Greenhouse Gases from Irrigated Rice Systems under Varying Severity of Alternate-Wetting and Drying Irrigation

Nimlesh Balaine
Dep. of Plant Sciences
Univ. of California
1 Shields Ave
Davis, CA 95616

Daniela R. Carrijo
Dep. of Crop and Soil Science
3050 SW Campus Way
Corvallis, OR 97331

M. Arlene Adviento-Borbe
Delta Water Management Research Unit
USDA Agricultural Research Service
504 University Loop
Jonesboro, AR 72401

Bruce Linquist*
Dep. of Plant Sciences
Univ. of California
1 Shields Ave
Davis, CA 95616

Rice (*Oryza sativa* L.) is normally grown under flooded conditions and is a significant source of methane (CH_4). Alternate wetting and drying (AWD) is one practice which has shown promise to reduce CH_4 emissions and global warming potential (GWP). Under AWD, the soil is allowed to dry periodically during the growing season. In this 2-yr field study, three different severities of drying were compared to a continuously flooded condition to quantify effects on rice yields, greenhouse gas emissions, GWP and yield-scaled GWP (GWP_Y). The AWD treatments in order of increasing drying severity were: Safe-AWD (AWD_S) where plots were reflooded when the perched water table fell 15 cm below the soil surface (volumetric water content of 41 to 44%); and AWD_{35} and AWD_{25} where plots were reflooded when the soil volumetric water content reached approximately 35 and 25%, respectively. Each of these treatments received two drying cycles (all occurring between 45 d after planting and heading). Grain yields and cumulative N_2O emissions (close to zero) did not vary significantly among treatments. The AWD_S reduced CH_4 emissions by 41% and the AWD_{35} and AWD_{25} by 56 to 73% and 60 to 67%, respectively. Since only CH_4 differed between treatments, AWD reduced GWP and GWP_Y by the same relative amount as CH_4. Increasing drying severity reduced CH_4, GWP and GWP_Y emissions up to a point (AWD_{35}) but continued drying (AWD_{25}) did not further reduce CH_4 emissions. Given the high early season CH_4 fluxes, drying earlier may result in greater reductions of CH_4 in wet seeded rice systems but this requires further study as there may be negative effects such as increased N_2O emissions.

Abbreviations: AWD, alternate wetting and drying; GHG, greenhouse gas; GWP, global warming potential; VWC, volumetric water content.

Core Ideas

- **Rice cultivation under flooded conditions is a significant source of methane.**
- **Increasing drying severity decreased methane by 41 to 71% compared to flooded conditions.**
- **Drying beyond a certain level did not result in further methane emission reductions.**
- **Co-management of nitrogen and drying time ensured that N_2O emissions remained low.**
- **Increasing drying severity resulted in no reduction in grain yields.**

Rice is normally grown under flooded conditions and is a significant source of atmospheric methane (CH_4), a potent greenhouse gas (GHG). Rice accounts for 11% of non-carbon dioxide greenhouse gas (GHG) emissions from agriculture (Smith et al., 2007); primarily due to high CH_4 emissions, as under flooded conditions the soil is anaerobic and conducive for methanogenesis (Conrad, 2002). Rice cultivation also results in N_2O emissions, a more potent greenhouse gas, but such emissions are generally low due waterlogged conditions (Cai et al., 1997). Due to the high CH_4 emissions, the global warming potential (GWP; $CH_4 + N_2O$) of rice is 2.5- to 5.5-fold higher than other major cereal crops (Linquist et al., 2012).

Therefore, GHG mitigation options need to focus on reducing CH_4 while at the same time minimizing any increase in N_2O emissions. Furthermore, since rice is the staple crop for more than half the world's population, many of which are poor (Seck et al., 2012), mitigation options should not negatively impact grain yields. Thus, the goal here is one of sustainable intensification, whereby yields are increased or maintained while the environmental burden of the cropping

Soil Sci. Soc. Am. J. 83:1533–1541
doi:10.2136/sssaj2019.04.0113
Received 15 Apr. 2019.
Accepted 26 July 2019.
*Corresponding author (balinquist@ucdavis.edu).

system is reduced (Godfray et al., 2011). A good metric to assess sustainable intensification is “yield-scaled GWP” (GWP_Y; van Groenigen et al., 2010); which is also referred to as GHG intensity (Mosier et al., 2006) and is the amount of CH_4 and N_2O emitted per unit of yield. Since CH_4 is the end product of organic matter decomposition under anaerobic conditions (Conrad, 2002), efforts to mitigate CH_4 most often focus on management of carbon (usually residues or manure) or water (Yan et al., 2005). Given that rice cultivation also requires more water than most crops (Mekonnen and Hoekstra, 2011), identifying practices that could both reduce water use and reduce CH_4 reductions without sacrificing yields presents an attractive option for achieving sustainable intensification.

Alternate wetting and drying (AWD) is one practice which has shown promise to reduce CH_4 emissions and water use. Under AWD, the soil is allowed to become aerobic by introducing periodic drying cycles during the growing season. The practice of AWD has been shown to reduce CH_4 emissions by 48 to 93% (Linquist et al., 2018; Yan et al., 2005; Qin et al., 2010) and water use by 23 to 33% (Carrijo et al., 2018; Farooq et al., 2009). Jiang et al. (2019) showed that with increasing drying severity (or increased number of drying events or number of drying days) during the AWD dry-downs, CH_4 emissions decreased. Recently, in the United States, the American Carbon registry approved voluntary emissions reductions program for rice systems where rice farmers are given carbon credits for adoption of emission reducing practices, including AWD (http://www.arb.ca.gov/cc/capandtrade/protocols/riceprotocol.htm). In addition, AWD also shows potential to reduce both methyl-mercury (Tanner et al., 2018; Rothenberg et al., 2016) and arsenic concentrations in the grain (Carrijo et al., 2019; La Hue et al., 2016; Hu et al., 2013).

Rice soils maintained in a flooded state, usually have low N_2O emissions because nitrification and denitrification (both of which can produce N_2O [Klemedtsson et al., 1988]) of mineral N is limited (Buresh et al., 2008). Furthermore, a large portion of the N_2O that is produced in anoxic, submerged rice soils is further reduced and emitted as N_2 (Firestone and Davidson, 1989; Hou et al., 2000; Aulakh et al., 2001), which has no impact on atmospheric GHG levels. However, imposing AWD practices allow for nitrification and denitrification to occur, increasing the potential for higher N_2O emissions. The increase in N_2O emissions from AWD is usually not enough to reduce the overall effect of AWD in decreasing GWP because N_2O emissions are generally low (Linquist et al., 2015; Wassman et al., 2000a); although it is not always the case (Kritee et al., 2018; Lagomarsino et al., 2016).

