there was no effect of N rate on growing season or annual GWP. Across sites and N rates, GWP based on growing season emissions contributed between 61 and 93% to total annual GWP (Table 4). Within each growing season, CH_4 emissions represented 96, 95, and 54% of GWP at CA2, AR, and CA1, respectively. Although the major contributor to annual GWP at CA2 was CH_4 emissions (89%), N_2O emissions contributed 52 and 33% to annual GWP at CA1 and AR, respectively (Table 4).

Yield-scaled growing season N_2O emissions were lowest at low to optimal N rates and increased at higher N fertilizer rates (Fig. 3a). In contrast, there was no effect of N rate on yield-scaled growing season CH_4 emissions (Fig. 3b). Moreover, there was no significant effect of N fertilizer rate on growing season or annual GWP_Y, although growing season GWP_Y was lowest at optimal N rates at both CA sites (Fig. 3c; Table 4). Averaged across N rates, the highest growing season GWP_Y occurred at CA2 (686 kg CO_2 eq Mg^{-1} $season^{-1}$) and the lowest at CA1 (130 kg CO_2 eq Mg^{-1} $season^{-1}$).

Discussion

Contributions of Methane and Nitrous Oxide to Seasonal and Annual Global Warming Potential

The main GHG emitted from these sites was CH_4, accounting for 82 and 68% of total growing season and annual GWP, respectively, when averaged across sites and N rates (Table 3). Such findings are consistent with Linquist et al. (2012a), who reported that CH_4 emissions contributed 89% to total growing season GWP based on meta-analysis results. During the winter fallow period, CH_4 emissions were only significant at the CA2 site, which was flooded. However, even at this site, CH_4 emissions were relatively low and accounted for only 7% of total annual CH_4 emissions. Low winter CH_4 emissions are likely due to cool temperatures, which slow rates of CH_4 production (Schütz et al., 1990). Pittelkow et al. (2013) reported that fallow period CH_4 emissions were, on average, 34 kg CH_4–C ha^{-1}, or 24% of total annual CH_4 emissions in a commercial California rice field. These results are lower than the winter CH_4 emissions found by Fitzgerald et al. (2000), who reported that 87 kg CH_4–C ha^{-1} $season^{-1}$ was emitted during the winter fallow, accounting for approximately 55% of annual CH_4 emissions. The reasons for these differences in CH_4 emissions remain unclear. In our study at the CA2 site and in the study by Fitzgerald et al. (2000), straw was retained and fields were flooded over the winter period. Cooler temperatures may have played a role; the average winter temperature was 3°C lower in our study at the CA2 site (8.6°C) than in Fitzgerald et al. (2000) (11.9°C). Maintaining nonflooded conditions during the winter fallow season might be considered as a practice to reduce annual CH_4 emissions, yet

Table 4. Global warming potential and yield-scaled global warming potential at the three study sites fertilized at various nitrogen rates.

Site†/N rate	Areal-scaled global warming potential‡			Yield-scaled global warming potential		
	Growing season§	Fallow season¶	Annual	Growing season	Fallow season	Annual
kg N ha^{-1}	— kg CO_2 eq ha^{-1} $season^{-1}$ —		kg CO_2 eq ha^{-1} yr^{-1}	— kg CO_2 eq Mg^{-1} $season^{-1}$ —		kg CO_2 eq Mg^{-1} yr^{-1}
CA1						
0	593b	65	658b	141	15	156
50	721b	95	816b	105	14	120
100	601b	111	712b	77	14	91
150	1283a	208	1491a	162	26	188
200	1339a	201	1541a	164	26	190
CA2						
0	4694	367	5061	784	60	844
50	5161	851	6012	659	113	772
100	5376	1392	6768	546	142	687
150	6337	789	7126	691	85	776
200	5432	868	6300	750	123	874
AR						
0	651b	416	1068b	172	106	278
112	1408a	610	2018a	184	80	265
168	1625a	444	2069a	202	55	257
224	1493a	744	2238a	191	95	286

† Field experiments were conducted on two commercial rice farms near Robbins, California (CA1: 38.90 N; 121.73 W; elevation 7 m; CA2: 39.01 N, 121.70 W; elevation 11 m) and on an experimental field (AR) at the University of Arkansas Rice Research & Extension Center near Stuttgart, AR (34.45 N, 91.40 W; elevation 62 m).

‡ Within each field, yield, and global warming potential followed by the same letter or without letters are not significantly different at $P < 0.05$.

§ Growing season refers to the period from seeding to harvest of rice.

¶ Fallow season refers to the period from harvest in the fall to spring cultivation.

these results suggest further work is needed to better understand and quantify the mitigation potential of this practice.

