Seasonal Methane and Nitrous Oxide Emissions of Several Rice Cultivars in Direct-Seeded Systems

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Abstract

An understanding of cultivar effects on field greenhouse gas (GHG) emissions in rice (*Oryza sativa* L.) systems is needed to improve the accuracy of predictive models used for estimating GHG emissions and to evaluate the GHG mitigation potential of different cultivars. We compared CH_4 and N_2O emissions, global warming potential (GWP = N_2O + CH_4), yield-scaled GWP (GWP_Y = GWP Mg^{-1} grain), and plant growth characteristics of eight cultivars within four study sites in California and Arkansas. Nitrous oxide emissions were negligible (<10% of GWP) and were not different among cultivars. Seasonal CH_4 emissions differed between cultivars by a factor of 2.1 and 1.4 at one California and one Arkansas site, respectively. Plant growth characteristics were generally not correlated with seasonal CH_4 emissions; however, the strongest correlations were observed for shoot and total plant (root + shoot) biomass at heading ($r = 0.60$) at one California site and for grain at maturity ($r = -0.95$) at one Arkansas site. Although differences in GWP and GWP_Y were observed, there were inconsistencies across sites, indicating the importance of the genotype × environment interaction. Overall, the cultivars with the lowest CH_4 emissions, GWP, and GWP_Y at the California and Arkansas sites were the lowest and highest yielding, respectively. These findings highlight the potential for breeding high-yielding cultivars with low GWP, the ideal scenario to achieve low GWP_Y, but environmental conditions must also be considered.

AGRICULTURE is a major source of global anthropogenic emissions of greenhouse gases (GHGs), accounting for an estimated 47 and 58% of CH_4 and N_2O emissions, respectively (Smith et al., 2007). With a radiative forcing capacity of 25 and 298 times greater than CO_2 on a 100-yr timescale, respectively, their unprecedented increase in atmospheric concentrations has led to international efforts to measure and mitigate emissions (Forster et al., 2007). The cultivation of rice (*Oryza sativa* L.) is an important source of global anthropogenic CH_4 emissions, with estimates ranging from 25.6 Tg CH_4 yr^{-1} (Yan et al., 2009) to 112 Tg CH_4 yr^{-1} (Chen and Prinn, 2006). Although agricultural soils in general contribute an estimated 5.6 Tg N_2O yr^{-1} (Smith et al., 2007), the vast majority (89%) of the global warming potential (GWP) of rice systems is due to CH_4 emissions (Linquist et al., 2012). Compared with other major cereal crops (e.g., wheat [*Triticum aestivum* L.] and maize [*Zea mays* L.]), the GWP of CH_4 and N_2O emissions from rice production is on average approximately four times greater (Linquist et al., 2012).

When rice fields are flooded, N_2O fluxes from soil remain low, and the primary pathway of N_2O emissions is via transport through the intracellular air spaces within the rice plants (aerenchyma cells), which comprises, on average, 80% (Yu et al., 1997) to 87% (Yan et al., 2000) of total N_2O emissions. During nonflooded conditions, a considerably lower proportion (18%) of total N_2O is emitted through the rice plant (Yan et al., 2000). Rice plants also regulate CH_4 emissions by facilitating its production, oxidation, and transport (Wassmann and Aulakh, 2000). Microbial decomposition of organic matter in flooded, oxygen-depleted soils is the process by which methanogenesis occurs (Conrad, 2005). Rice plants influence CH_4 production by supplying readily decomposable root-derived C substrates to methanogenic bacteria in the form of exudates, sloughed cells, mucilage, and litter (Lu et al., 2000b, 2002; Aulakh et al., 2001b). Methane transport from the soil to the atmosphere via aerenchyma cells of the rice plant accounts for the vast majority

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Abbreviations: GC, gas chromatograph; GHG, greenhouse gas; GWP, global warming potential; GWP_Y, yield-scaled global warming potential; SOC, soil organic carbon.

of CH_4 emissions (range of estimates, 80–98%); molecular diffusion through surface irrigation water and ebullition are secondary sources of CH_4 emissions (Holzapfel-Pschorn et al., 1986; Holzapfel-Pschorn and Seiler, 1986; Tyler et al., 1997; Yu et al., 1997). The aerenchyma cells also serve as a conduit for transport of O_2 from the atmosphere to the roots, providing a sufficient aerobic environment for root respiration in flooded soil conditions (Colmer, 2003; Suralta and Yamauchi, 2008) and, in turn, supporting CH_4 oxidation in the rhizosphere (Sigren et al., 1997; Eller and Frenzel, 2001). Some studies have shown differences in CH_4 emissions among cultivars due to varying degrees of controls over these mechanisms (Huang et al., 1997; Bilek et al., 1999). In a 2-yr study, Sigren et al. (1997) showed that two Texas cultivars differed in CH_4 emissions and attributed these differences in C substrate availability in the root zone and to the lack of differences in gas transport capacity. In contrast, Butterbach-Bahl et al. (1997) deduced that differences in CH_4 transport capacity were driving the observed differences in CH_4 emissions between two Italian cultivars because neither CH_4 oxidation nor CH_4 production differed between cultivars.

There is also evidence that cultivar differences in CH_4 emissions are not persistent over time. In a 7-yr field study, Wassmann et al. (2002) reported cultivar differences in CH_4 emissions in some seasons, but, over the course of nine growing seasons, no consistent distinctions among cultivars were found. Rather, the cultivars displayed high phenotypic plasticity due to complex interactions with their environment. Similarly, Lu et al. (2000a) found that the differences between hybrid and conventional cultivars in CH_4 emissions depended on the season.

Specific mechanisms for cultivar differences in CH_4 emissions have been related to plant growth and morphological characteristics. Aulakh et al. (2000) found that CH_4 transport capacity of 12 rice cultivars generally increased during the vegetative growth period, after which three divergent patterns in CH_4 transport capacity occurred; in hybrids it gradually increased to maturity, and in inbred cultivars it either rapidly declined from flowering to maturity or changed minimally. These distinctions in patterns of CH_4 transport capacity corresponded to root and shoot biomass during the vegetative growth period and to total root, shoot, and grain biomass from panicle initiation to maturity. These relationships were attributed to differences in the duration of radial development of aerenchyma and total number of outlets (tillers) of aerenchyma. Positive correlations have also been demonstrated between rates of root exudation and root, shoot, and grain biomass (Aulakh et al., 2001a) and between CH_4 production from root exudates and root and shoot biomass (Aulakh et al., 2001b).

With the significant contribution of rice cultivation to global CH_4 emissions and projections for increased rice production to meet global food demand, a clear challenge exists to improve yields while minimizing CH_4 emissions from rice production (Smith et al., 2007). Whereas soil, climate, and management factors are accounted for in many process-based models, cultivar-specific mechanisms are not. Although many of these models have the capacity to specify basic crop growth parameters, there is limited cultivar-specific data available for improving the scientific structure and calibration of these models, particularly in the rice growing regions in California and the southern U.S. states. A new understanding of the magnitude of cultivar differences is critical for accurate modeling of GHG emissions from rice systems, which is of growing importance due to emerging markets for C trading in the agricultural sector (Climate Action Reserve, 2013).