Importantly, AWD has been shown to reduce GWP without reducing yields; however, it largely depends on how severe the soil is dried during the dry-down periods. Carrijo et al. (2017) conducted a meta-analysis on AWD systems and found that rice yields declined when the soil dried to below −20 kPa or when the soil water table in the field fell below 15 cm below the soil level. Reflooding the field when the perched water table reached 15 cm below the soil level (referred to as “Safe-AWD”) or when the soil was above −20 kPa resulted in no yield loss, as others have reported (e.g., Lampayan et al., 2015). Safe AWD is a practice, which is widely and successfully adopted in Asian countries (Lampayan et al., 2015).

While the Jiang et al. (2019) meta-analysis provided insight into the effect of drying severity on CH_4 and N_2O emissions, such analyses are based on many studies, which have different severity treatments. However, there are very few individual studies that have evaluated emissions across a range of drying severities and quantified the effect on emissions. Thus, the objective of this study was to examine a range of AWD drying severities on yields, and GHG emissions, GWP and GWP_Y. Specifically, we hypothesized that increasing AWD severity will result in decreasing yields and decreasing CH_4 emissions. This hypothesis was tested over 2 yr in a field study which compared three AWD severities to a continuously flooded control.

MATERIALS AND METHODS

Site Description

A field study was conducted at the California Rice Experiment Station (30°27′47″ N, 121°43′35″ W) in Biggs, CA, during the 2015 and 2016 growing seasons. Historically, this site has been grown to rice, and since 2012 this site has been used to study AWD in rice systems. Results from 2012 to 2014 have been published by LaHue et al. (2016), and treatment plots were re-randomized following those experiments. In all years since 2012, as is common practice, the rice straw remaining following harvest at the end of the growing season was incorporated into the soil and the field flooded during the winter to facilitate straw decomposition (Linquist et al., 2006). The soil at the study site is an Esquon-Neerdobe complex, classified as fine, smectitic, thermic, Xeric Epiaquerts and Duraquerts. The soil has 45% clay, 26% silt and 29% sand; a pH of 5.3; and an organic C and total N content of 1.06% and 0.08%, respectively (Pittelkow et al., 2012).

Site Management and Treatments

A complete description of the study site and management practices are provided by Carrijo et al. (2018). In brief, following land preparation, each year a total of 171, 45, 25, and 2 kg N, P_2O_5, K_2O and S, respectively was banded to a depth of 5 to 7 cm in the soil. The fertilizer was a blend of mono-ammonium phosphate, urea, ammonium sulfate and muriate of potash. Following fertilizer application, rice seeds (variety M-206) were broadcast onto the soil surface just before flooding (May 22 and May 26 in 2015 and 2016, respectively). All plots were managed identically (including pesticide control) during the growing season (Table 1), except for water management as described in the different treatments. Plots were harvested, using a small plot combine to determine grain yields and yields were adjusted to 14% moisture content.

In each year, the plots (0.3 ha) were allotted in a randomized complete block design with three replicates for each treatment. The plots were separated by two packed levees with an in-between drain ditch that was below the soil level and prevented water movement between the plots. In 2015, there were three water treatments: Continuously Flooded (CF-control), AWD_{35} and AWD_{25}. In 2016, an additional treatment, safe AWD (AWD_S;

Lampayan et al., 2015) was added. The CF treatment was kept flooded (10–15 cm depth) throughout the growing season until ~3 wk before harvest when it was drained. In all AWD treatments there were two drying cycles implemented during each growing season. The first drying cycle began ~45 d after initial flood when all plots had reached a minimum of 60% canopy cover (this also corresponded to the onset of panicle initiation). The second drying cycle began approximately 1 wk after AWD_{25} treatment was reflooded from the first drying cycle. In each drying cycle, water was allowed to subside via evapotranspiration and percolation until the average volumetric water content (VWC) of all replicate plots reached 35% and 25% for AWD_{35} and AWD_{25} treatments, respectively. In AWD_S, water was allowed to subside until the average water table of all replicate plots reached 15 cm below surface.

Carrijo et al. (2017), based on a meta-analysis of AWD studies, found that details of water management and drying severity are often under reported in the literature, which makes it difficult to compare results among studies. Therefore, in this study soil moisture was quantified in several ways to allow for ease of comparison. Soil water measurement methodologies are fully described by Carrijo et al. (2018), but briefly, the VWC (0–15 cm) was measured throughout the season in all plots using soil moisture capacitance sensors (Decagon Devices 10HS, Inc., Pullman, WA). The 10-cm-long sensor probes were installed vertically in the soil, with their centers being positioned at 7.5-cm soil depth. The sensor had a volume of influence of 1 L, which spanned from 0.5- to 14.5-cm soil depth. Soil water potential was determined using electrical resistance sensors (Watermark 200SS, Irrometer Co Inc., Riverside, CA) in which the 8.3-cm-long sensor probes were installed vertically in the soil, with their centers being positioned at 7.5-cm soil depth. Finally, the soil perched water table was measured using perforated tubes (Lampayan et al., 2015) and gravimetric water content (GWC, 0–15 cm) was measured from soil core samples. The timing of the drying cycles and the soil moisture measured just before reflood are provided in Table 2. All treatments were reflooded from the second drying cycle before 50% heading and the plots were kept flooded until 3 wk before harvest.

Table 1. Dates for key management practices and crop stages in each year.

Practice	2015	2016
Fertilization	May 18	May 23
Sowing/Flooding	May 22	May 26
Canopy cover	July 1	July 11
50% heading	Aug. 11	Aug. 12
Pre harvest drain	Sept. 7	Sept. 19
Harvest	Sept. 30	Oct. 20

Greenhouse Gas Measurements

Greenhouse gas measurements were performed using a static closed vented flux chamber technique. The chambers consisted of an open PVC base, extensions of variable lengths to accommodate growing plants and a sealed lid which was equipped with a vent tube, fan and thermocouple wire. The PVC base (29.5 cm diameter) was permanently inserted to a depth of 15 cm into the soil before sowing. The base had two holes just above the surface and four 11-cm diameter holes were drilled in the below ground portion of the chamber base to prevent the restriction of water and roots. Aboveground holes allowed for water movement between the inside and outside of the chamber. These holes were plugged with rubber stoppers during sampling when the water level was below the holes to ensure that the chambers were airtight. Boardwalks were used to reach the sampling locations to ensure minimal soil disturbance which can artificially inflate gas fluxes. To avoid the effects of intensive gas sampling on the growth of plants within each chamber, two chambers were allocated to each plot and sampling alternated between them.

The gas samples (20 mL) were taken at daily to weekly intervals during both growing seasons, with more frequent sampling during periods when emissions were likely to change rapidly (i.e., during drying and flooding events). Gas samples were taken at

Table 2. Water management details for each year and alternate wetting and drying (AWD) treatments showing start (beginning when the soil had no standing water on top of it but it was saturated) and end (reflood) of each drying cycle. Soil (0-15 cm) moisture parameters just before reflood are volumetric water content (VWC), perched water table (PWT; 2016 only), soil water potential (SWP; 2016 only), and gravimetric water content (GWC; 2016 only).

