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Alternate wetting and drying in high yielding direct-seeded rice systems accomplishes multiple environmental and agronomic objectives

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ABSTRACT

Rice (*Oryza sativa* L.) cultivation is critically important for global food security, yet it also represents a significant fraction of agricultural greenhouse gas (GHG) emissions and water resource use. Alternate wetting and drying (AWD) of rice fields has been shown to reduce both methane (CH_4) emissions and water use, but its effect on grain yield is variable. In this three-year study we measured CH_4 and nitrous oxide (N_2O) emissions, rice grain total arsenic (As) concentrations, yield response to N rate, and grain yield from two AWD treatments (drill-seeded and water-seeded) and a conventionally managed water-seeded treatment (control). Grain yields (average = 10 Mg ha^{-1}) were similar or higher in the AWD treatments compared to the control and required similar or lower N rates to achieve these yields. Furthermore, AWD reduced growing season CH_4 emissions by 60–87% while maintaining low annual N_2O emissions (average = 0.38 kg N_2O–N ha^{-1}); N_2O emissions accounted for <15% of the annual global warming potential (GWP) in all treatments. Fallow season emissions did not vary by treatment and accounted for 22–53% of annual CH_4 emissions and approximately one third of annual GWP on average. The AWD treatments reduced annual GWP by 57–74% and growing season yield-scaled GWP by 59–88%. Milled grain total As, which averaged 0.114 mg kg^{-1} in the control, was reduced by 59–65% in the AWD treatments. These results show that AWD has the potential to mitigate GHG emissions associated with rice cultivation and reduce rice grain total As concentrations without sacrificing grain yield or requiring higher N inputs; however future research needs to focus on adapting AWD to field scales if adoption of this technology is to be realized.

1. Introduction

Agriculture in the 21st century is expected to double food production to meet the demand from a growing population while simultaneously reducing its environmental footprint in the face of challenges like widespread soil degradation, water scarcity, and climate change (Foley et al., 2011). Agriculture is responsible for over half of global anthropogenic non-CO_2 greenhouse gas (GHG) emissions, due predominately to nitrous oxide (N_2O) emissions from N fertilization and methane (CH_4) emissions from livestock and rice (*Oryza sativa* L.) cultivation (Smith et al., 2014). Rice is the dominant staple crop in much of the world and is critically important for global food security (Maclean et al., 2002), yet rice cultivation is a significant source of CH_4 emissions (Linquist et al., 2012), accounting for 9–11% of GHG emissions from agriculture (Smith et al., 2014). Furthermore, increases in rice production over the last half-century relied heavily on irrigated rice production, which is increasingly constrained by water scarcity (Cassman, 1999). Alternative management techniques are therefore needed to reduce the environmental burden associated with rice cultivation without jeopardizing rice production and global food security.

Alternate wetting and drying (AWD) of rice paddies, in which fields are drained and re-flooded one or more times during the growing season, has been promoted as a strategy to decrease irrigation water use and reduce GHG emissions from rice cultivation while maintaining or improving yields (Richards and Sander, 2014). It has principally been promoted in Asia, with the most widespread adoption to date occurring in Bangladesh, the

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Philippines, and Vietnam (Lampayan et al., 2015). While AWD has been shown to reduce CH_4 emissions by 48–93% (Linquist et al., 2015a; Pandey et al., 2014; Qin et al., 2010; Xu et al., 2015), it can result in increased N_2O emissions, producing a trade-off between CH_4 and N_2O emissions (Ahn et al., 2014; Yang et al., 2012). However, in most cases this trade-off does not eliminate the overall reduction in global warming potential (GWP) associated with AWD (Linquist et al., 2015a; Pandey et al., 2014; Xu et al., 2015). The effect of AWD management on rice grain yield is less clear. In studies conducted in China, Belder et al. (2004) found that AWD had no significant impact on grain yield, while Xu et al. (2015) observed yield decreases of up to 16%. This variability is likely due in part to differences in AWD water management between studies, as AWD treatments may vary widely in their severity (Zhang et al., 2009; Linquist et al., 2015a), timing (Bouman and Tuong, 2001; Linquist et al., 2015a), and soil moisture monitoring methodology (e.g. field water tubes (Lampayan et al., 2015), moisture sensors (Linquist et al., 2015a), or tensiometers (Zhang et al., 2009)). However, AWD may also affect grain yield by altering N cycling in rice systems (Dong et al., 2012). In flooded rice systems, fertilizer N loss from coupled nitrification-denitrification at the interface of the aerobic and anaerobic soil layers is generally minimal (Buresh et al., 2008). Without careful timing of AWD water management however, the introduction of aerobic cycles may lead to increased nitrification and subsequent N loss (including as N_2O emissions) through denitrification upon re-flooding (Cai et al., 1997; Hussain et al., 2015).