We conducted multi-year field studies in California and Arkansas. Our main objectives were (i) to determine if seasonal CH_4 and N_2O emissions, GWP, and yield-scaled GWP (GWP_Y = GWP Mg^{-1} grain) differ among several commonly grown cultivars in California and the southern United States and (ii) to determine the relative importance of plant growth characteristics in explaining the variability in seasonal GHG emissions. Our overall hypothesis was that cultivars differ in CH_4 emissions and have distinct plant growth characteristics related to differences in magnitude of emissions but do not differ in N_2O emissions due to minimal seasonal N_2O fluxes during the continuously flooded field conditions. Thus, cultivar GWP was predicted to differ according to differences primarily in CH_4 emissions. Specifically, we expected cultivars with the highest root and shoot biomass to have the highest GWP due to a higher capacity for CH_4 production via greater root exudation and to have a higher capacity for CH_4 transport via a larger, or a more extensive, aerenchyma system. Among cultivars with similar root and shoot biomass, those with higher grain yield were expected to have lower CH_4 emissions due to greater allocation of C to grain versus root exudation. Therefore, we predicted high-yielding cultivars with low root and shoot biomass at heading to have the lowest GWP_Y.

Materials and Methods

Field Experiment

Experiments were conducted in experimental fields in California and Arkansas during the 2011 and 2012 rice-growing seasons. In California, field sites were located at the Rice Experiment Station (CA-1) in Biggs in 2011 (39°27′47″ N, 121°43′35″ W) and at the University of California, Davis (CA-2) in 2012 (38°32′33.20″ N, 121°48′38.69″ W). In Arkansas, field sites were located at the University of Arkansas Rice Research and Extension Center near Stuttgart, AR, in 2011 (AR-1) and 2012 (AR-2) (34°28′8.64″ N, 91°25′7.19″ W and 34°27′54.6942″ N, 91°24′21.8484″ W, respectively). Soils at CA-1 and CA-2 are classified as Esquon-Neerdobe complex (Fine, smectitic, thermic Xeric Epiaquerts and Duraquerts) and Capay silty clay (Fine, smectitic, thermic Typic Haploxerert), respectively, and soils at AR-1 and AR-2 are classified as Dewitt silt loam (Fine, smectitic, thermic, Typic Albaqualfs).

Eight cultivars adapted to the California and southern U.S. environments were investigated for differences in seasonal CH_4 and N_2O emissions (Table 1). All of the cultivars used are commercially produced for conventional or specialty markets and thus are a representation of material from current varietal improvement programs. The field trials were arranged in a randomized complete block design, with three replications in CA-1, CA-2, and AR-2 and only one replication in AR-1.

Standard management practices for water-seeded and drill-seeded systems were followed at the California and Arkansas sites, respectively (Table 2). Plot sizes were 4.6 and 20 m^2 at CA-1 and CA-2, respectively, and 24 m^2 at AR-1 and AR-2.

Table 1. Description of cultivars tested and the locations of the field experiments.

Cultivar	Environment adapted to	Description	Market class	Study site†
Calmati-202	California	specialty	long-grain	CA-1, CA-2
L206	California	conventional	long-grain	CA-1, CA-2
M206	California	conventional	medium-grain	CA-1, CA-2
CLXL745	southern U.S.	hybrid	long-grain	CA-2, AR-2
CLXP4534	southern U.S.	hybrid	long-grain	CA-2, AR-1
Francis	southern U.S.	conventional	long-grain	AR-1, AR-2
Jupiter	southern U.S.	conventional	medium-grain	AR-1, AR-2
Sabine	southern U.S.	specialty	long-grain	AR-1, AR-2

† AR-1 and AR-2 refer to Arkansas field sites located at the University of Arkansas Rice Research and Extension Center near Stuttgart, AR, in 2011 and 2012, respectively; CA-1 and CA-2 refer to California field sites located at the Rice Experiment Station in Biggs in 2011 and at the University of California, Davis in 2012, respectively.

Table 2. Summary of management practices at the four study sites.

Management practice	Study site†			
	CA-1	CA-2	AR-1	AR-2
Previous year's crop	fallow	fallow for 4 yr	soybean	soybean
Residue management	crop residue burned	only weeds incorporated in soil	crop reside incorporated in soil	crop reside incorporated in soil
Water management	no winter flood	no winter flood	no winter flood	no winter flood
Method of direct seeding	water-seeded	water-seeded	drill-seeded	drill-seeded
Seeding rate, kg ha^{-1}	168	123 for non-hybrids, 50 for hybrids	123 for non-hybrids, 28 for hybrids	123 for non-hybrids, 28 for hybrids
Date of seeding	27 May 2011	4 June 2012	17 May 2011	11 Apr. 2012
Water management	continuous flood	continuous flood	one flush irrigation before continuous flood	continuous flood
Date of permanent flood	25 May 2011	18 May 2012	20 June 2011	17 May 2012
Date of drain	23 Sept. 2011	8 Oct. 2012	11 Sept. 2011	18 Aug. 2012
Fertility management				
Date of fertilization and fertilizer type	21 May 2011 (urea blend, 34:17:0) and 11 July 2011 [$(NH_4)_2SO_4$]	17 May 2012 [$Ca(H_2PO_4)2\cdot H_2O$ and K_2SO_4], 18 May 2012 (urea), 6 July 2012 (urea)	early spring pre-tillage 2011 [$Ca(H_2PO_4)2\cdot H_2O$ and KCl], 20 June 2011 (urea)	early spring pre-tillage 2012 [$Ca(H_2PO_4)2\cdot H_2O$ and KCl], 16 May 2012 (urea)
Total N, kg ha^{-1}	130	210	168	134
First application	95	160	168	134
Second application	30	50		
Total P, kg ha^{-1}	21	24	29	29
Total K, kg ha^{-1}	0	46	84	84
Date of harvest	24 Oct. 2011	29 Oct. 2012	26 Sept. 2011	28 Aug. 2012

† AR-1 and AR-2 refer to Arkansas field sites located at the University of Arkansas Rice Research and Extension Center near Stuttgart, AR, in 2011 and 2012, respectively; CA-1 and CA-2 refer to California field sites located at the Rice Experiment Station in Biggs in 2011 and at the University of California, Davis in 2012, respectively.

All sites were planted within the optimal planting dates for the region. Seeding rates and fertility management were based on a combination of considerations: recommendations for the region and type of seeding system, knowledge of the field site, and the specific cultivars tested. Due to failure of the first seeding on 18 May 2012 to germinate at CA-2, the plots were reseeded in the same field on 4 June 2012.

Soil Sampling

After spring tillage operations were completed and before seeding and flooding, soil samples were collected from 0 to 15 cm depth from each field to characterize soil chemical and physical properties at each site. Soil was analyzed for soil texture and various chemical properties (pH, electrical conductivity, total organic C, total N, extractable P, and exchangeable K) using standard methods (Table 3).

Gas Sampling and Analysis

Daily fluxes of CH_4 and N_2O were measured using a vented closed-chamber method (Hutchinson and Livingston, 1993) with four sampling times (0, 21, 42, 63 min.). The construction and installation of the chambers followed the methods described by Adviento-Borbe et al. (2013). Gas sampling began within 5 d of the onset of the permanent flood at the CA sites and at 22 and 12 d after the onset of the permanent flood at AR-1 and AR-2, respectively, and continued until harvest or within 4 d before harvest. The 63-min gas sampling period occurred between 0900 and 1400 h on a weekly basis at CA-2, AR-1, and AR-2; biweekly at CA-1; and up to daily during drainage or flooding events at all sites. Two chambers were installed at CA-2, AR-1, and AR-2 in each plot to reduce disturbance to the rice plants during sampling by alternating which chambers were used. At CA-1, one chamber was installed per plot due to less frequent sampling.