In all fields a large peak of CH_4 occurred several days after the field was drained before harvest and immediately after no standing water was present but before the soil started to crack. Averaged across sites and N rates, these peaks accounted for 11% of total annual CH_4 emissions. Large postdrainage CH_4 peaks have also been reported (Bossio et al., 1999; Denier van der Gon et al., 1996; Liang et al., 2013; Pittelkow et al., 2013; Wassmann et al., 1994) and are attributed to the release of entrapped CH_4 during the transition from flooded to aerated soil conditions (Denier van der Gon et al., 1996). Although the magnitude of postdrainage emissions can vary, Denier van der Gon et al. (1996) observed that the ratio of emissions during soil drainage to cumulative emissions is 10 ± 4%. The CH_4 emissions associated with these peaks lasted only a few days before CH_4 emissions decreased to ambient levels, highlighting the importance of frequent gas sampling after drainage events to ensure a full accounting of CH_4 emissions.

Nitrous oxide emissions were relatively low at all sites and accounted for 32% of total annual GWP on average. However, differences between sites illustrate the potential for elevated N_2O emissions due to anaerobic and aerobic soil conditions, which can influence the relative contribution of N_2O to GWP. For example, N_2O emissions represented 52% of annual GWP across N rates at CA1. Nonetheless, during the majority of the growing season when fields were flooded, N_2O emissions remained low to nondetectable at all sites, as would be expected due to the low redox potential of flooded soils (Hou et al., 2000). During the winter (Nov.–Feb.), N_2O emissions were also low or untraceable, regardless of whether fields experienced flooded or nonflooded conditions. Low N_2O emissions would be expected during this period due to low mean air temperatures (8.6°C), which slow or halt microbial activity (van Hulzen et al., 1999). Nitrous oxide emissions primarily occurred during transition periods in water management and soil water content (Fig. 1). In particular, N_2O emissions increased during tillage (AR) and/or during the early crop establishment phases at all sites due to rainfall or irrigation flushes for germination and crop establishment. In addition, N_2O emissions were detected after field drainage at CA1, which accounted for 75% of annual N_2O emissions. Although only observed at one site in this study, Towprayoon et al. (2005) observed increases in N_2O emissions after field drainage before harvest, suggesting that soil redox potential during this period is favorable for N_2O production. Similarly, N_2O emissions were detected in the fall (after harvest) and early spring (before tillage), likely due to adequate precipitation during these periods accompanied by relatively warm temperatures.

The IPCC (2006), along with previous studies (Cai et al., 1997; Zheng et al., 2004), suggests that it is important to quantify total annual emissions to assess the full impact of a cropping system. Although our results support this conclusion (e.g., winter flooding affected the total amount and type of GHG emission during the fallow period), we observed no memory effect of N rate on CH_4 and N_2O emissions into the winter fallow period. Few studies have examined how N management practices affect GHG emissions during the fallow season. Higher CH_4 emissions for treatments with high or excessive N rates might be expected during the fallow period due to the lower C/N ratios