While the effects of AWD on grain yield may vary, AWD has been shown to have agronomic benefits other than the aforementioned reduction in CH_4 emissions, such as lower grain arsenic (As) concentrations and reduced water inputs (Hu et al., 2013; Lampayan et al., 2015; Linquist et al., 2015a). There is increasing pressure to reduce water use in rice systems, as current water use levels are unsustainable in many rice-growing regions (Steffen et al., 2015). Water savings of 10–44% have been reported with AWD, mostly due to the elimination of unproductive flows such as lateral seepage and deep percolation (Lampayan et al., 2015; Linquist et al., 2015a; Rejesus et al., 2011). Concerns have also been raised about As accumulation in rice grains, especially among populations that have high rice consumption due to cultural practices or dietary constraints (Gilbert-Diamond et al., 2011; Williams et al., 2007; Zhu et al., 2008). Arsenic may be naturally present at high levels in some soils (Smith et al., 2013), or it may enter agricultural systems through historical pesticide usage or high-As irrigation water (Smith et al., 1998). Under the reduced conditions typically associated with flooded rice cultivation, the more mobile As(III) form predominates over the strongly adsorbed As(V) form, resulting in higher soil solution As concentrations and greater uptake by rice plants (Zhao et al., 2010). Decreased grain As accumulation has been shown with AWD (Linquist et al., 2015a), since drying events alter the redox potential of the soil and reduce the mobility and uptake of As.

The reductions in CH_4 emissions, rice grain As concentrations, and irrigation water use, as well as the observed variability in rice grain yield associated with AWD, highlight both the value of AWD and the importance of evaluating it across a wide range of agricultural environments. In this study we sought to compare rice grain yield, yield response to N rate, CH_4 and N_2O emissions, and rice grain total As concentrations for conventional flood irrigation and two AWD treatments in high-yielding California irrigated rice systems. We hypothesized that with appropriate AWD management (careful timing of prolonged flooded periods and rewetting events), grain yield could be maintained at similar N rates while reducing grain total As concentrations and the GWP from rice cultivation.

2. Materials and methods

2.1. Study site description

This study was conducted at the Rice Experiment Station (39°27′47″N, 121°43′35″W) in Biggs, CA from June 2012 to March 2015, which comprised three growing seasons and two fallow seasons. Historical management in these fields consisted of continuously flooded rice cultivation during the growing season and a flooded period during the winter fallow. The soils at the study site are an Esquon-Neerdobe complex, classified as fine, smectitic, thermic, Xeric Epiaquerts and Duraquerts, with approximately 29% sand, 26% silt, and 45% clay, a pH of 5.3, 1.06% organic C, and 0.08% total N (Pittelkow et al., 2012). The soil total As, Cd, Fe, Mn, and Zn were 0.99 ppm, 0.08 ppm, 30800 ppm, 424 ppm, and 58.8 ppm, respectively. To measure these elements, the soil was digested using Aqua Regia; the cations were measured by flame atomic absorption and the total As was measured by hydride generation-inductively coupled plasma atomic emission spectrometry. Over the duration of the experiment, the area received an average of approximately 405 mm of rainfall annually (~30 mm during the growing season), with a mean winter air temperature of ~12 °C and a mean summer air temperature of ~23 °C (CIMIS 2015).