To determine concentrations of CH_4 and N_2O in the chamber headspace, gas samples were analyzed using a GC-2014 gas chromatograph (GC) (Shimadzu Scientific, Inst.) with a flame ionization detector for CH_4 and a ^{63}Ni electron capture detector for N_2O. Detection limits of the GC instrument were 2.2 pg s^{-1} for CH_4 and 0.3 pg s^{-1} for N_2O based on the results given by the Shimadzu technical engineers who conducted the QC/QA of the instrument and corresponding packed columns for ambient GHG detections. We also calculated the flux chamber detection limits based on (i) four gas levels with time zero, (ii) chamber closure of 63 min, and (iii) linear flux equation (Parkin et al., 2012); they were 0.00076 ppm$_v$ N_2O min^{-1} and 0.0072 ppm$_v$ CH_4 min^{-1} for three time intervals. However, the detection limit of the GC was higher (less sensitive), and therefore those detection limits were used. Using the ideal gas law and measurements of air temperature and volume within the chambers, headspace gas concentrations were converted to mass per volume (g N_2O or CH_4 L^{-1}). Fluxes of CH_4 and N_2O were estimated from the slope of the linear regression of gas concentration by chamber closure time divided by the surface area within the chamber. Diurnal variation in GHG emissions was not accounted for in daily flux calculations based on the assumption that soil temperature represented average daily values during the period that gas sampling occurred (i.e., 0900–1400 h) (Bossio et al., 1999). Fluxes were set to zero if the change in emissions was less than the minimum detection limit of the GC. For quality assurance of the non-zero flux estimates, we used the distribution of all the RMSE values of the flux regressions as criteria for assessing the reliability of the data (i.e., whether there was excessive scatter about a particular regression, potentially due to measurement error, or a reasonable amount of scatter relative to the entirety of the dataset). Accordingly, if the RMSE of the linear regression of gas concentration by chamber closure time was >2 SD above the mean RMSE of all the linear regressions at a given site, the corresponding flux value was treated as an outlier, and the value was omitted from further analysis.

Cumulative seasonal emissions were estimated using linear interpolation of the daily fluxes. Total GWP of seasonal CH_4 and N_2O emissions was calculated in units of CO_2 equivalents (CO_2 eq) with a 100-yr time frame using radiative forcing potentials of 25 and 298 relative to CO_2, respectively (Forster et al., 2007). Yield-scaled GWP is the ratio of GWP to the mass of grain yield (i.e., kg CO_2 eq Mg^{-1}). One GWP data point and the corresponding GWP$_Y$ data point (for cultivar CLXL745, rep 3) were negative and therefore were treated as outliers and omitted.

Plant Sampling

Uniform stand areas within each plot were used for plant sampling. Root and shoot biomass were measured at the heading stage (exertion of the panicle) of the rice plants at all sites except AR-1. Root and shoot biomass per unit area was estimated from a 0.1-m^2 area at CA-1 and AR-2 and from a 0.07-m^2 area at CA-2. Whole plant samples were cleaned to remove soil and other debris, and roots were separated from the stem directly above the root crown. Both plant components were dried at 60°C to a constant mass. At harvest (i.e., physiological maturity), straw and grain biomass per unit area was estimated from a 1-m^2 area at CA-1 and AR-2 and from a 0.07-m^2 area within the gas chambers at CA-2 and AR-1.

Data Analysis

Before performing the ANOVA tests, the assumptions of normality and homogeneity of variance were evaluated. For each model, data that failed the Shapiro-Wilk test ($p < 0.05$) were log transformed to meet the assumption of normality. When the data failed the Levene's test of constant variance, a weighted least squares approach was used in which the weighting factor was the reciprocal of the estimated residual variance. To determine if there were differences among cultivars in root and above-ground biomass at heading and in grain and straw weights at physiological maturity, an ANOVA was performed for each site using the PROC GLM procedure

Table 3. Soil characteristics (0–15 cm) at the four study sites.

Soil parameters	Study sites†			
	CA-1	CA-2	AR-1	AR-2
Taxonomic classification	Fine, smectitic, thermic Xeric Epiaquerts and Duraquerts	Fine, smectitic, thermic Typic Haploxerert	Fine, smectitic, thermic, Typic Albaqualfs	Fine, smectitic, thermic, Typic Albaqualfs
Soil series	Esquon-Neerdobe complex	Capay silty clay	Dewitt silt loam	Dewitt silt loam
Soil particle size distribution, %				
Sand	23	19	13	NM‡
Silt	30	33	69	NM
Clay	47	48	18	NM
Chemical properties				
pH	4.8	6.4	6.2	6.3
Electrical conductivity, dS m^{-1}	0.19	NM	0.57	0.07
Total organic C, %	1.26	1.59	0.68	0.61
Total N, %	0.08	0.08	0.07	NM
Extractable P, mg kg^{-1}	9.3	NM	13.7	8.2
Exchangeable K, mg kg^{-1}	106	NM	198	111

† AR-1 and AR-2 refer to Arkansas field sites located at the University of Arkansas Rice Research and Extension Center near Stuttgart, AR, in 2011 and 2012, respectively; CA-1 and CA-2 refer to California field sites located at the Rice Experiment Station in Biggs in 2011 and at the University of California, Davis in 2012, respectively.

‡ Not measured.

in SAS, and unprotected Fisher's LSD was used for mean comparisons ($p < 0.05$) (SAS, 2002–2010). The same analysis was used to determine if there were cultivar differences in seasonal CH_4, N_2O, GWP, and GWP_Y within each site. For the correlation analysis, we focused on the relationships between the plant growth characteristics and seasonal CH_4 emissions. We used the PROC CORR procedure in SAS to quantify Pearson's correlation coefficients (r) of seasonal CH_4 emissions of the pooled cultivars with the plant parameters at each site and used the significance levels of 0.1 and 0.05. To assess these relationships across sites, the same analysis was conducted on the pooled site data normalized to the site averages to account for differences in magnitudes of the data across sites.

Results

Climate

Lower seasonal air temperature and precipitation were observed at the California sites compared with the Arkansas sites. Average daily air temperatures during the rice-growing period at CA-1 and CA-2 were 21.0 and 20.4°C, respectively, compared with 26.5 and 25.2°C at AR-1 and AR-2, respectively. Cumulative seasonal precipitation rates were 0.1 and 1.4 cm at CA-1 and CA-2, respectively, and 28.8 and 40.0 cm at AR-1 and AR-2, respectively.

Biomass Production of Cultivars

Site average grain yield across cultivars was about 32% greater on average in the California sites than in the Arkansas sites (Table 4). Average grain yields were 9.1 and 10.5 Mg ha^{-1} at CA-1 and CA-2, respectively, and 6.1 and 7.2 at AR-1 and AR-2, respectively. Cultivars differed in grain yield at all three of the replicated sites (CA-1, CA-2, AR-2), but differences in straw biomass were detected at CA-1 only. At CA-1 and CA-2, M206 was the highest yielding cultivar (10.5 and 12.4 Mg ha^{-1}, respectively), which was significantly greater than Calmati-202. At CA-1, M206 also had significantly greater straw biomass at maturity than L206 (9.8 and 7.9 Mg ha^{-1}, respectively). At CA-2, the hybrid cultivars CLXP4534 and CLXL745 were not different from M206, the highest yielding cultivar, whereas in Arkansas, the hybrid CLXL745 was higher yielding than all the other Southern cultivars (8.3 Mg ha^{-1} at AR-2).