	2015			2016					
Treatment†	Start date	Reflood date	VWC	Start date	Reflood date	PWT	VWC	SWP	GWC
			%			cm	%	kPa	%
				First drying cycle					
CF			47			+13	50	0	47
AWD_S	–	–	–	July 12	July 15	–19	41	0	44
AWD_{35}	July 7	July 16	30	July 12	July 19	–31	33	–32	29
AWD_{25}	July 7	July 19	24	July 12	July 22	–38	28	–69	22
				Second drying cycle					
CF			47			+13	50	0	47
AWD_S	–	–	–	July 26	July 29	–20	44	0	42
AWD_{35}	July 27	Aug. 3	33	July 26	Aug. 2	–34	31	–35	28
AWD_{25}	July 27	Aug. 9	27	July 26	Aug. 5	–43	28	–73	22

† CF, continuously flooded; AWD_S, “Safe-AWD” in which plots were reflooded when the perched water table fell 15 cm below the soil surface (volumetric water content of 41 to 44%); AWD_{35}, plots were reflooded when the soil volumetric water content reached approximately 35%; AWD_{25}, plots were reflooded when the soil volumetric water content reached approximately 25%. Data for the continuously flooded treatment (control) are season averages. There was no AWD_S treatment in 2015.

21, 42, and 63 min between 10:00 to 13:00 h and were injected into pre-evacuated glass vials (12.5 mL). During each sampling event, four ambient samples were also taken at 0 min. To prevent leakage between sampling and analysis, each glass vial was sealed with a rubber septa and silicon.

All samples were analyzed for N_2O and CH_4 on a GC-2014 gas chromatograph equipped with an electron capture detector and flame ionization detector (Shimadzu Scientific, Inst., Columbia, MD). The detection limits of the GC instrument were 0.203 ppm for CH_4 and 0.010 ppm for N_2O. For quality assurance, standards were analyzed along with the samples and standards were inserted after every 10 samples. When the standard gas calibrations produced $r^2 > 0.99$, results from the GC were considered acceptable, and the peak area for each sample was converted to concentration using the calibration curve. Fluxes were estimated from the linear increase of gas concentration over time, and these were converted to an elemental mass per unit area using the Ideal Gas Law using the chamber volume measured at each sampling event, the chamber air temperature measured for each gas sample taken, and an atmospheric pressure of 0.101 MPa. Similar to other studies (LaHue et al., 2016; Linquist et al., 2015; Pittelkow et al., 2012), gas fluxes with a linear correlation below a predetermined threshold ($r^2 = 0.9$) were treated as missing data, and those that were below the GC detection limits were set to zero flux for data analysis. Individual flux values were integrated across all time points using linear interpolation to calculate cumulative growing season emissions. Further details of the methodology used for gas sampling and analysis can be found in Adviento-Borbe et al. (2013).

Data Analysis

The GWP was calculated using the radiating forcing potential relative to CO_2, which was 298 for N_2O and 25 for CH_4 (IPCC, 2007). Yield-scaled GWP was calculated by dividing total GWP by the corresponding grain yield for each treatment. After checking data for normality and homogeneity, an analysis of variance on cumulative N_2O, CH_4 fluxes, GWP and GWP_Y using a general linear model was conducted using Minitab 18. Differences in emissions between treatments after treatments were initiated (~45 d after sowing) were also analyzed. Included in this analysis, the post-treatment cumulative CH_4 emissions were analyzed using pre-treatment cumulative emissions as a covariate in the general linear model (ANCOVA in Minitab). Data that did not pass the normality were log transformed. Tukey's test was used to detect significant differences among the treatments ($p < 0.05$). Graphs and tables present untransformed values.

RESULTS

Soil Conditions during the Drying Cycles

As is typical for this region of California, there was no rainfall during the dry-down periods. The duration of the drying periods in the AWD treatments from the day the perched water table was at the soil surface until the field was reflooded, varied from 3 d in AWD_S (2016) to 13 d in AWD_{25} (Table 2). From sowing to maturity (pre-harvest drain), volumetric water content (VWC) in the 0- to 15-cm soil profile in the CF control averaged 47% in 2015 and 50% in 2016 (Table 2; time series in Supplemental Fig. S1). In both years, the average VWC in the AWD_{35} and AWD_{25} treatments just before reflooding was close to what was targeted and ranged from 30 to 33% in AWD_{35} and 24 to 28% in AWD_{25}. In 2016, when additional soil moisture measurements were taken, the soil water potential (SWP) was reduced to −32 to −35 kPa for the AWD_{35} and −69 to −73 kPa for AWD_{25}; and GWC was reduced to 28 to 29% for the AWD_{35} and 22% for AWD_{25}.

For the AWD_S treatment (only in 2016), plots were reflooded based on the perched water table relative to the soil surface. Plots were reflooded when the perched water table was −19 cm (first drying period) and −20 cm (second drying period), which was slightly lower than the targeted value of −15 cm (Table 2). The AWD_S treatment did not reduce the SWP relative to the CF control; however, the VWC was reduced to 41 and 44%; the GWC reduced to 42 to 44%.

Greenhouse Gas Emissions

Fluxes of CH_4 were detected within 2 wk of soil flooding. In the CF treatment, in both years, CH_4 emissions peaked approximately 1 mo (in late June) after the initial flood then declined in mid-July, followed by another smaller peak and then declined steadily over the rest of the season (Fig. 1). Daily CH_4 fluxes peaked at roughly 8000 g CH_4–C ha^{-1} d^{-1} in 2015 and 6000 g CH_4–C ha^{-1} d^{-1} in 2016. In the AWD_{35} and AWD_{25} treatments, CH_4 emissions declined to zero during the first drying period and stayed close to zero for the remainder of the season. In contrast, CH_4 emissions in the AWD_S declined during the drying periods but never reached zero, and following each reflood, CH_4 emissions increased but never to the level of the CF treatment (Fig. 1).

Cumulative CH_4 emissions varied between treatments within each year. In the CF treatments, the cumulative CH_4–C flux in 2015 (338 kg CH_4–C ha^{-1}) was 56% higher than in 2016 (Table 3). While AWD treatments significantly reduced cumulative CH_4 emissions relative to the control, in neither year were there significant differences between AWD treatments. In 2015, CH_4 emissions were significantly reduced in both AWD treatments by 70%, on average, relative to the CF treatments. Similarly, in 2016, the AWD_{35} and AWD_{25} significantly decreased CH_4 emission on average by 58%. Cumulative CH_4 emissions in the AWD_S was not significantly reduced relative to the CF treatment although they were 41% lower. All treatments presumably had similar GHG emissions until the onset of the first dry-down period since they were managed identically up until that point. Statistical analysis done on post-treatment cumulative emissions (from the first dry-down until the end of the season) using pre-treatment cumulative emissions (emissions prior to the first dry-down) as covariate indicated that the AWD_S treatment significantly reduced CH_4 emissions relative to CF but emissions were higher than AWD_{35} and AWD_{25} (Table 4). Cumulative emissions between the first dry-down and end of season from the AWD_{35} and AWD_{25} were low (between 5 and 13 kg CH_4–C ha^{-1}).

