

## 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<sub>4</sub> and N<sub>2</sub>O 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<sub>Y</sub> = GWP Mg<sup>-1</sup> grain) is achieved. Each growing season, urea was applied at rates ranging from 0 to 224 kg N ha<sup>-1</sup> before the permanent flood. Emissions of CH<sub>4</sub> and N<sub>2</sub>O were measured daily to weekly during growing seasons and fallow periods. Annual CH<sub>4</sub> emissions ranged from 9.3 to 193 kg CH<sub>4</sub>-C ha<sup>-1</sup> yr<sup>-1</sup> across sites, and annual N<sub>2</sub>O emissions averaged 1.3 kg N<sub>2</sub>O-N ha<sup>-1</sup> yr<sup>-1</sup>. Relative to N<sub>2</sub>O emissions, CH<sub>4</sub> 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<sub>4</sub> emissions but contributing to greater N<sub>2</sub>O 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<sub>Y</sub> ranged from 130 to 686 kg CO<sub>2</sub> eq Mg<sup>-1</sup> season<sup>-1</sup> across sites and years. Fertilizer N rate had no significant effect on GWP<sub>Y</sub>; therefore, achieving the highest productivity is not at the cost of higher GWP<sub>Y</sub>.

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<sub>4</sub>, N<sub>2</sub>O, and CO<sub>2</sub>) (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<sub>Y</sub>) (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<sub>2</sub>O emissions were obtained in intensive cropping systems managed at near yield potential with high N use efficiency and that significant N<sub>2</sub>O 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<sub>2</sub>O emissions, much less is known about its effects on CH<sub>4</sub> emissions. Because CH<sub>4</sub> 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.

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**Abbreviations:** EF, emission factor; GC, gas chromatograph; GHG, greenhouse gas; GWP, global warming potential; GWP<sub>Y</sub>, 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<sub>4</sub> production, and, with the total harvested area of rice representing 14% of Earth's cropland, rice cultivation is the largest terrestrial source of CH<sub>4</sub> (Smith et al., 2007). Through its direct and indirect effects on methanogenesis and methanotrophy processes that lead to net CH<sub>4</sub> emissions, fertilizer N can contribute to variations in CH<sub>4</sub> fluxes (Schimel, 2000). It has been reported that the addition of fertilizer N can lead to an increase in CH<sub>4</sub> emissions (Shang et al., 2011; Singh et al., 1996) or a decrease in CH<sub>4</sub> emissions (Xie et al., 2010; Yao et al., 2012) or that it can have no effect on CH<sub>4</sub> 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<sub>4</sub> emissions and excessive N rates reducing CH<sub>4</sub> emissions. Regarding N<sub>2</sub>O, emissions are largely determined by water and N management practices. High N<sub>2</sub>O 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<sub>2</sub>O production (Dobbie et al., 1999). Therefore, lowering anthropogenic emissions of N<sub>2</sub>O and CH<sub>4</sub> while maintaining rice yields through efficient fertilizer N management remains a challenge for rice production.

A majority of field studies evaluating CH<sub>4</sub> and N<sub>2</sub>O 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<sub>4</sub> and N<sub>2</sub>O 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<sub>2</sub>O 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<sub>4</sub> 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<sub>2</sub>O emissions (Cai et al., 1997) and lead to higher GWP values. Although there has

been considerable research on CH<sub>4</sub> emissions from drill seeded rice in the United States (e.g., Lindau, 1994; Sass et al., 1992), there has been no measurement of N<sub>2</sub>O from these systems to adequately assess GWP. Here, we tested the hypothesis that the lowest GWP<sub>Y</sub> 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<sub>4</sub> and N<sub>2</sub>O 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<sup>2</sup> in size. Nitrogen rates ranged from 0 to 200 kg N ha<sup>-1</sup> at the CA sites and 0 to 224 kg N ha<sup>-1</sup> in AR (Table 2). The treatment of 100 kg N ha<sup>-1</sup> 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<sup>-1</sup>. 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<sup>-1</sup>, depending on location) and K<sub>2</sub>SO<sub>4</sub> (24–29 kg K ha<sup>-1</sup>, 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<sub>2</sub>O 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 <sup>-1</sup>			
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 <sup>-1</sup>	0.59	0.17	0.57
CEC,§ cmol kg <sup>-1</sup>	54.8	24.7	11.5
Total organic C, g kg <sup>-1</sup>	13.4	13.7	6.76
Total N, g kg <sup>-1</sup>	1.4	1.1	0.71
Extractable Olsen P, mg kg <sup>-1</sup>	20.9	21.2	13.7
Exchangeable K, mg kg <sup>-1</sup>	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<sub>4</sub> and N<sub>2</sub>O 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 <sup>-1</sup>	drill seeding/70 kg ha <sup>-1</sup>	drill seeding/28 kg ha <sup>-1</sup>
Drain period before harvest	27 Sept.–18 Oct. 2010	20–30 Sept. 2011	12–22 Sept. 2010
Annual N application, kg N ha <sup>-1</sup>	0, 50, 100, 150, and 200	0, 50, 100, 150, and 200	0, 112, 168, and 224
Annual P application, kg P ha <sup>-1</sup>	24	24	29
Annual K application, kg K ha <sup>-1</sup>	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  $^{63}\text{Ni}$  electron capture detector for  $\text{N}_2\text{O}$  concentrations and flame ionization detector for  $\text{CH}_4$  concentrations. Nitrous oxide and  $\text{CH}_4$  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  $\text{pg s}^{-1} \text{N}_2\text{O}$  and 2.2  $\text{pg s}^{-1} \text{CH}_4$ . The GC was calibrated using standard  $\text{N}_2\text{O}$  and  $\text{CH}_4$  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  $\text{N}_2\text{O}$  and  $\text{CH}_4$  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  $\text{N}_2\text{O}$  and  $\text{CH}_4$  were estimated from the linear increase of gas concentration over time. Gas concentrations were converted to mass per unit volume ( $\text{g N}_2\text{O}$  or  $\text{CH}_4 \text{L}^{-1}$ ) using the Ideal Gas Law at chamber air temperature measured during each sampling event and 0.101 MPa. Fluxes of  $\text{N}_2\text{O}$  and  $\text{CH}_4$  were computed as:

$$F = \frac{\Delta C}{\Delta t} \times \frac{V}{A} \times \alpha \quad [1]$$

where  $F$  is gas flux rate for  $\text{N}_2\text{O}$  ( $\text{g N}_2\text{O-N ha}^{-1} \text{d}^{-1}$ ) and  $\text{CH}_4$  ( $\text{g CH}_4\text{-C ha}^{-1} \text{d}^{-1}$ ),  $\Delta C/\Delta t$  denotes the increase or decrease of gas concentration in the chamber ( $\text{gL}^{-1} \text{d}^{-1}$ ),  $V$  is the chamber volume,  $A$  is the enclosed surface area (ha), and  $\alpha$  is a conversion coefficient for elemental N and C (28/44 for  $\text{N}_2\text{O}$ ; 12/16 for  $\text{CH}_4$ ). 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,  $\text{N}_2\text{O}$  and  $\text{CH}_4$  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  $\text{N}_2\text{O}$  emission factor ( $\text{EF}_{\text{N}_2\text{O}}$ ) was calculated as follows:

$$\text{EF}_{\text{N}_2\text{O}} = \left[ \frac{(\text{N}_2\text{O}_{\text{NF}} - \text{N}_2\text{O}_{\text{N0}})}{\text{N input}} \right] 100 \quad [2]$$

where  $\text{N}_2\text{O}_{\text{NF}}$  is total  $\text{N}_2\text{O}$  emission from N fertilizer rate treatment ( $\text{kg N}_2\text{O-N ha}^{-1} \text{yr}^{-1}$ ),  $\text{N}_2\text{O}_{\text{N0}}$  is the total  $\text{N}_2\text{O}$  emission from zero N fertilizer treatment ( $\text{kg N}_2\text{O-N ha}^{-1} \text{yr}^{-1}$ ), and N input is the corresponding fertilizer N rate applied ( $\text{kg N ha}^{-1} \text{yr}^{-1}$ ).

## 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<sup>2</sup> 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  $\text{g kg}^{-1}$  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 ( $P = 0.001\text{--}0.459$ ). 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  $\times$  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  $\text{N}_2\text{O}$  and  $\text{CH}_4$  was calculated in mass of  $\text{CO}_2$  equivalents ( $\text{kg CO}_2 \text{ eq ha}^{-1}$ ) over a 100-yr time horizon. Radiative forcing potentials relative to  $\text{CO}_2$  of 298 and 25 were used for  $\text{N}_2\text{O}$  and  $\text{CH}_4$ , respectively (Houghton et al., 2001). Yield-scaled GWP ( $\text{GWP}_Y$ ) expressed as GWP per unit mass of rice grain ( $\text{kg CO}_2 \text{ eq Mg grain}^{-1}$ ) was computed by taking the ratio of GWP ( $\text{kg CO}_2 \text{ eq ha}^{-1}$ ) and grain yield ( $\text{Mg ha}^{-1}$ ). 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