Root and shoot biomass at heading were measured only at CA-1, CA-2, and AR-2. Site average root biomass was approximately two to three times greater at AR-2 (5.9 Mg ha^{-1}) than at CA-1 and CA-2 (2.1 and 3.0 Mg ha^{-1}, respectively), whereas site average shoot biomass at heading was greatest at CA-2 (Table 4). Cultivar differences in root biomass were observed at CA-1 and CA-2 only, and these differences were not consistent. M206 and L206 had 20% greater root biomass than Calmati-202 on average at CA-1 but did not differ significantly at CA-2, although a similar trend was observed. However, at CA-2,

Table 4. Biomass of eight cultivars at heading and physiological maturity at the four study sites.

Cultivar	Heading		Physiological maturity	
	Root	Shoot	Grain	Straw
	——————————————— Mg ha^{-1} dry wt. ———————————————			
CA-1†				
Calmati-202	1.8 (0.3)‡b§	11.5 (2.2)a	7.3 (0.6)b	9.3 (0.6)ab
L206	2.3 (0.3)a	13.4 (0.9)a	9.5 (1.1)ab	7.9 (0.5)b
M206	2.2 (0.3)a	13.7 (1.4)a	10.5 (0.2)a	9.8 (0.2)a
CA-2				
Calmati-202	2.5 (0.4)b	15.4 (0.8)a	7.9 (0.7)b	11.9 (0.8)a
CLXL745	3.7 (0.6)a	21.9 (2.5)a	10.9 (0.9)a	12.7 (1.2)a
CLXP4534	NM¶	NM	10.1 (0.8)ab	15.1 (3.4)a
L206	2.9 (0.1)ab	16.5 (2.8)a	10.8 (0.1)a	11.9 (0.9)a
M206	2.5 (0.2)b	16.1 (1.3)a	12.4 (1.0)a	12.8 (1.1)a
AR-1#				
CLXP4534	NM	NM	7.0	11.5
Francis	NM	NM	5.4	11.7
Jupiter	NM	NM	6.9	10.1
Sabine	NM	NM	5.0	11.3
AR-2				
CLXL745	6.9 (1.0)a	17.5 (3.3)a	8.3 (0.6)a	10.8 (0.6)a
Francis	4.2 (0.3)a	13.5 (0.5)ab	7.1 (0.5)b	9.8 (0.7)a
Jupiter	6.1 (0.7)a	10.8 (1.7)b	6.8 (0.7)b	10.3 (1.6)a
Sabine	6.5 (1.1)a	13.3 (1.0)ab	6.6 (0.3)b	11.2 (1.3)a

† AR-1 and AR-2 refer to Arkansas field sites located at the University of Arkansas Rice Research and Extension Center near Stuttgart, AR, in 2011 and 2012, respectively; CA-1 and CA-2 refer to California field sites located at the Rice Experiment Station in Biggs in 2011 and at the University of California, Davis in 2012, respectively.

‡ Standard errors are in parentheses.

§ Within columns of the same study site, means not sharing a letter are significantly different according to LSD (0.05).

¶ Not measured.

Values shown for AR-1 are of a single replication and therefore no ANOVA was performed.

CLXL745 had 48% higher root biomass than Calmati-202 and M206 (Table 4). Cultivar differences in shoot biomass were detected only at AR-2; CLXL745 produced 39% more shoot biomass than Jupiter.

N_2O Emissions

Seasonal N_2O emissions were negligible across all cultivars and sites (LS means of cultivars were all <0.1 kg $N_2O–N$ ha^{-1} $season^{-1}$), comprising <10% of the positive proportion of seasonal GWP when averaged across sites, and no differences were detected among cultivars within sites (Fig. 1; Table 5).

CH_4 Emissions and Seasonal Patterns

Site averages at the two water-seeded sites (CA-1 and CA-2) were 63 and 13 kg $CH_4–C$ ha^{-1}, respectively, and at the two drill-seeded sites (AR-1 and AR-2) were 34 and 70 kg $CH_4–C$ ha^{-1}, respectively (Table 5). Seasonal patterns of daily CH_4 emissions were unique to each study site, and although there were observable cultivar differences in magnitudes of daily fluxes at a given site, seasonal patterns were generally similar among cultivars at the same site, except for minor variations in timing of peak emissions (Fig. 2). In general, daily CH_4 fluxes started to increase after about 1 mo of flooding and began to decline toward the end of the growing season before draining. Peak CH_4 emissions during the flooded period generally occurred in early August for all cultivars across all sites after about 2.5 mo of continuous flooding, except at AR-1, where the first peak in CH_4 emissions occurred after 1.5 mo of flooding. Flooding was delayed (day of year) at AR-1 compared with all other sites, although the interval between seeding and flooding at AR-1 (34 d) was shorter than at AR-2 (36 d). Furthermore, we observed two peaks at AR-1, the first 1.5 mo after flooding in early August and the second, similar to the other sites, about 2 mo after flooding in late August. After a sharp decline in CH_4 flux from 18 to 23 August at CA-2, a series of attenuated CH_4 fluxes was observed. After drainage at the end of the rice-growing season, spikes in CH_4 emissions were measured at all sites. However, the magnitudes of the peaks at CA-2 and AR-2 were relatively minor compared with the magnitude of the fluxes preceding the drainage event.
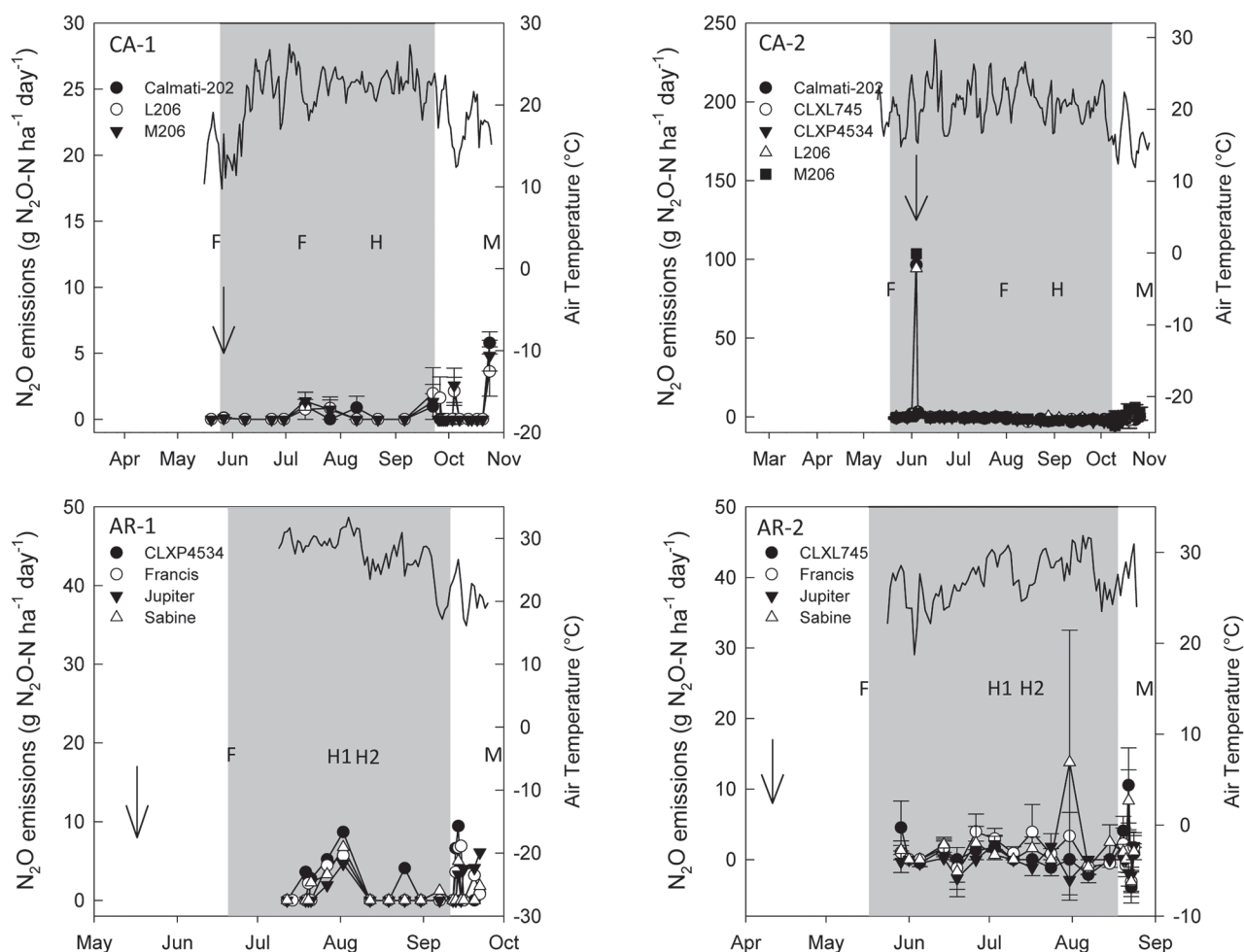