Daily N_2O emissions were low in both the years and ranged from −15 to 8 g N_2O-N ha^{-1} d^{-1} (Fig. 2). At only four sampling events were N_2O fluxes positive, and all of these occurred in 2015 and were mostly associated with the AWD_{25} treatment but one of the positive N_2O emissions was from the CF treatment. Given this, cumulative N_2O emissions in each year were slightly negative and ranged from −0.03 to −0.13 kg N_2O-N ha^{-1} with no differences between treatments (Table 3).

Grain Yield, GWP, and Yield-Scaled GWP

Rice grain yields were similar for all treatments and ranged from 13.8 and 14.1 Mg ha^{-1} and 11.1 and 11.4 Mg ha^{-1} in 2015 and 2016, respectively (Table 5). Since N_2O emissions were low and similar among treatments, differences in GWP between treatments largely reflected differences in CH_4 emissions between treatments (Tables 3 and 5).

Similarly, GWP_Y was largely a function of differences in CH_4 emissions between treatments because the yields and N_2O emissions were similar among treatments. In the control treatments, GWP_Y was 813 and 627 kg CO_2 eq Mg^{-1} in 2015 and 2016, respectively. Using AWD_{35} and AWD_{25} reduced GWP_Y by 70% in 2015 and 57% in 2016. The AWD_S treatment in 2016 reduced GWP_Y by 41%; while not significant based on seasonal emissions, CH_4 emissions were significantly reduced in this treatment based on emissions following the first dry-down (Table 4).

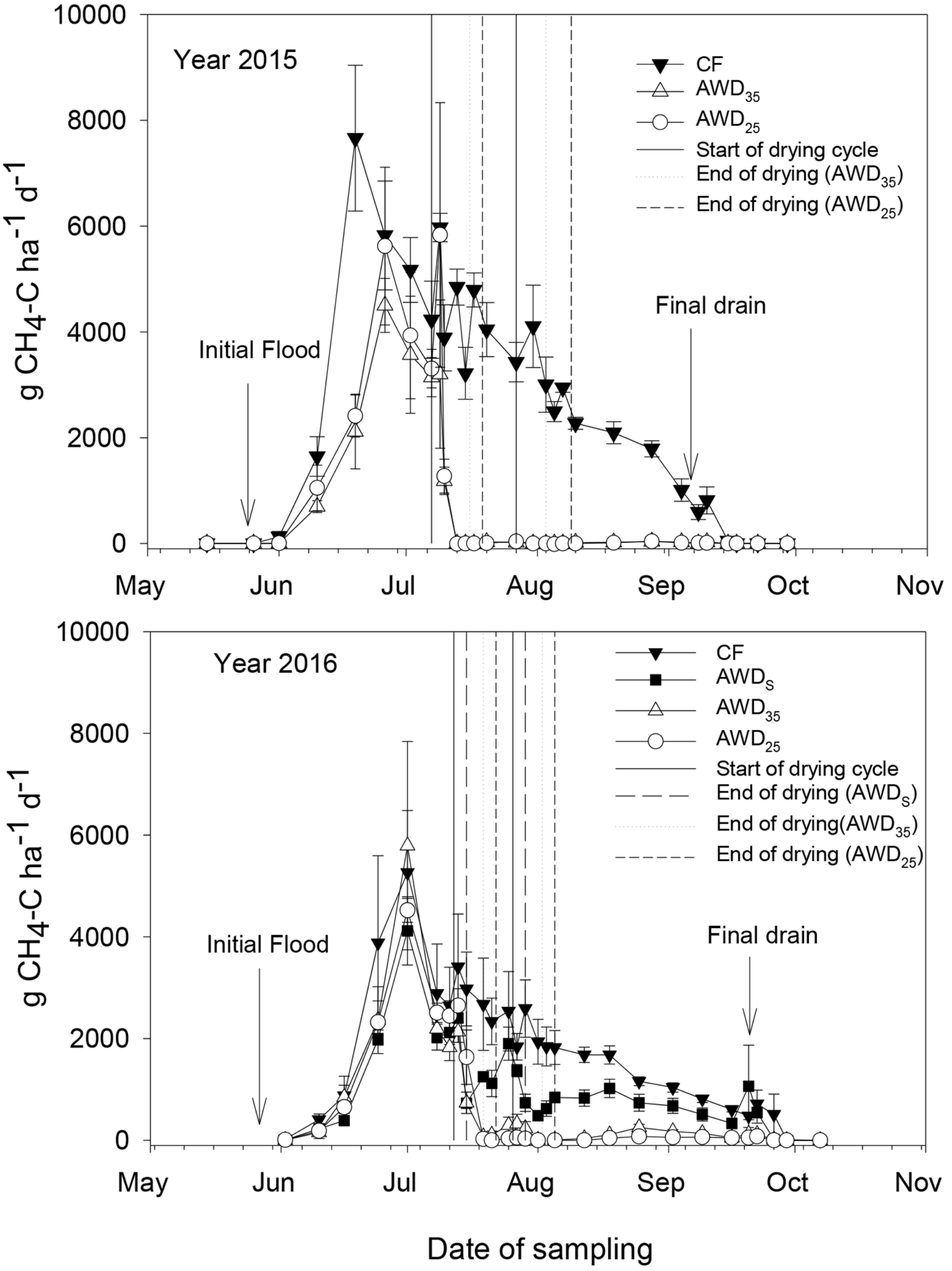

Fig. 1. Daily CH_4 emissions for each year and treatment. Within each time period the actual drying time for each treatment varied (see Table 2). Error bars represent the standard errors.

DISCUSSION

Methane Emissions

Methane emissions from the CF control varied between the 2 yr of this study with 2015 emitting 122 kg CH_4–C ha^{-1} $season^{-1}$ more than in 2016. Both values are higher than the average reported mean for California (163 kg CH_4–C ha^{-1} $season^{-1}$ with 95% confidence levels around the mean being 115 and 213 kg CH_4–C ha^{-1} $season^{-1}$) reported by Linquist et al. (2018) and higher than those reported by LaHue et al. (2016) at this same location. However, Pittelkow et al. (2014) also reported high cumulative CH_4 emissions (335 kg CH_4–C ha^{-1} $season^{-1}$) from this site in a 2008 field study. The cause of annual year-to-year variation is uncertain; however, such observations are common in GHG field studies and the variation is often not possible to explain (Wassman et al., 2000b).

The high total CH_4 emissions, in both years, are due to high early season CH_4 fluxes which peaked at 6000 to 8000 g CH_4–C ha^{-1} d^{-1}. Residues left in the field from the

Table 3. Total seasonal CH_4 and N_2O emissions for each season and treatment. Numbers in parentheses are the standard errors.