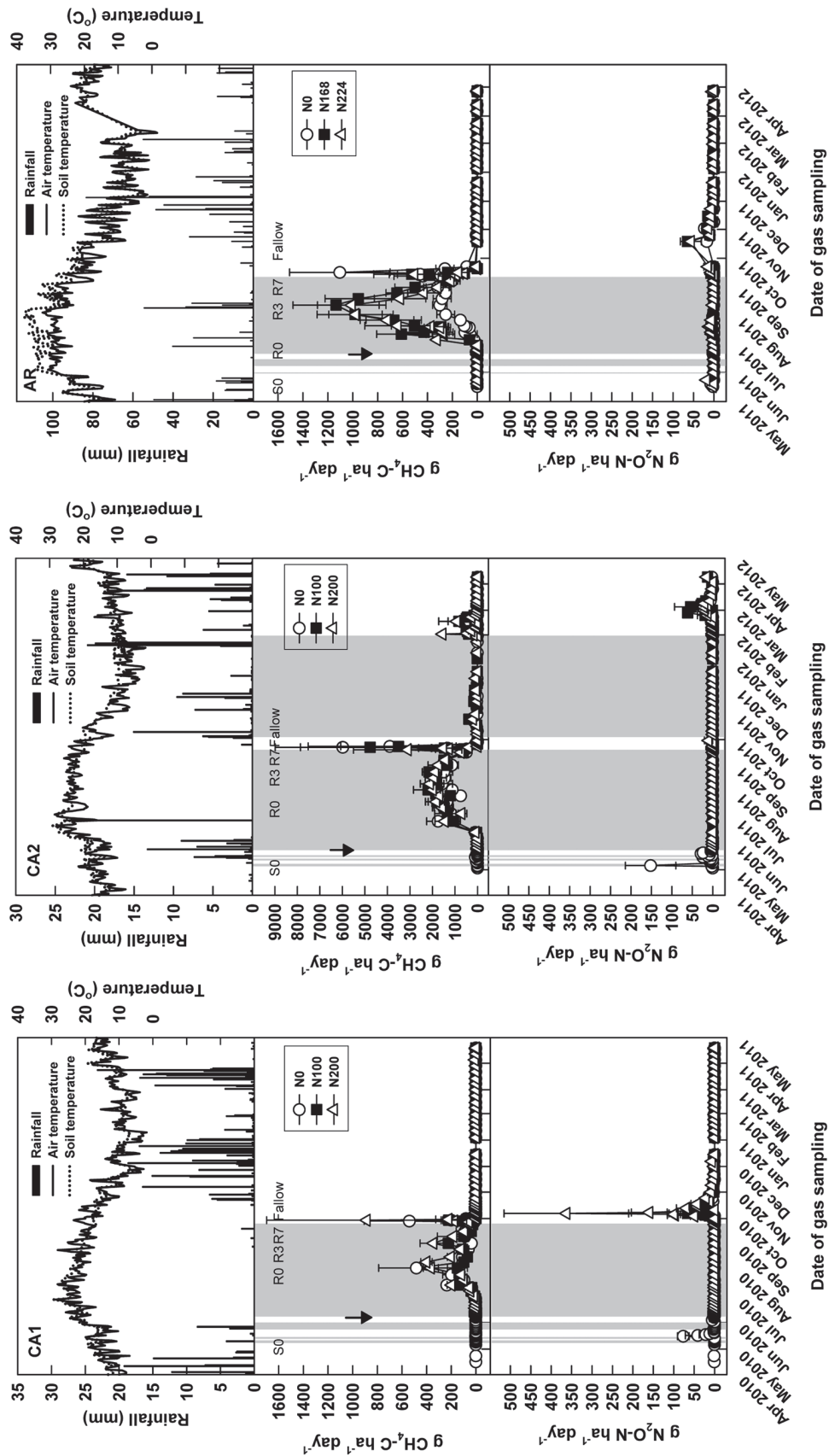


Fig. 1. Soil/air temperature, rainfall, methane, and  $\text{N}_2\text{O}$  emissions from drill seeded rice in CA1 and CA2 fertilized at 0, 100, and 200  $\text{kg N ha}^{-1}$  and in AR field fertilized at 0, 168, and 224  $\text{kg N ha}^{-1}$ . Arrow and shaded area locations indicate date of fertilizer 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<sup>-1</sup> without N fertilizer addition (Fig. 2). Fertilizer N rates required to reach maximum yields were 100 kg N ha<sup>-1</sup> in both CA fields and 112 kg N ha<sup>-1</sup> 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<sub>2</sub>O emissions was similar in all fields, with emissions averaging 1.30 kg N<sub>2</sub>O–N ha<sup>-1</sup> yr<sup>-1</sup> and ranging from 490 kg to 1915 g N<sub>2</sub>O–N ha<sup>-1</sup> yr<sup>-1</sup> (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<sub>2</sub>O emissions were <14.3 g N<sub>2</sub>O–N ha<sup>-1</sup> d<sup>-1</sup> and were usually nondetectable. Annual N<sub>2</sub>O emissions in the 0N fertilizer treatment were 490, 854, and 833 g N<sub>2</sub>O–N ha<sup>-1</sup> yr<sup>-1</sup> in AR, CA1, and CA2, respectively.

The relative amount of N<sub>2</sub>O emissions during the growing and fallow seasons differed among fields. Averaged across N rates, growing season N<sub>2</sub>O 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<sub>2</sub>O 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<sub>2</sub>O emissions during the growing season, no significant effect

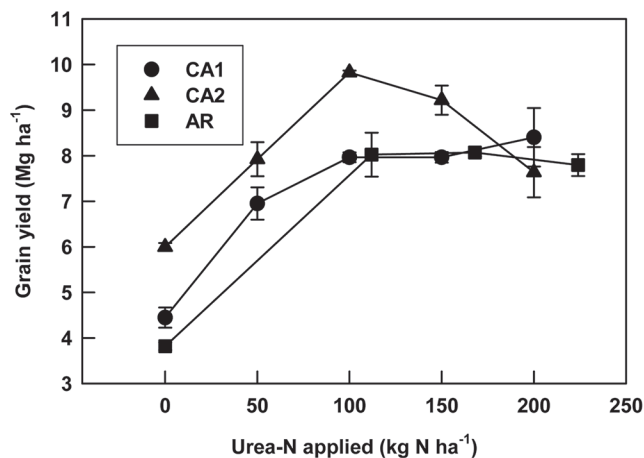


Fig. 2. Average grain yield at different fertilizer N rates in CA1, CA2, and AR. Vertical bars indicate standard errors of three replicates in each field. Field experiments were conducted on two commercial rice farms near Robbins, California (CA1: 38.90 N; 121.73 W; elevation 7 m; CA2: 39.01 N, 121.70 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).

of N fertilizer rate on N<sub>2</sub>O emissions was observed during the winter fallow period (Table 3).

Averaged across all sites and N rates, the mean fertilizer-induced N<sub>2</sub>O emission factor (EF) during the growing season was 0.22%. Whereas several N rates had no fertilizer-induced effect on N<sub>2</sub>O emissions in CA2, the highest emission factor of 0.79% was observed at 150 kg N ha<sup>-1</sup> in CA1. When emission factors were calculated based on annual N<sub>2</sub>O 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).

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 <sub>4</sub> emissions‡		Cumulative N <sub>2</sub> O emissions‡		Fertilizer-induced emissions§
	kg CH <sub>4</sub> -C ha <sup>-1</sup>	kg CO <sub>2</sub> eq ha <sup>-1</sup>	g N <sub>2</sub> O–N ha <sup>-1</sup>	kg CO <sub>2</sub> eq ha <sup>-1</sup>	
	<b>Annual</b>				
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 <sub>4</sub> emissions‡		Cumulative N <sub>2</sub> O emissions‡		Fertilizer-induced emissions§
	kg CH <sub>4</sub> -C ha <sup>-1</sup>	kg CO <sub>2</sub> eq ha <sup>-1</sup>	g N <sub>2</sub> O-N ha <sup>-1</sup>	kg CO <sub>2</sub> eq ha <sup>-1</sup>	%
<b>Growing season¶</b>					
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
<b>Fallow season#</b>					
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<sub>4</sub> and N<sub>2</sub>O seasonal, annual, site emissions and global warming potential followed by the same letter are not significantly different at  $P < 0.05$ .