Fig. 1. Seasonal patterns of daily N_2O emissions of eight cultivars and air temperature during the rice-growing season at CA-1, CA-2, AR-1, and AR-2 (AR-1 and AR-2 refer to Arkansas field sites located at the University of Arkansas Rice Research and Extension Center near Stuttgart, AR, in 2011 and 2012, respectively; CA-1 and CA-2 refer to California field sites located at the Rice Experiment Station in Biggs in 2011 and at the University of California, Davis in 2012, respectively). Data are plotted on different scales for each plot. Error bars represent SE of the replicates. If no error bar is indicated, only one replicate was available. Daily mean air temperature is plotted above the emissions profile in each graph panel. Dates of seeding (arrow), N fertilization (F), the continuously flooded period (shaded), and harvest (M) are shown. Heading dates (H) of the cultivars are indicated as follows: (CA-1) H = all cultivars (15–21 Aug.), (CA-2) H = all cultivars (4–12 Sept.), (AR-1) H1 = CLXP4534 (31 July), H2 = all other cultivars (10–12 Aug.), (AR-2) H1 = CLXL745 (11–14 July), and (AR-2) H2 = all other cultivars (15–20 July).

There was no clear relationship between heading of the rice plants and seasonal patterns in CH_4 emissions (Fig. 2). Whereas the relationship between the heading of individual cultivars and peak CH_4 emissions during the flooded period depended on the site and cultivar, the difference in magnitude of cumulative emissions before and after heading depended on the site (Fig. 2; Table 5). During the flooded period at all sites, heading for each cultivar occurred at the beginning of, or within 1 mo after, the maximum CH_4 flux except at AR-2 where heading occurred within 2 wk before peak CH_4 emissions for all cultivars. Regardless of cultivar, in the CA water-seeded systems the majority of seasonal CH_4 emissions occurred before the heading stage (>76% on average) (Table 5). Conversely, in the AR drill-seeded systems, all the cultivars except Jupiter at AR-1 had a higher proportion of seasonal CH_4 emissions occur after heading (>72% on average) (Table 5).

Cultivar Comparisons in Seasonal CH_4 within Sites

The greatest range in seasonal emissions among cultivars at the same site was observed at AR-1, with 15 kg CH_4–C ha^{-1} in Jupiter and 55 kg CH_4–C ha^{-1} in Sabine (Table 5). However, at AR-1 these values represent a single replication. At AR-2 there was only a 3% difference in mean seasonal CH_4 emissions of these same cultivars; this difference was not statistically significant. At the water-seeded sites (CA-1 and CA-2), Calmati-202 tended to have the lowest mean seasonal CH_4 emissions, but it was

only significantly lower than L206 at one of the sites (CA-2). The hybrid cultivars CLXP4534 and CLXL745 were moderate emitters of CH_4 at CA-2 relative to the other cultivars, whereas CLXL745 had the lowest seasonal CH_4 emissions at AR-2 (56 kg CH_4–C ha^{-1}) ($p < 0.05$), and CLXP4534 had the second to lowest at AR-1 (25 kg CH_4–C ha^1). At AR-2 the disparity between CLXL745 and the other cultivars in CH_4 emissions occurred at the end of the season, starting in late July (Fig. 2).

Global Warming Potential

Seasonal GWP was strongly related to CH_4 emissions at all sites, but N_2O emissions were only a minor contributor to GWP (Table 5). Site average seasonal GWP values at the water-seeded sites (CA-1 and CA-2) were 2144 and 314 kg CO_2 eq ha^{-1}, respectively, and at the drill-seeded sites (AR-1 and AR-2) were 1254 and 2399 kg CO_2 eq ha^{-1}, respectively. At least 90% of seasonal GWP at each site on average was due to CH_4 emissions; this finding was consistent among cultivars.

Seasonal GWP_Y was similar to GWP and CH_4 emissions in terms of relative differences among sites and cultivars. The CA-2 had the lowest mean GWP_Y (24 kg CO_2–eq Mg^{-1}), which was about 14 times less than the site average at AR-2 (339 kg CO_2–eq Mg^{-1}) (Table 5). CA-1 and AR-1 had similar mean GWP_Y (240 and 222 kg CO_2–eq Mg^{-1}, respectively). The greatest variability in GWP_Y among cultivars was observed at CA-2, with an approximately 3-fold difference in GWP_Y between L206 and

Table 5. Seasonal CH_4 and N_2O fluxes, global warming potential, and yield-scaled global warming potential of eight cultivars at the four study sites.

| Cultivar	Seasonal CH_4	Seasonal N_2O	Seasonal GWP†	Seasonal GWP_Y‡	Heading date(s)	Cumulative CH_4 emissions	
						Before heading	After heading
	kg CH_4–C ha^{-1}	kg N_2O–N ha^{-1}	kg CO_2 eq ha^{-1}	kg CO_2 eq^{-1} Mg^{-1}		—— kg CH_4–C ha^{-1} ——	
				CA-1§			
Calmati-202	58 (2.9)a¶	0.05 (0.021)a	1988 (90)a	277 (19)a	20 Aug.	32 (4.5)a	26 (2.9)a
L206	60 (12)a	0.06 (0.004)a	2074 (399)a	218 (29)a	21 Aug.	42 (12)a	19 (2.9)b
M206	69 (9.6)a	0.06 (0.018)a	2370 (319)a	225 (30)a	15 Aug.	44 (10)a	25 (0.73)a
				CA-2			
Calmati-202	6.7 (0.9)b	−0.15 (0.016)a	83 (31)b	10 (3.6)b	12 Sept.	5.9 (0.7)b	0.80 (0.2)b
CLXL745	11 (3.1)ab	−0.19 (0.025)a	309‡ (99)ab	29# (12)ab	4 Sept.	8.5 (2.3)ab	2.5 (0.8)a
CLXP4534	11 (0.4)ab	−0.16 (0.037)a	229 (40)ab	22 (2.6)ab	12 Sept.	10 (0.4)a	1.2 (0.01)ab
L206	14 (2.2)a	−0.13 (0.016)a	353 (62)a	33 (6.1)a	4 Sept.	11 (1.1)a	3.5 (1.3)a
M206	11 (1.1)ab	−0.11 (0.028)a	277 (61)ab	23 (6.1)ab	4 Sept.	8.6 (0.2)ab	2.8 (0.9)a
				AR-1††			
CLXP4534	25	0.17	981	140	31 July	4.2	20
Francis	43	0.10	1526	282	10 Aug.	16	27
Jupiter	15	0.08	573	83	12 Aug.	7.7	7.2
Sabine	55	0.10	1936	384	12 Aug.	24	31
				AR-2			
CLXL745	56 (9.2)b	0.02 (0.047)a	1899 (344)b	232 (44)b	11–14 July	16 (4.9)a	40 (4.4)b
Francis	77 (14)a	0.10 (0.052)a	2677 (459)a	381 (81)a	15–20 July	18 (4.0)a	59 (10)a
Jupiter	72 (16)ab	−0.01 (0.022)a	2397 (534)ab	345 (59)ab	20–22 July	29 (8.8)a	43 (7.0)b
Sabine	75 (7.5)ab	0.11 (0.114)a	2623 (154)a	397 (30)a	19–20 July	37 (11)a	38 (11)b