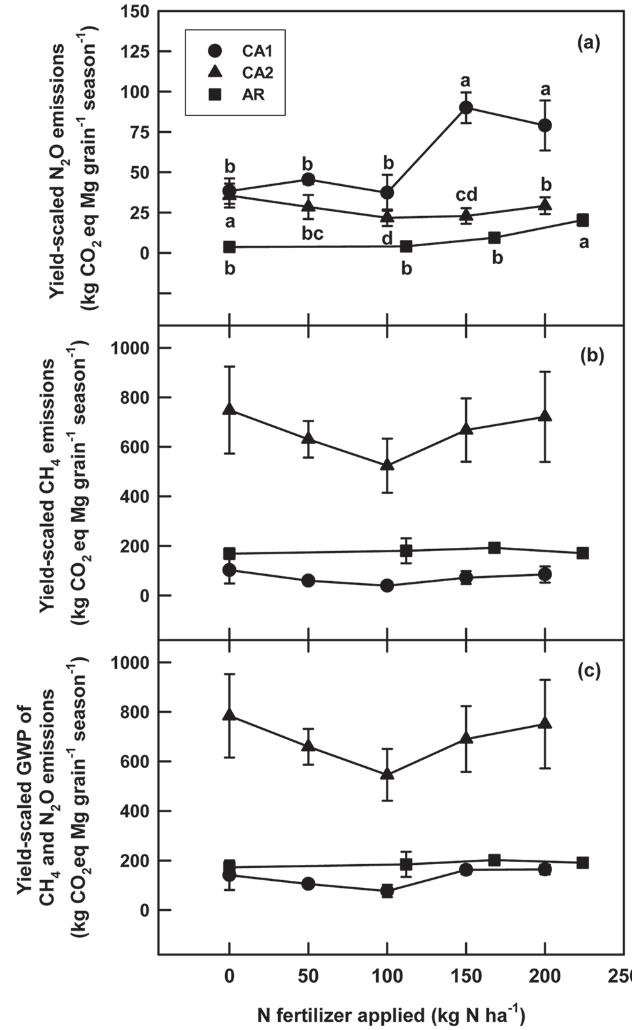

Fig. 3. Yield-scaled global warming potential and CH_4 and N_2O emissions at various fertilizer N rates in CA1, CA2, and AR. Vertical bars indicate standard errors of three replicates in each field. Yield-scaled N_2O emissions in each field followed by same letter are not significant at $P < 0.05$. Field experiments were conducted on two commercial rice farms near Robbins, CA (CA1: 38.90 N; 121.73 W; elevation 7 m; CA2: 39.01 N, 121.70 W; elevation 11 m), and on an experimental field (AR) at the University of Arkansas Rice Research & Extension Center near Stuttgart, AR (34.45 N, 91.40 W; elevation 62 m).

of rice straw (data not shown) (Denier van der Gon and Neue, 1995; Lauren et al., 1994). However, any effects of N rate on CH_4 and N_2O emissions were confined to the growing season (Table 3), suggesting that the growing season should remain the focus when evaluating the impacts of fertilizer N rate on GHG emissions from drill seeded rice.

Nitrogen Rate, Yield, and Greenhouse Gas Emissions

Because the majority of annual GHG emissions occurred during the growing season and because there was no memory effect of higher N rates into the fallow period, the discussion hereafter is restricted to the growing season. The effect of fertilizer N rate on rice yields was generally as expected in the CA sites, where optimal N rates for this variety are close to 100 kg N ha^{-1} (Fig. 2). In contrast, the N rate that maximized yields in AR was 112 kg N ha^{-1}, which is lower than the typically recommended rate of 168 kg N ha^{-1}. Fertilizer N application above the optimal

N rate led to similar (CA1, AR) or declining (CA2, where lodging occurred) yields relative to the optimum N rate.

In our study we found that, on a relative basis, N management had a much greater effect on N_2O emissions than on CH_4 emissions (Table 3). In all locations, N_2O emissions were higher with N addition compared with treatments without N addition, although this difference was only significant at CA1 (Table 3). At this site, high N_2O emissions (more than double the amount emitted at the optimal N rate) were observed at N rates in excess of that required for optimum yields. Such findings support those of Ma et al. (2007), who also found that excessive N rates led to elevated N_2O emissions and suggested that application of fertilizer N based on crop demand is an effective way to achieve economic and environmental benefits without comprising yield. At the other sites, N_2O emissions were variable and therefore inconclusive regarding N rate. Although fertilizer-induced N_2O EFs showed no clear relationship with N rate, the lowest EFs (ranging from 0 to 0.28%) were observed at optimal N rates (Table 3), well within the range reported by Akiyama et al. (2005) for continuously flooded fields.

In contrast to N_2O emissions, increasing fertilizer N rate had no effect on CH_4 emissions in either CA field. However, CH_4 emissions in AR were higher in all treatments receiving N (Table 3). Although the effects of fertilizer N rate on CH_4 emissions are often found to be contradictory with reports of CH_4 emissions increasing (Shang et al., 2011) or decreasing (Yao et al., 2012), Linquist et al. (2012b) suggested that much of these discrepancies could be explained by differences in N rate. They found that low to optimal N rates tended to increase CH_4 emissions, whereas excessive N rates reduced CH_4 emissions, in part due to the potential for NH_4^+ to stimulate the oxidation of CH_4 (Bodelier and Laanbroek, 2004). Our results do not fully support these findings. Moreover, apart from the AR site where CH_4 emissions were higher with N addition, there was little further effect of fertilizer N on CH_4 emissions.

Variation of Seasonal Greenhouse Gas Emissions among Sites

Previous studies in conventional wet seeded rice systems in California have reported average CH_4 emissions ranging from 50 to 164 kg CH_4–C ha^{-1} season^{-1} (Bossio et al., 1999; Fitzgerald et al., 2000; McMillan et al., 2007; Redeker et al., 2000). This range is similar to the average value of 168 kg CH_4–C ha^{-1} season^{-1} observed at CA2. However, average CH_4 emissions at CA1 were much lower (14 kg CH_4–C ha^{-1} season^{-1}). The large difference in CH_4 emissions between these sites occurred despite similar N management, agronomic practices, cultivar, and climatic conditions (Tables 1 and 4; Fig. 1). Although such differences are not unusual, they can be difficult to fully explain (Wassmann et al., 2000). We can only hypothesize here as to what caused these differences, but there are at least two possibilities. First, the soil at CA2 (which had higher emissions) had a higher sand content than CA1. Others have reported that coarser-textured soils emit greater amounts of CH_4, which was attributed to improved diffusive transport of CH_4 through the soil (Huang et al., 2002; Jäckel et al., 2001). Second, Yan et al. (2005) reported that maintaining nonflooded conditions during the fallow period could have a large effect on lowering CH_4 emissions in the subsequent growing season. In agreement with these findings, the CA2 field was flooded during the fallow period before the initiation of the experiment, whereas the CA1 field was not.