§ The N<sub>2</sub>O emission factor was calculated by dividing the total kg N<sub>2</sub>O-N emitted minus background N<sub>2</sub>O 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<sub>4</sub> emissions ranged from 9 to 193 kg CH<sub>4</sub>-C ha<sup>-1</sup> yr<sup>-1</sup> (Table 3). At all sites, significant CH<sub>4</sub> fluxes were measured approximately 2 to 3 wk after fields were permanently flooded (Fig. 1). The highest CH<sub>4</sub> emissions occurred between panicle initiation and heading and decreased thereafter. Immediately after field drainage and before harvest, there was a large increase in CH<sub>4</sub> emissions. Total CH<sub>4</sub> emissions during this postdrainage event ranged from 3 to 18% of total annual CH<sub>4</sub> emissions.

During the winter fallow, CH<sub>4</sub> 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<sub>4</sub> emissions occurred during the growing season. At CA1 and AR, CH<sub>4</sub> emissions during the growing season contributed >94% to the total annual CH<sub>4</sub> emissions.

Annual CH<sub>4</sub> emissions from treatments without N addition were 13, 140, and 20 kg CH<sub>4</sub>-C ha<sup>-1</sup> yr<sup>-1</sup> in CA1, CA2, and AR, respectively (Table 3). Differences in growing season and annual



CH<sub>4</sub> emissions among N treatments were not significant with one exception; fertilizer N addition increased CH<sub>4</sub> emissions during the growing season in AR.

## Global Warming Potential

Estimated GWP based on annual GHG emissions ranged from 658 to 7126 kg CO<sub>2</sub> eq ha<sup>-1</sup> yr<sup>-1</sup> (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<sub>4</sub> 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<sub>4</sub> emissions (89%), N<sub>2</sub>O emissions contributed 52 and 33% to annual GWP at CA1 and AR, respectively (Table 4).

Yield-scaled growing season N<sub>2</sub>O 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<sub>4</sub> emissions (Fig. 3b). Moreover, there was no significant effect of N fertilizer rate on growing season or annual GWP<sub>Y</sub>, although growing season GWP<sub>Y</sub> was lowest at optimal N rates at both CA sites (Fig. 3c; Table 4). Averaged across N rates, the highest growing season GWP<sub>Y</sub> occurred at CA2 (686 kg CO<sub>2</sub> eq Mg<sup>-1</sup> season<sup>-1</sup>) and the lowest at CA1 (130 kg CO<sub>2</sub> eq Mg<sup>-1</sup> season<sup>-1</sup>).

## Discussion

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

The main GHG emitted from these sites was CH<sub>4</sub>, 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<sub>4</sub> emissions contributed 89% to total growing season GWP based on meta-analysis results. During the winter fallow period, CH<sub>4</sub> emissions were only significant at the CA2 site, which was flooded. However, even at this site, CH<sub>4</sub> emissions were relatively low and accounted for only 7% of total annual CH<sub>4</sub> emissions. Low winter CH<sub>4</sub> emissions are likely due to cool temperatures, which slow rates of CH<sub>4</sub> production (Schütz et al., 1990). Pittelkow et al. (2013) reported that fallow period CH<sub>4</sub> emissions were, on average, 34 kg CH<sub>4</sub>-C ha<sup>-1</sup>, or 24% of total annual CH<sub>4</sub> emissions in a commercial California rice field. These results are lower than the winter CH<sub>4</sub> emissions found by Fitzgerald et al. (2000), who reported that 87 kg CH<sub>4</sub>-C ha<sup>-1</sup> season<sup>-1</sup> was emitted during the winter fallow, accounting for approximately 55% of annual CH<sub>4</sub> emissions. The reasons for these differences in CH<sub>4</sub> 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<sub>4</sub> 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 <sup>-1</sup>	— kg CO <sub>2</sub> eq ha <sup>-1</sup> season <sup>-1</sup> —		kg CO <sub>2</sub> eq ha <sup>-1</sup> yr <sup>-1</sup>	— kg CO <sub>2</sub> eq Mg <sup>-1</sup> season <sup>-1</sup> —		kg CO <sub>2</sub> eq Mg <sup>-1</sup> yr <sup>-1</sup>
<b>CA1</b>						
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
<b>CA2</b>						
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
<b>AR</b>						
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<sub>4</sub> 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<sub>4</sub> emissions. Large postdrainage CH<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> emissions associated with these peaks lasted only a few days before CH<sub>4</sub> emissions decreased to ambient levels, highlighting the importance of frequent gas sampling after drainage events to ensure a full accounting of CH<sub>4</sub> 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<sub>2</sub>O emissions due to anaerobic and aerobic soil conditions, which can influence the relative contribution of N<sub>2</sub>O to GWP. For example, N<sub>2</sub>O emissions represented 52% of annual GWP across N rates at CA1. Nonetheless, during the majority of the growing season when fields were flooded, N<sub>2</sub>O 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<sub>2</sub>O emissions were also low or untraceable, regardless of whether fields experienced flooded or nonflooded conditions. Low N<sub>2</sub>O 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<sub>2</sub>O 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<sub>2</sub>O emissions were detected after field drainage at CA1, which accounted for 75% of annual N<sub>2</sub>O emissions. Although only observed at one site in this study, Towprayoon et al. (2005) observed increases in N<sub>2</sub>O emissions after field drainage before harvest, suggesting that soil redox potential during this period is favorable for N<sub>2</sub>O production. Similarly, N<sub>2</sub>O 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<sub>4</sub> and N<sub>2</sub>O emissions into the winter fallow period. Few studies have examined how N management practices affect GHG emissions during the fallow season. Higher CH<sub>4</sub> emissions for treatments with high or excessive N rates might be expected during the fallow period due to the lower C/N ratios