† Global warming potential.

‡ Yield-scaled global warming potential.

§ AR-1 and AR-2 refer to Arkansas field sites located at the University of Arkansas Rice Research and Extension Center near Stuttgart, AR, in 2011 and 2012, respectively; CA-1 and CA-2 refer to California field sites located at the Rice Experiment Station in Biggs in 2011 and at the University of California, Davis in 2012, respectively.

¶ Within columns of the same study site, means not sharing a letter are significantly different according to LSD (0.05). Standard errors are in parentheses.

Mean of two replicates due to removal of outlier.

†† Values shown for AR-1 are of a single replicate, and therefore no ANOVA was performed.
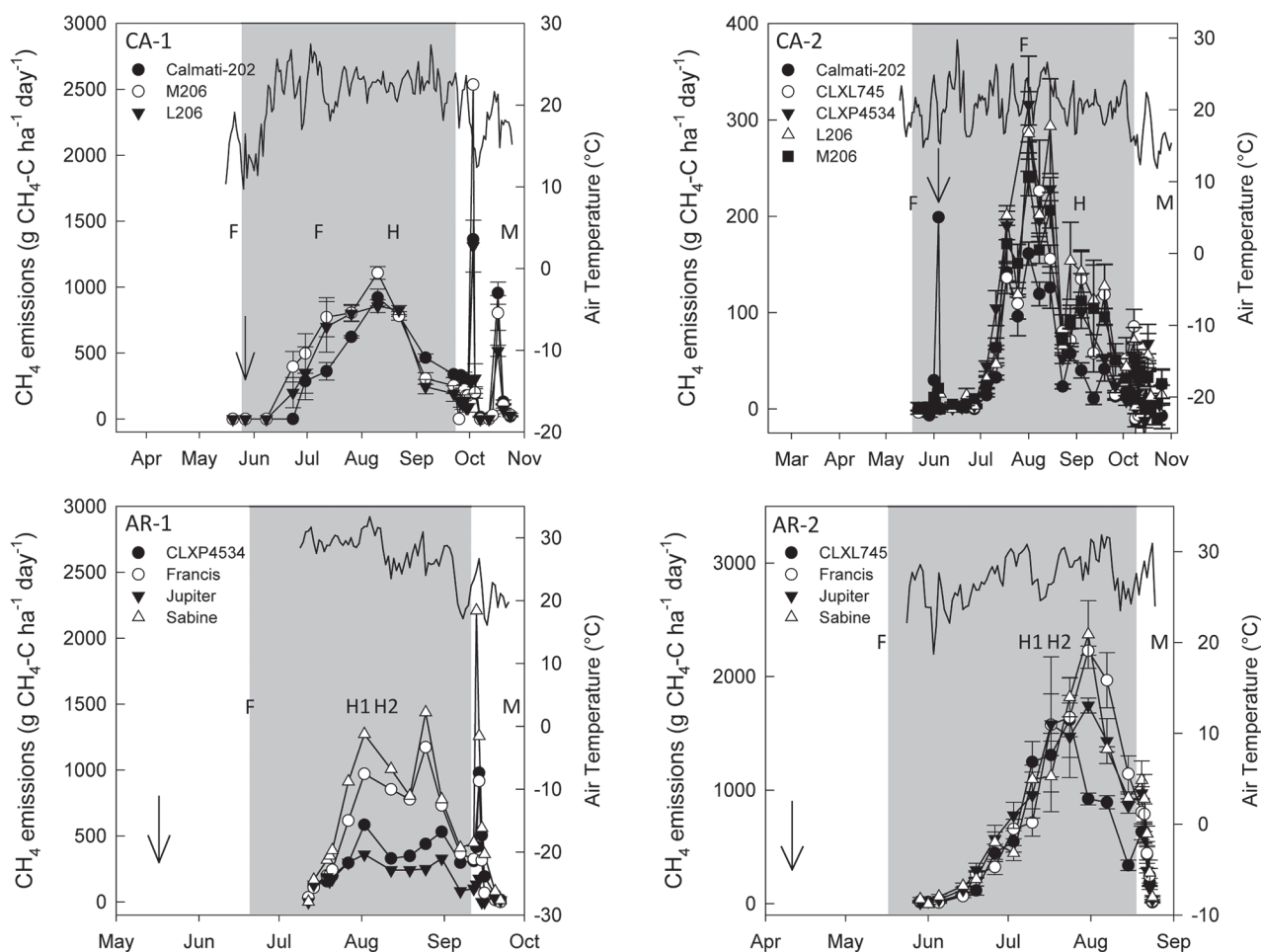
Fig. 2. Seasonal patterns of daily CH_4 emissions of eight cultivars and air temperature during the rice-growing season at CA-1, CA-2, AR-1, and AR-2 (AR-1 and AR-2 refer to Arkansas field sites located at the University of Arkansas Rice Research and Extension Center near Stuttgart, AR, in 2011 and 2012, respectively; CA-1 and CA-2 refer to California field sites located at the Rice Experiment Station in Biggs in 2011 and at the University of California, Davis in 2012, respectively). The data are plotted on different scales for each plot. Error bars represent the SE of the replicates. If no error bar is indicated, only one replicate was available. Daily mean air temperature is plotted above the emissions profile in each graph panel. Dates of seeding (arrow), N fertilization (F), the continuously flooded period (shaded), and harvest (M) are shown. Heading dates (H) of the cultivars are indicated as follows: (CA-1) H = all cultivars (15–21 Aug.), (CA-2) H = all cultivars (4–12 Sept.), (AR-1) H1 = CLXP4534 (31 July), H2 = all other cultivars (10–12 Aug.), (AR-2) H1 = CLXL745 (11–14 July), and (AR-2) H2 = all other cultivars (15–20 July).

Calmati-202 (32.7 and 10.0 kg CO_2–eq Mg^{-1}, respectively). Variability in GWP_Y among the cultivars at CA-1 was minimal, ranging from 218 to 277 kg CO_2–eq Mg^{-1}, and no differences were detected among cultivars. At AR-2, the hybrid CLXL745 had the lowest GWP_Y (232 kg CO_2–eq^{-1} Mg^{-1}), which was significantly less than Sabine and Francis (396.7 and 380.7 kg CO_2–eq^{-1} Mg^{-1}, respectively).