Considerable research on CH_4 emissions from drill seeded rice systems has been conducted in Louisiana and Texas. Estimates of CH_4 emissions have been as low as 57 kg CH_4–C ha^{-1} in Texas (Sass et al., 1992) and 78 kg CH_4–C ha^{-1} in Louisiana (Lindau, 1994). However, the average emission at AR was 30 kg CH_4–C ha^{-1}, below that reported elsewhere in the southern United States. In part, these differences may be related to variety. Varietal effects on CH_4 emissions are known to exist and can be significant. For example, a roughly 2-fold difference in CH_4 emissions was reported between varieties in Texas and Louisiana (Lindau et al., 1995; Sigren et al., 1997; Huang et al., 1997). It is possible that the hybrid variety used at the AR site in our study emits less CH_4 relative to the varieties evaluated in Louisiana and Texas, which are all nonhybrids.

Achieving Low Yield-Scaled Global Warming Potential

The objective of this study was to test the hypothesis that the lowest GWP_Y is achieved at optimal N rates. Our results for yield-scaled N_2O emissions support the meta-analysis results of van Groenigen et al. (2010) at the CA1 and AR locations, where yield-scaled N_2O emissions were lowest at optimal and suboptimal N rates but increased at N rates that were above optimal (Fig. 3a). At CA2, yield-scaled N_2O emissions were also lowest at optimal N rates but were higher at suboptimal and above optimal N rates. In contrast, yield-scaled CH_4 emissions were not significantly affected by fertilizer N rate (Fig. 3b). However, a similar trend was observed at both CA sites, where the lowest yield-scaled CH_4 emissions occurred at optimal N rates. Combining CH_4 and N_2O emissions and expressing GWP as a function of yield, large differences in growing season GWP_Y occurred between sites, with values ranging from an average of 130 (CA1) to 686 (CA2) kg CO_2 eq Mg^{-1} season^{-1}, a roughly 5-fold difference (Fig. 3c). Within each site, however, GWP_Y was not significantly different among N rates. As with the trend in yield-scaled CH_4, the lowest GWP_Y at both CA sites was observed at optimal N rates. Although other researchers have reported an approximately 40% reduction in growing season GWP_Y at optimal N rates in rice (Feng et al., 2013), we found that GWP_Y for drill seeded rice was independent of N rate. Therefore, from a management perspective that seeks to address environmental degradation and global food security, the recommendation is to apply N rates for optimal grain yields, similar to the recommendations by others for other rice systems (Liang et al. (2013) and Pittelkow et al., 2013).

Conclusions

To our knowledge, this is the first study reporting both seasonal and annual CH_4 and N_2O emissions from drill seeded rice systems. Growing season emissions contributed the most to total annual GHG emissions in all sites. In turn, CH_4 emissions contributed on average 82% of GWP during the growing season, suggesting that strategies to reduce GWP in these rice systems should focus on reducing growing season CH_4 emissions. Excessive N rates increased N_2O and yield-scaled N_2O emissions, but N rate had little or no effect on CH_4 emissions. Above-optimal fertilizer N rates resulted in higher yield-scaled

GWP at optimal N rates due to the combined effects of low grain yield and high GWP. We were not able to confirm our hypothesis that the lowest GWP_Y would be achieved at optimal N rates because GWP_Y was independent of N rate. However, our findings support the recommendation of applying optimal N rates to achieve global food security objectives. Although this study shows no negative effect of overapplication of N fertilizer in terms of GWP_Y, economics would likely not favor it.

Acknowledgments

This project was funded by the California Rice Research Board and Mars, Inc. The authors thank Cesar Abrenilla, Christopher Mikita, Eduardo Cassiolato, Shelly Kerr, Tara Moss, Gabriella Amalfi, M. Carmella Andrea, Khoi Vu, Megan Houg, Rafael Pedroso, Gay Padilla, Meagan Simmonds, Mark Lundy, Timothy Doane, and Emilie Kirk for their valuable help during field data collection and laboratory analyses; the rice growers who collaborated with us on this project; and RiceTec, Inc. for providing the hybrid rice seed.

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