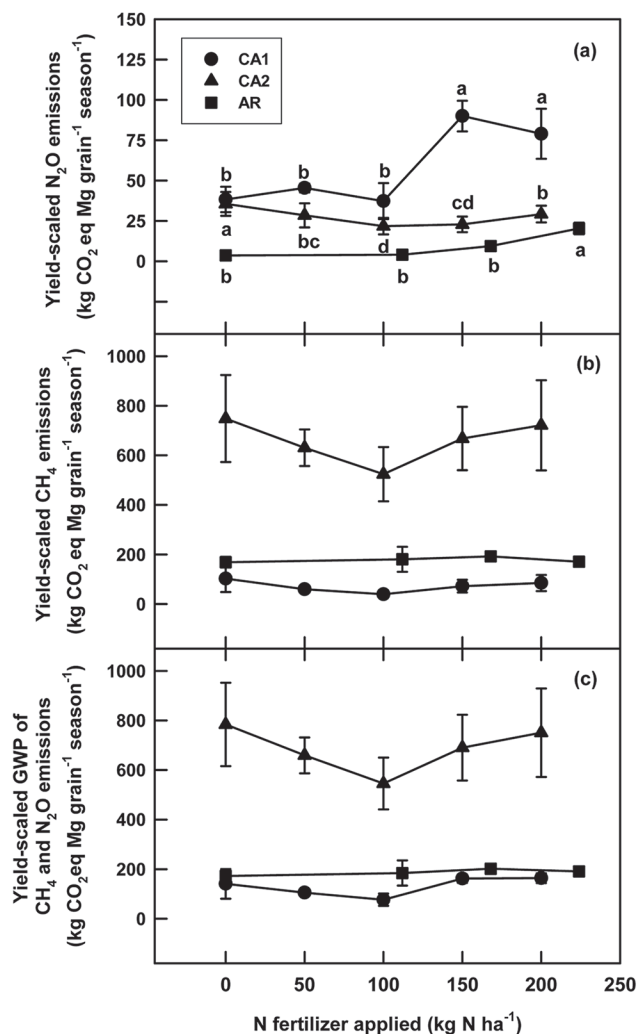


Fig. 3. Yield-scaled global warming potential and CH<sub>4</sub> and N<sub>2</sub>O emissions at various fertilizer N rates in CA1, CA2, and AR. Vertical bars indicate standard errors of three replicates in each field. Yield-scaled N<sub>2</sub>O emissions in each field followed by same letter are not 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<sub>4</sub> and N<sub>2</sub>O 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<sup>-1</sup> (Fig. 2). In contrast, the N rate that maximized yields in AR was 112 kg N ha<sup>-1</sup>, which is lower than the typically recommended rate of 168 kg N ha<sup>-1</sup>. 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<sub>2</sub>O emissions than on CH<sub>4</sub> emissions (Table 3). In all locations, N<sub>2</sub>O 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<sub>2</sub>O 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<sub>2</sub>O 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<sub>2</sub>O emissions were variable and therefore inconclusive regarding N rate. Although fertilizer-induced N<sub>2</sub>O 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<sub>2</sub>O emissions, increasing fertilizer N rate had no effect on CH<sub>4</sub> emissions in either CA field. However, CH<sub>4</sub> emissions in AR were higher in all treatments receiving N (Table 3). Although the effects of fertilizer N rate on CH<sub>4</sub> emissions are often found to be contradictory with reports of CH<sub>4</sub> 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<sub>4</sub> emissions, whereas excessive N rates reduced CH<sub>4</sub> emissions, in part due to the potential for NH<sub>4</sub><sup>+</sup> to stimulate the oxidation of CH<sub>4</sub> (Bodelier and Laanbroek, 2004). Our results do not fully support these findings. Moreover, apart from the AR site where CH<sub>4</sub> emissions were higher with N addition, there was little further effect of fertilizer N on CH<sub>4</sub> emissions.

## Variation of Seasonal Greenhouse Gas Emissions among Sites

Previous studies in conventional wet seeded rice systems in California have reported average CH<sub>4</sub> emissions ranging from 50 to 164 kg CH<sub>4</sub>-C ha<sup>-1</sup> season<sup>-1</sup> (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<sub>4</sub>-C ha<sup>-1</sup> season<sup>-1</sup> observed at CA2. However, average CH<sub>4</sub> emissions at CA1 were much lower (14 kg CH<sub>4</sub>-C ha<sup>-1</sup> season<sup>-1</sup>). The large difference in CH<sub>4</sub> 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<sub>4</sub>, which was attributed to improved diffusive transport of CH<sub>4</sub> 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<sub>4</sub> 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<sub>4</sub> emissions from drill seeded rice systems has been conducted in Louisiana and Texas. Estimates of CH<sub>4</sub> emissions have been as low as 57 kg CH<sub>4</sub>-C ha<sup>-1</sup> in Texas (Sass et al., 1992) and 78 kg CH<sub>4</sub>-C ha<sup>-1</sup> in Louisiana (Lindau, 1994). However, the average emission at AR was 30 kg CH<sub>4</sub>-C ha<sup>-1</sup>, below that reported elsewhere in the southern United States. In part, these differences may be related to variety. Varietal effects on CH<sub>4</sub> emissions are known to exist and can be significant. For example, a roughly 2-fold difference in CH<sub>4</sub> 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<sub>4</sub> 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<sub>y</sub> is achieved at optimal N rates. Our results for yield-scaled N<sub>2</sub>O emissions support the meta-analysis results of van Groenigen et al. (2010) at the CA1 and AR locations, where yield-scaled N<sub>2</sub>O 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<sub>2</sub>O emissions were also lowest at optimal N rates but were higher at suboptimal and above optimal N rates. In contrast, yield-scaled CH<sub>4</sub> 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<sub>4</sub> emissions occurred at optimal N rates. Combining CH<sub>4</sub> and N<sub>2</sub>O emissions and expressing GWP as a function of yield, large differences in growing season GWP<sub>y</sub> occurred between sites, with values ranging from an average of 130 (CA1) to 686 (CA2) kg CO<sub>2</sub> eq Mg<sup>-1</sup> season<sup>-1</sup>, a roughly 5-fold difference (Fig. 3c). Within each site, however, GWP<sub>y</sub> was not significantly different among N rates. As with the trend in yield-scaled CH<sub>4</sub>, the lowest GWP<sub>y</sub> at both CA sites was observed at optimal N rates. Although other researchers have reported an approximately 40% reduction in growing season GWP<sub>y</sub> at optimal N rates in rice (Feng et al., 2013), we found that GWP<sub>y</sub> 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<sub>4</sub> and N<sub>2</sub>O emissions from drill seeded rice systems. Growing season emissions contributed the most to total annual GHG emissions in all sites. In turn, CH<sub>4</sub> 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<sub>4</sub> emissions. Excessive N rates increased N<sub>2</sub>O and yield-scaled N<sub>2</sub>O emissions, but N rate had little or no effect on CH<sub>4</sub> 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<sub>Y</sub> would be achieved at optimal N rates because GWP<sub>Y</sub> 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<sub>Y</sub>, economics would likely not favor it.