Correlations between Plant Growth Parameters and Seasonal CH_4 Emissions

The relationships between seasonal CH_4 emissions and the plant parameters of the pooled cultivars were not consistent across sites (Table 6); seasonal CH_4 emissions were not significantly correlated with any plant parameters at CA-2 or AR-2 but were positively correlated with shoot and total plant (root + shoot) biomass at heading at CA-1 ($r = 0.60$) and negatively correlated with grain yield at AR-1 ($r = -0.95$). Excluding AR-1 (where no root measurements were taken), there was a positive correlation ($r = 0.33$) between root biomass at heading and seasonal CH_4

emissions when sites were pooled and data were normalized to the corresponding site averages.

Discussion

Relative Importance of CH_4 and N_2O to Global Warming Potential

Our research shows that CH_4 emissions contributed at least 90% to seasonal GWP when cultivars were averaged within sites, which is consistent with other field studies on GHG emissions in wet- and drill-seeded rice systems (Adviento-Borbe et al., 2013; Pittelkow et al., 2013) and with the findings from a meta-analysis of 16 studies in transplanted rice systems (Linquist et al., 2012). Seasonal N_2O emissions included negative and positive fluxes but were minimal (Table 5). Consumption of N_2O in anoxic soils is via denitrification when N_2O is reduced to N_2. Such fluxes from the atmosphere to soil have been reported from rice systems (Chen et al., 1997; Xu et al., 1997, 2004) and from natural ecosystems, with the highest values from wetland and peatland ecosystems (Schlesinger, 2013). Our estimate of N_2O contribution to GWP may be underestimated at the AR sites due

to gas sampling not starting until after the onset of the permanent flood, approximately 6 wk after planting and 2 to 3 wk after N fertilization, which likely missed some peaks in N_2O emissions. For example, at CA-2 the highest peak in N_2O emissions was observed approximately 2 wk after N fertilization. However, this flux was observed on the same day as water seeding, which may have been an artifact of that disturbance. Indeed, other studies in drill- and water-seeded systems have found low to undetectable N_2O emissions after N fertilization when fields are immediately flooded (Adviento-Borbe et al., 2013; Pittelkow et al., 2013), which is to be expected from flooded soils due to their low redox potential (Hou et al., 2000). Nitrous oxide emissions are typically low before flooding because the fertilizer N has not yet been applied (Adviento-Borbe et al., 2013). Nitrous oxide emissions during this period likely played a relatively insignificant role in the cultivar differences in GWP because without surface floodwater the primary pathway for N_2O emissions is through the soil (Yan et al., 2000) and not through the plant.

Because the objective of this study was to evaluate cultivar differences in seasonal GHG emissions, postharvest N_2O and CH_4 emissions were not accounted for. The annual effect of cultivar on GWP is likely determined by emissions during the growing season when the plants are present. Although N_2O fluxes after harvest may have persisted depending on soil moisture status, precipitation, and N availability, we would not expect the additional emissions to greatly influence total cumulative seasonal N_2O emissions or GWP ($CH_4 + N_2O$) of cultivars.

Cumulative CH_4 Emissions and Seasonal Patterns among Sites

The site average seasonal CH_4 emissions at three of the four sites (CA-1, AR-1, AR-2) ranged from 34 to 70 kg CH_4–C ha^{-1} season^{-1}, which is within the lower ranges reported for U.S. rice systems (Bossio et al., 1999; Fitzgerald et al., 2000; Sass et al., 2002; Pittelkow et al., 2013) (Table 5). Seasonal CH_4 emissions at CA-2, on the other hand, were particularly low (site average of 13 kg CH_4–C ha^{-1}), likely because this field had been fallow the previous 4 yr and residue inputs into this system were limited to weeds only, reducing C substrate and ultimately lowering CH_4 production potential in this soil (Zhang et al., 2013). Additionally,

the field was not flooded during the extended fallow period. Low historic inputs of organic matter and lack of previous water-logged conditions have been shown to reduce CH_4 emissions in subsequent rice-growing seasons (Yan et al., 2005). Furthermore, although CA-2 had higher soil organic C (SOC) content than all other sites, the clay content was 48%, which is known to adsorb and protect SOC from decomposition (Baldock and Skjemstad, 2000), further decreasing the methanogenic source strength of this soil. High clay content is also known to increase entrapment of CH_4 (Wang et al., 1993), ultimately lowering CH_4 transport from the soil to the atmosphere. Although there is less than a 1°C difference in mean seasonal daily air temperature between the two CA sites, CA-2 was 6.1 and 4.8°C lower than AR-1 and AR-2, respectively, perhaps also contributing to the relatively low CH_4 emissions.

The seasonal trends in daily CH_4 emissions do not appear to be driven by development stage of the rice plant because heading was observed to occur before, during, and after peaks in CH_4 emissions (Fig. 2). Trends in daily CH_4 emissions also do not appear to consistently respond to changes in air temperature (Fig. 2). The dual CH_4 peaks observed at CA-2 and AR-1 can also be seen in the seasonal CH_4 patterns of other studies (Chidthaisong and Watanabe, 1997; Wassmann et al., 2002; Pittelkow et al., 2014). In a ^{13}C-tracer experiment, Chidthaisong and Watanabe (1997) observed two CH_4 peaks. The first peak occurred 40 to 80 d after flooding and was related to the previous seasons' straw residue–derived CH_4 but was primarily derived from SOC and the roots. A second peak occurred past 80 d after flooding, at the heading stage, and represented the increase in emissions driven by an increase in plant-derived C sources with relatively minimal contribution from straw and SOC. This suggests that the C source of initial CH_4 emissions was from all C pools, including roots, SOC, and plant residue, whereas for late-season emissions the C source was primarily from root-derived organic material.

All sites showed a decline in CH_4 emissions before draining, which could be due to a number of factors related to increased CH_4 oxidation, decreased CH_4 production, and decreased CH_4 transport capacity of the rice plants (Fig. 2). The proportion of CH_4 oxidized after heading (30–70%) increased compared with pre-heading (10–20%) (Sigren et al., 1997). In a greenhouse

Table 6. Pearson's correlation coefficients of the pooled cultivar seasonal CH_4 emissions with plant biomass parameters within and across study sites.

Study site†	Sample size (n)	Heading			Physiological maturity		
		Root	Shoot	Total (root + shoot)	Grain	Straw	Total (grain + straw)
CA-1	9	0.45	0.60‡	0.60‡	0.53	0.27	0.51
CA-2	12§, 15¶	0.40	0.12	0.17	0.37	0.08	0.28
AR-1	4	NM#	NM	NM	−0.95*	0.63	−0.58
AR-2	12	0.20	−0.47	−0.35	−0.14	0.17	0.07
All sites††	33§, 40¶	0.33‡	−0.03	0.09	0.09	0.14	0.23

* Significant at the 0.05 probability level.

† AR-1 and AR-2 refer to Arkansas field sites located at the University of Arkansas Rice Research and Extension Center near Stuttgart, AR, in 2011 and 2012, respectively; CA-1 and CA-2 refer to California field sites located at the Rice Experiment Station in Biggs in 2011 and at the University of California, Davis in 2012, respectively.

‡ Significant at the 0.1 probability level.

§ For root or shoot.

¶ For grain and straw.

Not measured; root and shoot measurements were not taken at AR-1.