2.2. Treatments

Three water management treatments – drill-seeded with AWD (DS-AWD), water-seeded with AWD (WS-AWD), and water-seeded with conventional flood irrigation (control, WS-C) – were implemented in all three years on 0.3 ha field plots in a randomized complete block design with three replicates. The treatment layout in the main plots was maintained over the course of this experiment, so that each plot had the same water management treatment for three years. Bunds were compacted with heavy machinery in order to minimize lateral seepage, but as some lateral seepage could not be avoided, drainage ditches were constructed between plots to prevent flooded plots from affecting drained plots and vice versa. The volumetric water content (θ_V) was measured throughout the season for all three replicates of both AWD treatments using EC-10 soil moisture sensors placed vertically to a depth of 10 cm (Decagon Devices, Inc., Pullman, WA). For both WS treatments a continuous flood was initiated immediately after broadcast seeding (Table 1), which was done to simulate the conventional practice of aerial seeding in California. Pre-germinated seed is typically broadcast into flooded fields by airplane, but given the scale of this experiment, pre-germinated seed was broadcast onto dry fields with a tractor-mounted seeder and the fields were then promptly flooded. The WS-C treatment was continuously flooded (10–15 cm deep) until physiological maturity (Fig. 1A). The WS-AWD treatment was managed identically to the WS-C treatment (continuously flooded) until constant ceptometer measurements indicated that canopy closure was achieved (51 days after planting on average). This initial flooded period was included in the WS-AWD treatment since the timing of flooding is critically important for weed control (Tuong et al., 2005), and having complete canopy coverage reduces the potential for weed problems associated with draining a field; this also coincides with when complete fertilizer N uptake is observed in WS rice systems that are managed as outlined here (Linquist et al., 2006). After this point the floodwater was allowed to subside (via evapotranspiration and percolation), the soils were dried until the average θ_V of the three replicates reached 0.35 $m^3 m^{-3}$, and the plots were then re-flooded to the same 10–15 cm floodwater depth maintained in the WS-C treatment. Floodwater was held during anthesis and grain fill, as water stress at these times can result in yield reductions of 60–75% (Boonjung and Fukai, 1996); as a result,

Table 1
Dates of important management practices for the 2012–2014 rice growing seasons.

Management	2012			2013			2014		
	WS–C[a]	*WS–AWD*	*DS–AWD*	*WS–C*	*WS–AWD*	*DS–AWD*	*WS–C*	*WS–AWD*	*DS–AWD*
Planted	6 June	6 June	6 June	23 May	23 May	23 May	21 May	21 May	21 May
Fertilized	1 June	1 June	2 July	21 May	21 May	20 June	19 May	19 May	16 June
Flooded	7 June	7 June	–	25 May	25 May	–	25 May	25 May	–
Flushed	–	–	8 June	–	–	25 May	–	–	25 May
	–	–	20 June	–	–	6 June	–	–	6 June
DS Flood	–	–	20 July	–	–	20 June	–	–	16 June
AWD Flood	–	14 Aug.	13 Aug.	–	23 July	23 July	–	22 July	21 July
	–	28 Aug.	27 Aug.	–	15 Aug.	15 Aug.	–	13 Aug.	13 Aug.
	–	15 Sept.	14 Sept.	–	–	–	–	–	–
	–	1 Oct.	1 Oct.	–	–	–	–	–	–
Drained	NR[b]	NR	NR	14 Sept.	14 Sept.	20 Sept.	7 Sept.	7 Sept.	16 Sept.
Harvest	7 Nov.	7 Nov.	7 Nov.	11 Oct.	11 Oct.	11 Oct.	1 Oct.	1 Oct.	9 Oct.
Winter flood	19 Nov.	19 Nov.	19 Nov.	18 Nov.	19 Nov.	19 Nov.	21 Oct.	21 Oct.	21 Oct.

[a] The treatments are: water-seeded with conventional continuous flood irrigation (WS-C), water-seeded with alternate wetting and drying (WS-AWD), and drill-seeded with alternate wetting and drying (DS-AWD).
[b] Dates not recorded are indicated by "NR".

only two drain events comprised AWD water management in this experiment (Fig. 1B). Typical management for DS systems involves multiple flush irrigations (and/or rainfall) for stand establishment. In this experiment the DS-AWD treatment was flush irrigated twice after planting dry seed with a tractor-pulled drill seeder (Fig. 1C; Table 1); N fertilizer was applied approximately one month after planting and a flood was initiated immediately thereafter (also typical of DS systems). The initial flood period was maintained for 25–28 days to ensure complete fertilizer N uptake before the drying event and to achieve full canopy coverage as in the WS treatments. Water management in the DS-AWD treatment after canopy closure was the same as in the WS-AWD treatment, though the DS-AWD plots were drained for harvest a week later due to delayed maturity (Fig. 1; Table 1).