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## References

- Akiyama, H., K. Yagi, and X. Yan. 2005. Direct N<sub>2</sub>O emissions from rice paddy fields: Summary of available data. *Global Biogeochem. Cycles* 19:GB1005. doi:10.1029/2004GB002378
- Bodelier, P.L., and H.J. Laanbroek. 2004. Nitrogen as a regulatory factor of methane oxidation in soils and sediments. *FEMS Microbiol. Ecol.* 47:265–277. doi:10.1016/S0168-6496(03)00304-0
- Bossio, D.A., W.R. Horwath, R.G. Mutters, and C. van Kessel. 1999. Methane pool and flux dynamics in a rice field following straw incorporation. *Soil Biol. Biochem.* 31:1313–1322. doi:10.1016/S0038-0717(99)00050-4
- Cai, Z., Y. Shan, and H. Xu. 2007. Effects of nitrogen fertilization on CH<sub>4</sub> emissions from rice fields. *Soil Sci. Plant Nutr.* 53:353–361. doi:10.1111/j.1747-0765.2007.00153.x
- Cai, Z., G. Xing, X. Yan, H. Xu, H. Tsuruta, K. Yagi, and K. Minami. 1997. Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilisers and water management. *Plant Soil* 196:7–14. doi:10.1023/A:1004263405020
- Cassman, K., A. Dobermann, and D. Walters. 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. *Ambio* 31:132–140.
- Denier van der Gon, H.A.C., and H.U. Neue. 1995. Influence of organic matter incorporation on the methane emission from a wetland rice field. *Global Biogeochem. Cycles* 9:11–22. doi:10.1029/94GB03197
- Denier van der Gon, H.A.C., N. van Breemen, H.U. Neue, R.S. Lantin, J.B. Aduna, M.C.K. Alberto, and R. Wassmann. 1996. Release of entrapped methane from wetland rice fields upon soil drying. *Global Biogeochem. Cycles* 10:1–7. doi:10.1029/95GB03460
- Dobermann, A., C. Witt, and R. Buresh. 2008. Ecological intensification of irrigated rice systems in Asia. In: *Recognizing past achievements, meeting future needs. Proceedings of 5th International Crop Science Congress*, 13–18 Apr. 2009, Jeju, Korea.
- Dobbie, K.E., I.P. McTaggart, and K.A. Smith. 1999. Nitrous oxide emissions from intensive agricultural systems: Variations between crops and seasons, key driving variables, and mean emission factors. *J. Geophys. Res.* 104:26891–26899. doi:10.1029/1999JD900378
- Feng, J., C. Chen, Y. Zhang, Z. Song, A. Deng, C. Zheng, and W. Zhang. 2013. Impacts of cropping practices on yield-scaled greenhouse gas emissions from rice fields in China: A meta-analysis. *Agric. Ecosyst. Environ.* 164:220–228. doi:10.1016/j.agee.2012.10.009
- Fitzgerald, G.J., K.M. Scow, and J.E. Hill. 2000. Fallow season straw and water management effects on methane emissions in California rice. *Global Biogeochem. Cycles* 14:767–776. doi:10.1029/2000GB001259
- Food and Agriculture Organization (FAO). 2012. FAOSTAT. <http://fao.org> (accessed 26 May 2012).
- Hill, J.E., D.E. Bayer, S. Bocchi, and W.S. Clappett. 1991. Direct seeded rice in the temperate climates of Australia, Italy, and the United States. In: *Direct seeded flooded rice in the tropic: Selected papers from the International Rice Research Conference Seoul, Korea 27–31 Aug. 1990*. International Rice Research Institute, Philippines. pp. 91–102.
- Hou, A.X., G.X. Chen, Z.P. Wang, O. van Cleemput, and W.H. Patrick, Jr. 2000. Methane and nitrous oxide emissions from a rice field in relation to soil redox and microbiological processes. *Soil Sci. Soc. Am. J.* 64:2180–2186. doi:10.2136/sssaj2000.6462180x
- Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson. 2001. Radiative forcing of climate change In: *Climate Change 2001: The scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge Univ. Press, Cambridge, UK, and New York.
- Huang, Y., R.L. Sass, and F.M. Fisher, Jr. 1997. Methane emission from Texas rice paddy soils: 1. Quantitative multi-year dependence of CH<sub>4</sub> emission on soil, cultivar and grain yield. *Glob. Change Biol.* 3:479–489. doi:10.1046/j.1365-2486.1997.00083.x
- Huang, Y., Y. Jiao, L. Zong, X. Zheng, R.L. Sass, and F.M. Fisher. 2002. Quantitative dependence of methane emission on soil properties. *Nutr. Cycling Agroecosyst.* 64:157–167. doi:10.1023/A:1021132330268