†† All data normalized to the corresponding site mean.

study on the CH_4 transport capacity of rice plants, Aulakh et al. (2000) reported a decline in CH_4 transport capacity from flowering to maturity of all four high-yielding dwarf cultivars (IR72, IR52, IR64, and PSBRc20), two of the three traditional tall cultivars (Dular and B40), and one of the three new plant type cultivars (IR65598).

Cultivar Differences in CH_4 emissions, Global Warming Potential, and Yield-Scaled Global Warming Potential

Methane emissions from flooded rice soils are the net effect of plant-regulated mechanisms that affect CH_4 production, oxidation, and transport of gases between the rhizosphere and atmosphere and their interaction with the environment and management factors. Some studies have found no persistent cultivar effect on CH_4 emissions due to strong interactions with the environment (e.g., Wassmann et al., 2002). Our study of two site-years in Arkansas and California provides support that relative differences or similarities in seasonal CH_4 among some cultivars are consistent across sites, whereas other cultivars are not. At both CA sites, M206 and L206 were similar, whereas Calmati-202 tended to be lower but only significantly lower than L206 at one site (CA-2). Although the statistical significance at the AR sites could only be tested at the replicated site (AR-2), a similar trend was observed among the Southern cultivars at both sites; Francis and Sabine were similar in seasonal CH_4 emissions and were greater than the hybrid (CLXP4534 or CLXL745). In contrast, Jupiter was more variable in seasonal CH_4 emissions relative to the other cultivars at AR-1 and AR-2, and the ranking of this cultivar in comparison to the hybrid was reversed across sites. All of the cultivars studied are being commercially produced and represent a very narrow and elite subset of rice germplasm that is available. Although few statistical differences among the cultivars were observed, this may not reflect the genetic diversity that is available for mitigating GHG emissions. A better understanding of the genotype × environment interaction is necessary to determine to what extent choice of rice cultivar may affect GWP relative to cultural management and environmental factors.

Watanabe et al. (1995) did not find any correlation between CH_4 emissions and shoot or root biomass despite significant cultivar differences in CH_4 emissions. However, in our study there was a small positive correlation of root biomass at heading with seasonal CH_4 emissions when evaluated across sites (Table 6). This relationship was similar to findings of Wang et al. (1997), who attributed it to total C released from roots, indicating that the cultivar differences in CH_4 emissions were mainly due to differences in their effect on CH_4 production.

In a study investigating microbial controls on differences in CH_4 emissions among three rice cultivars, Ma et al. (2010) found that the cultivar with higher shoot biomass had lower CH_4 emissions due to its higher CH_4 oxidation potential. In contrast, our research shows a positive correlation between seasonal CH_4 emissions and shoot biomass at CA-1, although there were no differences in shoot biomass or CH_4 emissions among cultivars at CA-1 (Tables 4 and 5). Variability in the mechanisms driving CH_4 emissions, and in the associated plant traits, may be just as great within cultivars as the variability among cultivars due to genotypic plasticity in response to micro-environment effects.

On the other hand, at CA-2 and AR-2, cultivars differed in seasonal CH_4 emissions (Table 5) and in root and shoot biomass, respectively (Table 4), but there were no significant correlations between CH_4 emissions and the measured plant parameters at either site (Table 6). These findings highlight that plant biomass parameters alone are not dependable proxies for relative differences in CH_4 emissions or the processes driving CH_4 emissions.

Among cultivars with similar root and shoot biomass at heading, we expected those with higher grain yield to have lower CH_4 emissions based on the reasoning that CH_4 transport would be similar but CH_4 production would be less in the higher yielding cultivar due to greater allocation of C to grain versus root exudation. Denier van der Gon et al. (2002) observed an increase in CH_4 emissions after removing spikelets and thereby artificially decreasing yield potential by lowering the capacity of the reproductive organs to accept C assimilates. In other words, the yield gap (the expected grain yield based on the maximum estimated harvest index times the total above-ground biomass minus actual yield) was proportional to CH_4 emissions, which is presumably via leakage of excess photosynthetically fixed C from roots. This may explain the significant negative correlation ($r = -0.96$) between CH_4 emissions and yield at AR-1 (Table 6). Data supporting this hypothesis were observed at AR-2, in which CLXL745 had similar root and shoot biomass, higher yield, and the lowest CH_4 emissions compared with Francis and Sabine. The disparity between CLXL745 and the other cultivars occurred at the end of the season (Fig. 2) when root-derived C has been shown to be the main contributor to CH_4 emissions (Chidthaisong and Watanabe, 1997). However, a general conclusion on the net effect of yield on seasonal CH_4 emissions in cultivars with similar root and shoot biomass cannot be made due to conflicting results at CA-2, in which L206 had similar root and shoot biomass, higher yield, and higher CH_4 emissions compared with Calmati-202 (Tables 4 and 5).

Evaluating differences in GHG emissions from agriculture relative to yield (GWP_Y), as opposed to land area alone (GWP), has become increasingly relevant due to the recognition that global food security and environmental health should be considered in evaluating GHG mitigation options (van Groenigen et al., 2010; Grassini and Cassman, 2012; Linquist et al., 2012). The optimal scenario for a cultivar with the lowest GWP_Y is for it to have the highest yield and the lowest GWP and for these characteristics to persist across environments and years. Three Southern hybrid cultivars, including CLXL745 tested in the present study, have been shown to yield 1 to 1.7 Mg ha^{-1} more than the highest-yielding conventional alternative (Francis) in Arkansas (Lyman and Nalley, 2013), which is corroborated by our results at AR-1 and AR-2 (Table 4). Thus, given that the lowest CH_4–emitting cultivar at AR-2 was the hybrid, CLXL745, and that hybrids tend to yield more than conventional Southern cultivars, lower GWP_Y values are expected (Table 5). This shows there is potential for breeding high-yielding cultivars with low GWP and GWP_Y.

Conclusions

Development of carbon offset protocols for GHG mitigation in agriculture is underway, such as for rice systems in California (Climate Action Reserve, 2013). Process-based biogeochemical models are proposed for estimation of GHG emissions. There

are options in some models to customize plant parameters (e.g., C:N ratios of biomass, biomass ratios, and maximum yield), but the variation in the mechanisms driving cultivar differences in GHG emissions (i.e., CH_4 production, oxidation, and transport capacity) are not explicit. We found that, within study sites, cultivars were similar in seasonal N_2O emissions due to the continuously flooded conditions for the majority of plant growth and development, and most cultivars were also similar in seasonal CH_4 emissions. However, there were two cases in which cultivars differed in seasonal CH_4 emissions by a factor of 2.1 and 1.4. Accordingly, cultivar differences in GWP were similar to differences in CH_4 emissions and not N_2O emissions. Our research shows that relative seasonal CH_4 emissions among some cultivars were consistent across two site-years, whereas other cultivars varied, presumably due to varying degrees to which cultivar phenotypic characteristics related to CH_4 emissions respond to external factors. We found contradictory relationships between combinations of crop growth characteristics and seasonal CH_4 emissions, highlighting that plant biomass parameters alone are not dependable proxies for relative differences in CH_4 emissions or for the processes driving CH_4 emissions due to complex interactions among plant phenotypes, the environment, and mechanisms driving CH_4 production, oxidation, and transport. At one of the Arkansas sites, the hybrid had the highest yield, similar root and shoot biomass at heading, and lower GWP and GWP_Y compared with two of the three inbred cultivars. This result may have important implications for breeding high-yielding cultivars with low GWP and GWP_Y.

Acknowledgments

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