	Total CH_4 emissions		Total N_2O emissions	
Treatment†	**CH_4–C**	**CO_2 equivalent**	**N_2O-N**	**CO_2 equivalent**
	kg CH_4–C ha^{-1} $season^{-1}$	kg CO_2 eq ha^{-1} $season^{-1}$	kg N_2O-N ha^{-1} $season^{-1}$	kg CO_2 eq ha^{-1} $season^{-1}$
		2015		
CF	338 (15.4) a‡	11288 (516) a	−0.06 (0.01) a	−27 (5) a
AWD_{35}	92 (13.7) b	3055 (458) b	−0.11 (0.06) a	−52 (28) a
AWD_{25}	111 (16.2) b	3696 (542) b	−0.03 (0.03) a	−15 (15) a
		2016		
CF	216 (51) a	7201 (1678) a	−0.10 (0.03) a	−45 (13) a
AWD_S	128 (8) ab	4272 (270) ab	−0.09 (0.04) a	−41 (18) a
AWD_{35}	96 (23) b	3218 (764) b	−0.04 (0.02) a	−18 (8) a
AWD_{25}	87 (6) b	2902 (204) b	−0.13 (0.1) a	−62 (45) a

† CF, continuously flooded; AWD_S, "Safe-AWD" in which plots were reflooded when the perched water table fell 15 cm below the soil surface (volumetric water content of 41 to 44%); AWD_{35}, plots were reflooded when the soil volumetric water content reached approximately 35%; AWD_{25}, plots were reflooded when the soil volumetric water content reached approximately 25%.

‡ For each year and column, means followed by the same letter are not significantly different at $P < 0.05$.

previous crop can increase CH_4 emissions the following season as they provide a carbon substrate for methanogenesis (Yan et al., 2005). Furthermore, early CH_4 emissions are often attributed to the decomposition of the previous crops residues (Chidthaisong and Watanabe, 1997). Thus, higher early season CH_4 emissions suggest that more residues were present at the start of the season due to either higher yields in the previous season (leading to higher straw residue; rice has a harvest index of approximately 0.5) or reduced decomposition of residues during the winter fallow period. Yields at this location in 2015 were among the highest recorded at this location (>13.5 Mg ha^{-1}; Table 5); thus, high early season 2016 CH_4 emissions may be due to a greater amount of residue from that crop. However, yields in 2014 were similar to average yields at this location with all treatments yielding less than 11 Mg ha^{-1} (LaHue et al., 2016). Thus, the higher CH_4 emissions during the early growing season of 2015 may be related to poorer straw decomposition during the winter fallow, leaving more straw carbon available for decomposition; however, it was not quantified. When straw was incorporated in the fall and fields flooded over the winter, Linquist et al. (2006) found that approximately half the straw had decomposed by the end of the winter fallow period; however it may vary depending on winter fallow climate conditions.

Table 4. Post-treatment (from the initiation of the first drying event to the end of the season) cumulative CH_4 emissions.

	Methane emissions	
Treatment†	**2015**	**2016**
	— kg CH_4–C ha^{-1} $season^{-1}$ —	
CF	172 a‡	116 a
AWD_S	NA§	62 b
AWD_{35}	5 b	13 c
AWD_{25}	6 b	10 c

† CF, continuously flooded; AWD_S, "Safe-AWD" in which plots were reflooded when the perched water table fell 15 cm below the soil surface (volumetric water content of 41 to 44%); AWD_{35}, plots were reflooded when the soil volumetric water content reached approximately 35%; AWD_{25}, plots were reflooded when the soil volumetric water content reached approximately 25%.

‡ For each year and column, means followed by the same letter are not significantly different at $P < 0.05$.

§ NA, not applicable.

The AWD_{35} and AWD_{25} treatments reduced CH_4 emissions on average by 70 and 58% relative to the CF control in 2015 and 2016, respectively. These reductions are less than reported on based on a meta-analysis by Linquist et al. (2018) for multiple AWD dry-downs in the United States (83%), but are closer to that reported by Yan et al. (2005) and more recently Jiang et al. (2019) which are global analyses. The reduction in CH_4 emissions is limited due to the higher than normal CH_4 fluxes early in the growing season (see discussion in previous paragraph) which all occurred before the AWD dry-downs began. Furthermore, it would not have been possible to reduce CH_4 emissions much more than observed here because CH_4 emissions after the first dry-down in both the AWD_{35} and AWD_{25} treatments were negligible (<13 kg CH_4–C ha^{-1}) (Table 4). Reducing CH_4 emissions beyond what was accomplished here would require drying fields earlier when CH_4 fluxes were highest. Recent studies (Faiz-ul Islam et al., 2018; Tariq et al., 2017) have demonstrated that drying earlier led to greater reduction in CH_4 emissions than drying mid-season. However, this practice may have drawbacks, such as increasing the potential for N_2O emissions if preplant fertilizer N was applied (discussed below) or increasing weed pressure as the canopy would not be fully closed; however, it remains an excellent area for further research.

Safe-AWD (AWD_S) is becoming an increasingly common practice in Asia (Lampayan et al., 2015). It has been shown to reduce water use and greenhouse gas emissions, while at the same time not impact yield (Liang et al., 2016; Pandey et al., 2014). In this study, we also show that AWD_S reduced CH_4 emissions by 41%. Unlike the more severe AWD treatments (AWD_{35} and AWD_{25}), imposing AWD_S never resulted in zero CH_4 emissions either during or after the drying events (Fig. 1); however, CH_4 emissions were significantly reduced after the initial drying event relative to the control (Table 4). The reason for this is that the soil water potential remained close to zero (saturated) during these dry-down events (Table 2) based on soil sensor readings. The soil sensors quantified soil water potential at roughly the 3- to 12-cm soil depth; however, the soil GWC (which included the surface soil) and VWC was lower in the AWD_S than in the control. Thus, the reduction in CH_4 emissions may be due to soil in the top few centimetres of this treatment becoming aerobic during the drying events. Lampayan et al. (2015) also found that with Safe-AWD, soil water potential could remain close to saturation, but this depended on soil characteristics.

From this study we found that increasing the severity of AWD reduced CH_4 emissions to AWD_{35}; however, drying the soil longer to AWD_{25} had no further benefit in reducing CH_4 emissions. Similar results were reported by Linquist et al. (2015), where drying further did not reduce CH_4 emissions but did decrease yields. Interestingly, in this same study, further drying also did not result in further reductions to grain arsenic uptake (Carrijo et al., 2018). Such information is critical in that increased drying will eventually lead to decreased grain yields (Carrijo et al., 2017; Bouman and Tuong, 2001), but will not necessarily lead to further environmental or health benefits.