- Hutchinson, G.L., and G.P. Livingston. 1993. Use of chamber systems to measure trace gas fluxes. In: L. Harper, et al., editors, *Agricultural ecosystem effects on trace gases and global climate change*. ASA Spec. Publ. 55. ASA, CSSA, SSSA, Madison, WI. p. 63–78.
- Hutchinson, G.L., and A.R. Mosier. 1981. Improved soil cover method for field measurement of nitrous oxide fluxes. *Soil Sci. Soc. Am. J.* 45:311–316. doi:10.1234/12345678.
- Intergovernmental Panel on Climate Change (IPCC). 2006. Agriculture, forestry and other land use. In: H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Ngara, editors, *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Prepared by the National Greenhouse Gas Inventories Programme. Institute for Global Environmental Strategies, Hayama, Japan.
- Jäckel, U., S. Schnell, and R. Conrad. 2001. Effect of moisture, texture and aggregate size of paddy soil on production and consumption of CH<sub>4</sub>. *Soil Biol. Biochem.* 33:965–971. doi:10.1016/S0038-0717(00)00248-0
- Lauren, J.G., G.S. Pettygrove, and J.M. Duxbury. 1994. Methane emissions associated with a green manure amendment to flooded rice in California. *Biogeochemistry* 24:53–65. doi:10.1007/BF02390179
- Liang, X.Q., H. Li, S.X. Wang, Y.S. Ye, G.M. Tian, C. van Kessel, and B.A. Linquist. 2013. Nitrogen management to reduce yield-scaled global warming potential in rice. *Field Crops Res.* 146:66–74.
- Lindau, C.W. 1994. Methane emissions from Louisiana rice fields amended with nitrogen fertilizers. *Soil Biol. Biochem.* 26:353–359. doi:10.1016/0038-0717(94)90284-4
- Lindau, C.W., P.K. Bollich, and R.D. DeLaune. 1995. Effect of rice variety on methane emission from Louisiana rice. *Agric. Ecosyst. Environ.* 54:109–114. doi:10.1016/0167-8809(95)00587-1
- Linquist, B.A., S.M. Brouder, and J.E. Hill. 2006. Winter straw and water management effects on soil nitrogen dynamics in California rice systems. *Agron. J.* 98:1050–1059. doi:10.2134/agronj2005.0350
- Linquist, B., K.J. van Groenigen, M.A.A. Adviento-Borbe, C. Pittelkow, and C. van Kessel. 2012a. An agronomic assessment of greenhouse gas emissions from major cereal crops. *Glob. Change Biol.* 18:194–209. doi:10.1111/j.1365-2486.2011.02502.x
- Linquist, B.A., M.A.A. Adviento-Borbe, C.M. Pittelkow, C. van Kessel, and K.J. van Groenigen. 2012b. Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review analysis. *Field Crops Res.* 135:10–21. doi:10.1016/j.fcr.2012.06.007
- Ma, J., X.L. Li, H. Xu, Y. Han, Z.C. Cai, and K. Yagi. 2007. Effects of nitrogen fertilizer and wheat straw application on CH<sub>4</sub> and N<sub>2</sub>O emissions from a paddy rice field. *Aust. J. Soil Res.* 45:359–367. doi:10.1071/SR07039
- McMillan, M.S., M.L. Goulden, and S.C. Tyler. 2007. Stoichiometry of CH<sub>4</sub> and CO<sub>2</sub> flux in a California rice paddy. *J. Geophys. Res.* 112:G01008. doi:10.1029/2006JG000198
- Mosier, A.R., A.D. Halvorson, C.A. Reule, and X.J. Liu. 2006. Net global warming potential and greenhouse gas intensity in irrigated cropping systems in Northeastern Colorado. *J. Environ. Qual.* 35:1584–1598. doi:10.2134/jeq2005.0232
- National Agricultural Statistics Service (NASS). Rice. [http://www.nass.usda.gov/Statistics\\_by\\_Subject/index.php?sector=CROPS](http://www.nass.usda.gov/Statistics_by_Subject/index.php?sector=CROPS) (accessed 26 May 2012).
- Nouchi, I., S. Mariko, and K. Aoki. 1990. Mechanism of methane transport from the rhizosphere to the atmosphere through rice plants. *Plant Physiol.* 94:59–66. doi:10.1104/pp.94.1.59
- Pathak, H., S. Sankhyan, S.S. Dubey, A. Bhatia, and N. Jain. 2013. Dry direct-seeding of rice for mitigating greenhouse gas emission: Field experimentation and simulation. *Paddy Water Environ.* 11:593–601. doi:10.1007/s10333-012-0352-0
- Pittelkow, C.M., M.A.A. Adviento-Borbe, J.E. Hill, J. Six, C. van Kessel, and B.A. Linquist. 2013. Yield-scaled global warming potential of annual N<sub>2</sub>O and CH<sub>4</sub> emissions from continuously flooded rice systems in response to N input. *Agric. Ecosyst. Environ.* 177:10–12.