2.3. Field management

Fields were planted with the rice variety M206 in all years of the experiment at the standard grower rates of 112 kg ha^{-1} (DS) and 168 kg ha^{-1} (WS). Weed control was achieved using herbicide applications typical for these systems. In 2013 and 2014, N-trial subplots (3 by 6 m) were established in each main plot with N rates of 0, 60, 120, 180, and 240 kg N ha^{-1}, and the location of these subplots was changed between years. Fertilizer was surface-applied as urea and lightly incorporated into the soil in the WS plots prior to planting, while in the DS plots urea was broadcast approximately four weeks after planting and immediately prior to the extended flood period (Table 1; Fig. 1). All plots received 50 kg P_2O_5 ha^{-1} and 50 kg K_2O ha^{-1} prior to planting. The initial flood (or flush for DS-AWD) was initiated on May 25th in 2013 and 2014, and the fields were drained for harvest on September 14th or 20th in 2013 and September 7th or 16th in 2014, with the earlier dates corresponding to the WS plots and the later dates corresponding to the DS plots (Table 1). Grain yields were measured using a small plot combine (the harvest area was approximately 10 m^2) and adjusted to the standard 14% moisture content. Prior to the combine harvest, whole plant subsamples were taken from each N-trial plot, oven-dried, and the grain and the straw were separated for calculation of the harvest index. Following harvest the rice straw was lightly incorporated in all plots and the plots were subsequently flooded for the winter fallow season to facilitate rice straw decomposition (Linquist et al., 2006). Further management details and dates can be found in Table 1.

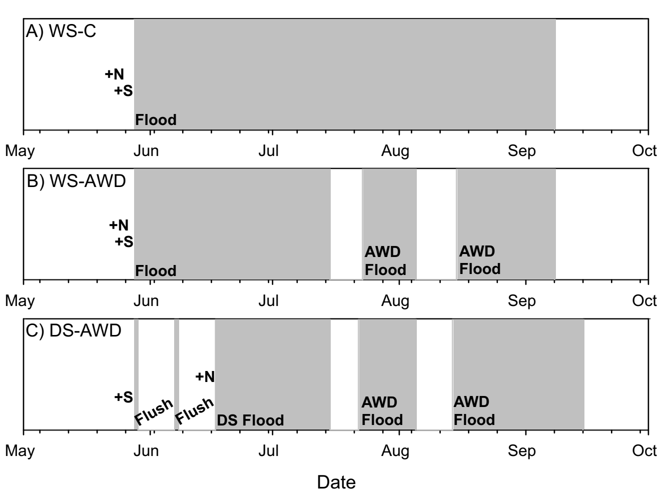

Fig. 1. Growing season water management for the three treatments: A) water-seeded with conventional continuous flood irrigation (WS-C), B) water-seeded with alternate wetting and drying (WS-AWD), and C) drill-seeded with alternate wetting and drying (DS-AWD). Gray shading indicates periods during which fields are flooded. Seeding and nitrogen fertilization are indicated by "+S" and "+N" respectively.

2.4. Soil analyses

During the 2014 growing season, soil samples were taken weekly from the 0 and 180 kg N ha^{-1} subplots in each main plot over a 5-week period that immediately followed N fertilization in the DS-AWD plots and included the first floodwater drain in the AWD plots. Samples were homogenized and stored on ice for less than 24 h before measurement of total soil extractable N (NH_4^+–N and NO_3^-–N). Three sub-samples (20 g) of each soil sample were added to 100 mL of 2 M KCl and mixed for one hour on a mechanical shaker. The solution was filtered through Whatman No. 42 filter paper (GE Healthcare UK Limited, Buckinghamshire, UK) and stored at 4 °C prior to colorimetric analysis for NH_4^+–N and NO_3^-–N on a spectrophotometer (Keeney and Nelson, 1982).

As field measurement of soil water potential was not practical due to the shrink-swell characteristics of the smectitic clays, a soil-moisture release curve was measured in the laboratory from 0 to 50 kPa on homogenized sieved soils using pressure cells according to methods adapted from Dane et al. (2002). In brief, a composite sample from all nine field plots was re-packed into three replicate cores, saturated for at least 48 h, and inserted into pressure cells connected to a pressurized gas cylinder at the top and a 100 kPa ceramic plate and a volumetric cylinder at the bottom; the volume of water released by the cores was measured as the pressure was increased in 5 kPa steps and enough time passed between pressure steps for hydraulic equilibrium to be achieved. The mean soil θ_V was just above 0.35 $m^3 m^{-3}$ at a water potential of −50 kPa (unpublished results), which is consistent with published estimates of soil-water characteristics for similarly textured soils (Saxton and Rawls, 2006).