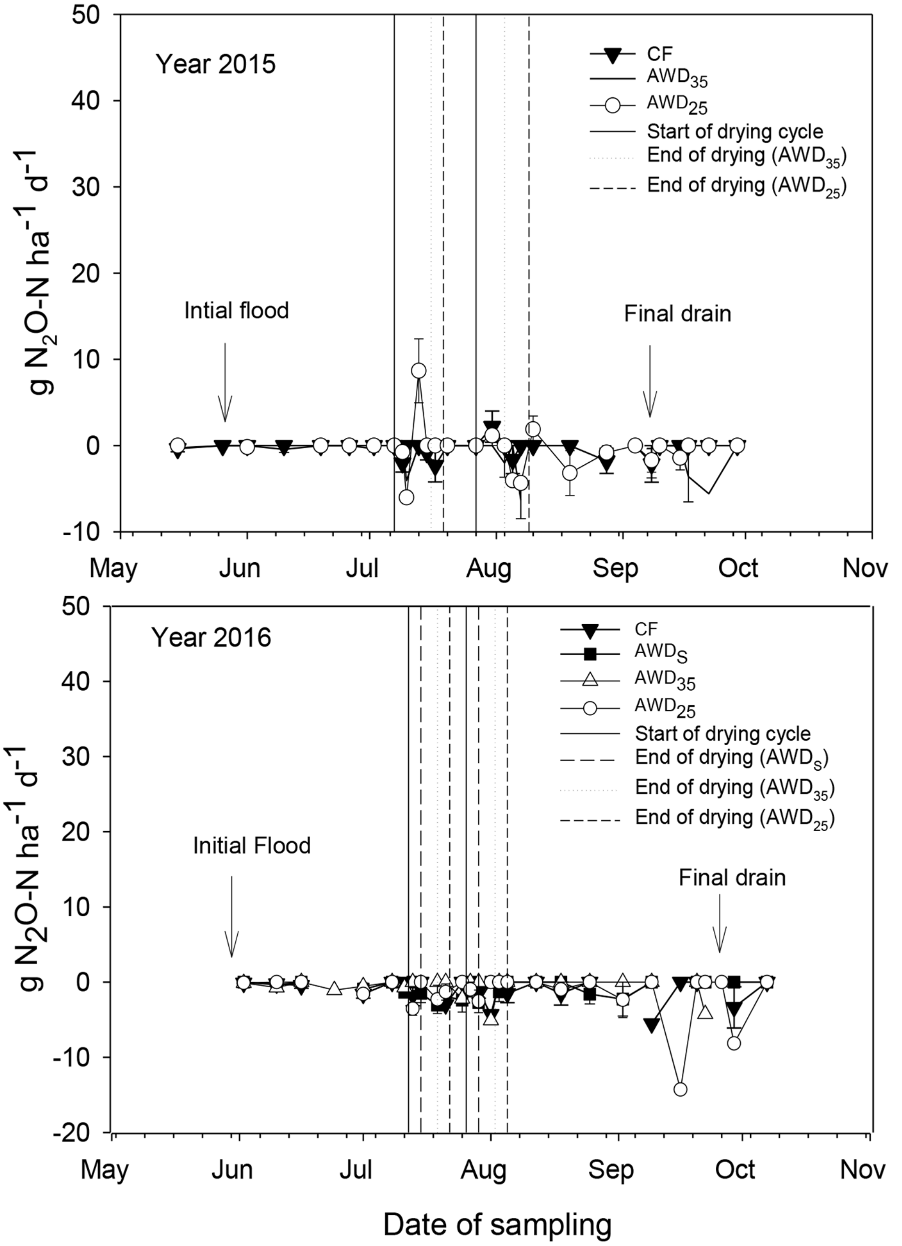

Fig. 2. Daily N_2O emissions for each year and treatment. Within each time period the actual drying time for each treatment varied (see Table 2). Error bars represent standard errors.

Nitrous Oxide Emissions

Generally, N_2O emissions are low in anoxic, submerged rice soils as most of the N_2O that is produced is further reduced and emitted as N_2 (Firestone and Davidson, 1989; Hou et al., 2000; Aulakh et al., 2001), which has no impact on atmospheric GHG levels. One concern with implementing AWD is that it imposes soil conditions that favor N_2O emissions. Drying a soil and then reflooding it results in favorable conditions for nitrification and subsequent denitrification on flooding (Buresh et al., 2008). Both of these processes can result in the release of N_2O gas (Klemedtsson et al., 1988; Dobbie et al., 1999). A number of studies have reported increased N_2O emissions as a result of AWD (Jiang et al., 2019; Kritee et al., 2018; Tariq et al., 2017; Linquist et al., 2015, Lagomarsino et al., 2016). In most cases, however, the reduction of CH_4 emissions more than offset the increased N_2O emissions leading to lower GWP in AWD (Jiang et al., 2019; Wassman et al., 2000a). Here we found no increase in N_2O emissions as a result of AWD, in fact N_2O emissions were close to zero or negative in all treatments. Negative N_2O fluxes suggest N_2O uptake which can be significant in rice fields (Majumdar, 2013). LaHue et al. (2016) also reported low N_2O emissions with AWD and attributed the low emissions to the low amount of mineral N in the soil at the time of drying. Delaying the initial dry-down until 6 or 7 wk after planting (when the fertilizer N was applied), ensures that the N fertilizer has been taken up and thus little mineral N remains in the soil to undergo nitrification and denitrification. Critically, as reported by several authors (Kritee et al., 2018; Lagomarsino et al., 2016), if water and N inputs are not managed properly together (i.e., dry-downs occur when there are high amounts of mineral N present in the soil) N_2O emissions can be high, negating any benefit of reduced CH_4 emissions.

Yield, GWP, and Yield-Scaled GWP

Based on a meta-analysis, Carrijo et al. (2017) reported that yields did not decline under mild AWD treatments (such as the AWD_S in this study); however, yields did decline when the drying became more severe. In contrast, despite a wide variation in the severity of the AWD drying treatments, none of the

Table 5. Grain yield, global warming potential (GWP), and yield-scaled GWP for each season and treatment. Numbers in parentheses are the standard errors.

Treatment†	Yield	GWP	Yield-scaled GWP
	Mg ha^{-1}	kg CO_2 eq ha^{-1} $season^{-1}$	kg CO_2 eq Mg^{-1} $season^{-1}$
		2015	
CF	13.8 (0.09) a‡	11262 (511) a	813 (32) a
AWD_{35}	13.5 (0.15) a	3003 (441) b	222 (32) b
AWD_{25}	13.7 (0.43) a	3681 (531) b	271 (48) b
		2016	
CF	11.4 (0.08) a	7156 (1675) a	627 (148) a
AWD_S	11.4 (0.18) a	4231 (278) ab	371 (26) ab
AWD_{35}	11.4 (0.09) a	3201 (757) b	280 (64) b
AWD_{25}	11.1 (0.28) a	2840 (222) b	256 (19) b

† CF, continuously flooded; AWD_S, "Safe-AWD" in which plots were reflooded when the perched water table fell 15 cm below the soil surface (volumetric water content of 41 to 44%); AWD_{35}, plots were reflooded when the soil volumetric water content reached approximately 35%; AWD_{25}, plots were reflooded when the soil volumetric water content reached approximately 25%.

‡ For each year and column, means followed by the same letter are not significantly different at $P < 0.05$.

treatments in this study reduced grain yields (Table 5). Carrijo et al. (2018) suggested that this may be due to the presence of rice roots near the shallow water table at this location. Based on this, they suggested that improved site-specific understanding of soil hydrology and rooting depth would potentially allow the practice of AWD to expand into areas where more severe dry-downs could be used, thus optimizing benefits.