- Redeker, K.R., N.Y. Wang, J.C. Low, A. McMillan, S.C. Tyler, and R.J. Cicerone. 2000. Emissions of methyl halides and methane from rice paddies. *Science* 290:966–969. doi:10.1126/science.290.5493.966
- Sass, R.L., F.M. Fisher, and Y.B. Yang. 1992. Methane emissions from rice fields: The effect of floodwater management. *Global Biogeochem. Cycles* 6:249–262. doi:10.1029/92GB01674
- Schütz, H., A. Holzapfel-Pschorn, R. Conrad, H. Rennenberg, and W. Seiler. 1989. A 3-year continuous record on the influence of daytime, season, and fertilizer treatment on methane emission rates from an Italian rice paddy. *J. Geophys. Res.* 94:405–416.
- Schütz, H., W. Seiler, and R. Conrad. 1990. Influence of soil temperature on methane emission from rice paddy fields. *Biogeochemistry* 11:77–95. doi:10.1007/BF00002060
- Schimel, J. 2000. Rice, microbes and methane. *Nature* 403:375–377. doi:10.1038/35000325
- Shang, Q., X. Yang, C. Gao, P. Wu, Y. Xu, Q. Shen, J. Zou, and S. Guo. 2011. Net annual global warming potential and greenhouse gas intensity in Chinese double rice-cropping systems: A 3-year field measurement in long-term fertilizer experiments. *Glob. Change Biol.* 17:2196–2210. doi:10.1111/j.1365-2486.2010.02374.x
- Sigren, L.K., S.T. Lewis, F.M. Fisher, and R.L. Sass. 1997. Effects of field drainage on soil parameters related to methane production and emission from rice paddies. *Global Biogeochem. Cycles* 11:151–162. doi:10.1029/97GB00627
- Singh, J.S., S. Singh, A.S. Raghubanshi, S. Singh, and A.K. Kashyap. 1996. Methane flux from rice/wheat agroecosystem as affected by crop phenology, fertilization and water level. *Plant Soil* 183:323–327. doi:10.1007/BF00011448
- Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, and O. Sirotenko. 2007. Agriculture. In: B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer, editors, *Climate change 2007: Mitigation. Contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge Univ. Press, Cambridge, UK, and New York. p. 497–540.
- Statistical Analysis Systems (SAS). 2003. SAS system version 8.0 manual. SAS, Cary, NC.
- Tilman, D., J. Fargione, B. Wolff, C. D'Antonio, A. Dobson, R. Howarth, D. Schindler, W.H. Schlesinger, D. Simberloff, and D. Swackhamer. 2001. Forecasting agriculturally driven global environmental change. *Science* 292:281–284. doi:10.1126/science.1057544
- Towprayoon, S., K. Smakgahn, and S. Poonkaew. 2005. Mitigation of methane and nitrous oxide emissions from drained irrigated rice fields. *Chemosphere* 59:1547–1556. doi:10.1016/j.chemosphere.2005.02.009
- van Groenigen, J.W., G.L. Velthof, O. Oenema, K.J. van Groenigen, and C. van Kessel. 2010. Towards an agronomic assessment of N<sub>2</sub>O emissions: A case study for arable crops. *Eur. J. Soil Sci.* 61:903–913. doi:10.1111/j.1365-2389.2009.01217.x
- van Hulzen, J.B., R. Segers, P.M. van Bodegom, and P.A. Leffelaar. 1999. Temperature effects on soil methane production: An explanation for observed variability. *Soil Biol. Biochem.* 31:1919–1929. doi:10.1016/S0038-0717(99)00109-1
- Wassmann, R., H.U. Neue, R.S. Lantin, J.B. Aduna, M.C.R. Alberto, M.J. Andales, M.J. Tan, H.A.C. Denier van der Gon, H. Hoffman, H. Papen, H. Rennenberg, and W. Seiler. 1994. Temporal patterns of methane emissions from wetland rice fields treated by different modes of N application. *J. Geophys. Res.* 99:16457–16462. doi:10.1029/94JD00017
- Wassmann, R., H.U. Neue, R.S. Lantin, K. Makarim, N. Chareonsilp, L.V. Buendia, and H. Rennenberg. 2000. Characterization of methane emissions from rice fields in Asia: II. Differences among irrigated, rainfed, and deepwater rice. *Nutr. Cycling Agroecosyst.* 58:13–22. doi:10.1023/A:1009822030832
- Xie, B., X. Zheng, Z. Zhou, J. Gu, B. Zhu, X. Chen, Y. Shi, Y. Wang, Z. Zhao, C. Liu, Z. Yao, and J. Zhu. 2010. Effects of nitrogen fertilizer on CH<sub>4</sub> emission from rice fields: Multi-site field observations. *Plant Soil* 326:393–401. doi:10.1007/s11104-009-0020-3
- Yan, X., K. Yagi, H. Akiyama, and H. Akimoto. 2005. Statistical analysis of the major variables controlling methane emission from rice fields. *Glob. Change Biol.* 11:1131–1141. doi:10.1111/j.1365-2486.2005.00976.x
- Yang, S., S. Peng, J. Xu, Y. Luo, and D. Li. 2012. Methane and nitrous oxide emissions from paddy field as affected by water-saving irrigation. *Phys. Chem. Earth* 53–54:30–37. doi:10.1016/j.pce.2011.08.020
- Yao, Z., X. Zheng, H. Dong, R. Wand, B. Mei, and J. Zhu. 2012. A 3-year record of N<sub>2</sub>O and CH<sub>4</sub> emissions from a sandy loam paddy during rice seasons as affected by different nitrogen application rates. *Agric. Ecosyst. Environ.* 152:1–9. doi:10.1016/j.agee.2012.02.004
- Zheng, X., S. Han, Y. Huang, Y. Wang, and M. Wang. 2004. Re-quantifying the emission factors based on field measurements and estimating the direct N<sub>2</sub>O emission from Chinese croplands. *Global Biogeochem. Cycles* 18:GB2018. doi:10.1029/2003GB002167
- Zheng, X., M. Wang, Y. Wang, R. Shen, J. Gou, J. Li, J. Jin, and L. Li. 2000. Impacts of soil moisture on nitrous oxide emission from croplands: A case study on the rice-based agro-ecosystem in Southeast China. *Chemosphere* 2:207–224.
- Zou, J., Y. Huang, J. Jiang, X. Zheng, and R.L. Sass. 2005. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application. *Global Biogeochem. Cycles* 19:GB2021. doi:10.1029/2004GB002401