In the CF control, the GWP (sum of CH_4 and N_2O emissions in CO_2 equivalents) ranged between 7,200 and 11,300 kg CO_2 eq ha^{-1} $season^{-1}$ (Table 5). These values are double to triple the average value for rice systems estimated by Linquist et al. (2012) and are high due to the high CH_4 emission from this location in these years as discussed earlier. However, given the high yields, the GWP_Y of 627 to 813 kg CO_2 eq Mg^{-1} $season^{-1}$ was comparable to average rice systems (Linquist et al., 2012). The AWD treatments reduced GWP and GWP_Y by roughly the same relative amount as the change in CH_4 emissions because N_2O emissions (Table 3) and yields (Table 5) were similar across treatments. GWP_Y was reduced by 57 to 70% in the two more severe AWD treatments (with no difference between them) and by 41% in the AWD_S treatment. This reduction in GWP_Y due to AWD was greater (especially for the more severe AWD treatments) than reported for two drying events (31% reduction) based on a global meta-analysis by Jiang et al. (2019) which may be due to the fact that the drying severities in this study were greater than conducted for most AWD studies.

Importantly when considering sustainable intensification goals, the reductions in GWP_Y occurred without a reduction in grain yields. Thus, AWD can represent a win-win scenario in which there is no reduction in yields but significant environmental gains. Furthermore, Carrijo et al. (2018) also pointed out that AWD_{35} and AWD_{25} both reduced total grain arsenic by 56 to 68%.

CONCLUSIONS

We found, as have others, that AWD is an effective practice which results in lower CH_4 emissions and GWP from flooded rice fields. Importantly, despite drying soils longer than the considered "safe" level, yields were not reduced, highlighting the importance of understanding soil hydrology and rooting patterns in a particular cropping system. Second, drying beyond a certain limit did not result in greater CH_4 reductions. Third, with careful management of both nitrogen and drying time, N_2O emissions were negligible. Finally, we hypothesize that CH_4 reductions could have been reduced further by implementing the drying phases earlier in the season when CH_4 emissions were at their peak, but early drying may have other negative effects and requires further study.

SUPPLEMENTAL MATERIAL

Supplemental material is available with the online version of this article.

ACKNOWLEDGMENTS

This research was supported with a grant from the California Rice Research Board (#RR-11-RM-4) and the Innovation Program of CAAS (Y2016PT12, Y2016XT01), CAPES–Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brazil. We are thankful to Cesar Abrenilla, Nadeem Akbar, and Ray Stogsdill for their help with fieldwork and data collection.

REFERENCES

Adviento-Borbe, M.A., C.M. Pittelkow, M. Anders, C. van Kessel, J.E. Hill, A.M. McClung, J. Six, and B.A. Linquist. 2013. Optimal fertilizer N rates and yield-scaled global warming potential in drill seeded rice. J. Environ. Qual. 42:1623–1634. doi:10.2134/jeq2013.05.0167

Aulakh, M.S., T.S. Khera, J.W. Doran, and K.F. Bronson. 2001. Denitrification, N_2O and CO_2 fluxes in rice-wheat cropping system as affected by crop residues, fertilizer N and legume green manure. Biol. Fertil. Soils 34:375–389. doi:10.1007/s003740100420

Bouman, B.A.M., and T.P. Tuong. 2001. Field water management to save water and increase its productivity in irrigated lowland rice. Agric. Water Manage. 49:11–30. doi:10.1016/S0378-3774(00)00128-1

Buresh, R.J., K.R. Reddy, and C. van Kessel. 2008. Nitrogen transformations in submerged soils. In: J.S. Schepers and W.R. Raun, editors, Nitrogen in agricultural systems. Agronomy Monograph 49. ASA, Madison, WI. p. 401–436. doi:10.2134/agronmonogr49.c11

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 fertilizers and water management. Plant Soil 196:7–14. doi:10.1023/A:1004263405020

Carrijo, D.R., P. Green, A. Gaudin, N. Akbar, A. Borja Reis, C. Li, S. Parikh, and B. Linquist. 2018. Impacts of variable soil drying in alternate wetting and drying rice systems on yields, grain arsenic concentration and soil moisture dynamics. Field Crops Res. 222:101–110. doi:10.1016/j.fcr.2018.02.026

Carrijo, D.R., C. Li, S.J. Parikh, and B.A. Linquist. 2019. Irrigation management for arsenic mitigation in rice grain: Timing and severity of soil drying. Sci. Total Environ. 649:300–307. doi:10.1016/j.scitotenv.2018.08.216

Carrijo, D.R., M.E. Lundy, and B.A. Linquist. 2017. Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. Field Crops Res. 203:173–180. doi:10.1016/j.fcr.2016.12.002

Chidthaisong, A., and I. Watanabe. 1997. Methane formation and emission from flooded rice soil incorporated with ^{13}C-labeled rice straw. Soil Biol. Biochem. 29:1173–1181. doi:10.1016/S0038-0717(97)00034-5

Conrad, R. 2002. Control of microbial methane production in wetland rice fields. Nutr. Cycling Agroecosyst. 64:59–69. doi:10.1023/A:1021178713988

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

Faiz-ul Islam, S., J.W. van Groenigen, L.S. Jensen, B.O. Sander, and A. de Neergaard. 2018. The effective mitigation of greenhouse gas emissions from rice paddies without compromising yield by early-season drainage. Sci. Total Environ. 612:1329–1339. doi:10.1016/j.scitotenv.2017.09.022

Farooq, M., N. Kobayashi, A. Wahid, O. Ito, and S.M.A. Basra. 2009. Strategies for producing more rice with less water. Adv. Agron. 101:351–388.

Firestone, M.K., and E.A. Davidson. 1989. Microbial basis of NO and N_2O production and consumption in soils. In: M.O. Andreae and D.S. Schimel, editors, Exchange of trace gases between terrestrial ecosystems and the atmosphere. John Wiley & Sons, New York. p. 7–21.

Godfray, H.C.J., J. Pretty, S.M. Thomas, E.J. Warham, and J.R. Beddington. 2011. Linking policy on climate and food. Science 331:1013–1014. doi:10.1126/science.1202899

Hou, A.X., G.X. Chen, Z.P. Wang, O. Van Cleemput, and W.H. Patrick. 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

Hu, P., J. Huang, Y. Ouyang, L. Wu, J. Song, S. Wang, Z. Li, C. Han, L. Zhou, and Y. Huang. 2013. Water management affects arsenic and cadmium accumulation in different rice cultivars. Environ. Geochem. Health 35:767–778. doi:10.1007/s10653-013-9533-z

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate change 2007-The physical science basis. In: S. Solomon, D. Qin, M. Manning, M. Marquis, K. Averyt, M.M.B. Tignor, and J. Henry LeRoy Miller, editors, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Cambridge.

Jiang, Y., D. Carrijo, S. Huang, J. Chen, N. Balaine, W. Zhang, K.J. van Groenigen, and B. Linquist. 2019. Water management to mitigate the global warming potential of rice systems: A global meta-analysis. Field Crops Res. 234:47–54. doi:10.1016/j.fcr.2019.02.010

Klemedtsson, I., B.H. Stevsson, and T. Rosswall. 1988. Relationships between soil moisture content and nitrous oxide production during nitrification and denitrification. Biol. Fertil. Soils 6:106–111.

Kritee, K., D. Nair, D. Zavala-Araiza, J. Proville, J. Rudek, T.K. Adhya, T. Loecke, T. Esteves, S. Balireddygari, O. Dava, K. Ram, S.R. Abhilash, M. Madasamy, R.V. Dokka, D. Anandaraj, D. Athiyaman, M. Reddyf, R. Ahuja, and S.P. Hamburg. 2018. High nitrous oxide fluxes from rice cultivation indicate the need to manage water for both long- and short-term climate impacts. Proc. Natl. Acad. Sci. 115:9720-972. doi:10.1073/pnas.1809276115

Lagomarsino, A., A.E. Agnelli, B. Linquist, M.A.A. Adviento-Borbe, A. Agnelli, G. Gavina, and M. Ravaglia. 2016. Alternate wetting and drying of rice reduced CH_4 but triggered N_2O peaks in a clayey soil of central Italy. Pedosphere 26:533–548. doi:10.1016/S1002-0160(15)60063-7

LaHue, G.T., R.L. Chaney, M.A. Adviento-Borbe, and B.A. Linquist. 2016. Alternate wetting and drying in high yielding direct-seeded rice systems accomplishes multiple environmental and agronomic objectives. Agric. Ecosyst. Environ. 229:30–39. doi:10.1016/j.agee.2016.05.020

Lampayan, R.M., R.M. Rejesus, G.R. Singleton, and B.A.M. Bouman. 2015. Adoption and economics of alternate wetting and drying water management for irrigated lowland rice. Field Crops Res. 170:95–108. doi:10.1016/j.fcr.2014.10.013

Liang, K., X. Zhong, N. Huang, R.M. Lampayan, J. Pan, K. Tian, and Y. Liu. 2016. Grain yield, water productivity and CH_4 emission of irrigated rice in response to water management in south China. Agric. Water Manage. 163:319–331. doi:10.1016/j.agwat.2015.10.015

Linquist, B.A., M. Anders, M.A. Adviento-Borbe, R.L. Chaney, L.L. Nalley, E.E.F. da Rosa, and C. van Kessel. 2015. Reducing greenhouse gas emissions, water use and grain arsenic levels in rice systems. Glob. Change Biol. 21:407–417. doi:10.1111/gcb.12701

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.A., M. Marcos, M.A. Adviento-Borbe, M. Anders, D. Harrell, S. Linscombe, M. Reba, B. Runkle, L. Tarpley, and A. Thomson. 2018. Greenhouse gas emissions and management practices that affect them in US rice systems. J. Environ. Qual. 47:395–409. doi:10.2134/jeq2017.11.0445

Linquist, B.A., K.J. van Groenigen, M.A. Adviento-Borbe, C. Pittelkow, and C. van Kessel. 2012. 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

Majumdar, D. 2013. Biogeochemistry of N_2O uptake and consumption in submerged soils and rice fields and implications in climate change. Crit. Rev. Environ. Sci. Technol. 43:2653–2684. doi:10.1080/10643389.2012.694332

Mekonnen, M.M., and A.Y. Hoekstra. 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15:1577–1600. doi:10.5194/hess-15-1577-2011

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

Pandey, A., V.T. Mai, D.Q. Vu, T.P.L. Bui, T.L.A. Mai, L.S. Jensen, and A. de Neergaard. 2014. Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in Vietnam. Agric. Ecosyst. Environ. 196:137–146. doi:10.1016/j.agee.2014.06.010

Pittelkow, C.M., Y. Assa, M. Burger, W.R. Horwath, R.G. Mutters, C.A. Greer, L.A. Espino, J.E. Hill, C. van Kessel, and B.A. Linquist. 2014. Nitrogen management and methane emissions in direct-seeded rice systems. Agron. J. 106:968–980. doi:10.2134/agronj13.0491

Pittelkow, C.M., A.J. Fischer, M.J. Moechnig, J.E. Hill, K.B. Koffler, R.G. Mutters, C.A. Greer, Y.S. Cho, C. van Kessel, and B.A. Linquist. 2012. Agronomic productivity and nitrogen requirements of alternative tillage and crop establishment systems for improved weed control in direct-seeded rice. Field Crops Res. 130:128–137.

Qin, Y., S. Liu, Y. Guo, Q. Liu, and J. Zou. 2010. Methane and nitrous oxide emissions from organic and conventional rice cropping systems in Southeast China. Biol. Fertil. Soils 46:825–834. doi:10.1007/s00374-010-0493-5

Rothenberg, S.E., M. Anders, N.J. Ajami, J.F. Petrosino, and E. Balogh. 2016. Water management impacts rice methylmercury and the soil microbiome. Sci. Total Environ. 572:608–617. doi:10.1016/j.scitotenv.2016.07.017

Seck, P.A., A. Diagne, S. Mohanty, and M.C.S. Woperies. 2012. Crops that feed the world 7: Rice. Food Secur. 4:7–24. doi:10.1007/s12571-012-0168-1

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 and New York.

Tanner, K., L. Windham-Myers, M. Marvin-DiPasquale, J.A. Fleck, and B.A. Linquist. 2018. Alternate wetting and drying decreases methylmercury in flooded rice (*Oryza sativa*) systems. Soil Sci. Soc. Am. J. 82:115–125. doi:10.2136/sssaj2017.05.0158

Tariq, A., Q.D. Vu, L.S. Jensen, S. de Tourdonnet, B.O. Sander, R. Wassmann, T.V. Mai, and A. de Neergaard. 2017. Mitigating CH_4 and N_2O emissions from intensive rice production systems in northern Vietnam: Efficiency of drainage patterns in combination with rice residue incorporation. Agric. Ecosyst. Environ. 249:101–111. doi:10.1016/j.agee.2017.08.011

van Groenigen, J.W., G.L. Velthof, O. Oenema, K.J. van Groenigen, and C. van Kessel. 2010. Towards an agronomic assessment of N_2O emissions: A case study for arable crops. Eur. J. Soil Sci. 61:903–913. doi:10.1111/j.1365-2389.2009.01217.x

Wassmann, R., R.S. Lantin, H.U. Neue, L.V. Buendia, T.M. Corton, and Y. Lu. 2000a. Characterization of methane emissions from rice fields in Asia. III. Mitigation options and future research needs. Nutr. Cycling Agroecosyst. 58:23–36. doi:10.1023/A:1009874014903

Wassmann, R., H.U. Neue, R.S. Lantin, K. Makarim, N. Chareonsilp, L.V. Buendia, and H. Rennenberg. 2000b. 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

Yan, X., K. Yagi, H. Akiyama, and H. Akimoto. 2005. Statistical analysis of the major variables controlling methane emissions from rice fields. Glob. Change Biol. 11:1131–1141. doi:10.1111/j.1365-2486.2005.00976.x