2.5. Arsenic analysis

Milled rice grain samples were ground to a fine powder using a UDY Cyclone Sample Mill (UDY Corporation, Fort Collins, CO). Samples were mixed with 5 mL of HNO_3, 2 mL 25% HCl, and 1.5 mL H_2O and digested in a Milestone Ultrawave microwave system pressurized to 40 bar, slowly ramping to 260 °C and holding for 25 min (pressure in the chamber during digestion will reach 130 bar), cooled, and diluted to 15 mL volume with deionized water. This method has been shown to recover all of the organic As by hydrolysis, while cooler temperatures may not hydrolyze DMA-As. Total As in the digests was measured using hydride generation. An aliquot of the digest was transferred to a separate tube, and 3 mL of 5% potassium iodide/5% ascorbic acid, 2.5 mL of 1.73 M sulfamic acid, and 1.5 mL concentrated HCl were mixed with 4 mL of the sample to reduce all arsenate to arsenite. Using a mixing block, the pre-reduced solutions are combined with 0.5% sodium borohydride in 0.05% sodium hydroxide in order to analyze for total As using a flow injection hydride generation system with inductively coupled plasma-atomic emission spectrometry. NIST and other standard reference materials with certified total As concentrations were analyzed with all batches of samples, as were blanks; testing of the recovery of As from spiked samples and blanks was also conducted. All quality assurance checks were within the normal variance range of the standards.

2.6. Greenhouse gas measurements and flux calculations

Greenhouse gas samples were taken daily to weekly during the 2013 and 2014 growing seasons, and daily to monthly during the winter fallow seasons. During periods of high variability, such as floodwater drain events, sampling was conducted every day or every other day. Closed vented flux chambers were used for gas sampling, which consisted of a permanent base installed prior to each field season, a variable-height extension to accommodate rice plants, and a sealed chamber with a vent tube for pressure equalization (Adviento-Borbe et al., 2013; Pittelkow et al., 2012). Gas samples (25 mL) were taken through silicon septa at 21, 42, and 63 min and injected into pre-evacuated 12.5-mL glass vials (Labco Ltd., Buckinghamsire, UK). Four ambient gas samples were also taken at 0 min during each sampling event. Gas sampling was conducted between 09:00 and 12:00 h, as soil temperatures and gas fluxes are expected to be representative of their average daily values during this time period (Adviento-Borbe et al., 2013). In order to minimize the effects of intensive gas sampling on the rice plants, two collars were installed per main plot and sampling alternated between collars. Boardwalks were established prior to each field season so as to minimize soil compaction and prevent artificially inflated flux values. A more complete discussion of the sampling protocol for GHG flux measurements can be found in Adviento-Borbe et al. (2013).

All samples were analyzed for CH_4 and N_2O peak area on a GC-2014 gas chromatograph equipped with a ^{63}Ni electron capture detector set at 325 °C for N_2O concentrations and a flame-ionization detector (FID) for CH_4 concentrations (Shimadzu Scientific, Inst, Columbia, MD, USA). Nitrous oxide was separated by a stainless steel column packed with Hayesep D, 80/100 mesh at 75 °C. The detection limits of the GC instrument were 2.2 pg s^{-1} for CH_4 and 0.3 pg s^{-1} for N_2O. Results of the GC analyses were accepted if voltage output produced a linear relationship with the gas concentrations of CH_4 and N_2O standards with $r^2 > 0.99$ (1, 3.05, and 9.95 ppm for N_2O; 1.8, 10.18, 19.7, 100, 503, and 1020 ppm for CH_4); the peak area for each gas sample was then converted to a concentration based on this linear relationship. Fluxes were estimated from the linear increase of gas concentration over time, and gas concentrations were converted to elemental mass per unit area (g $ha^{-1} d^{-1}$) using the Ideal Gas Law with the chamber volume measured at each sampling event, the chamber air temperature measured as each gas sample was taken, and an atmospheric pressure of 0.101 MPa. Fluxes of CH_4 and N_2O were computed as:

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

where F is the gas flux rate (g N_2O–N or CH_4–C $ha^{-1} d^{-1}$), $\Delta C/\Delta t$ denotes the increase or decrease (N_2O only) of gas concentration in the chamber (g $L^{-1} d^{-1}$), V is the chamber volume (L), A is area covered by the chamber (ha), and α is a conversion coefficient for elemental C ($\alpha = 0.749$) or N ($\alpha = 0.636$). For N_2O, a t-test was used to determine if each gas flux was significantly different from zero at $p < 0.05$. Similar to other studies (Adviento-Borbe et al., 2013; Linquist et al., 2015a; Pittelkow et al., 2012), gas fluxes with a linear correlation below a predetermined threshold ($r^2 \geq 0.9$) 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 with linear interpolation to calculate cumulative seasonal emissions (spring tillage to harvest), cumulative fallow season emissions (non-growing season emissions), and cumulative annual emissions.

2.7. Data analysis

All data met the assumptions of normality and homogeneity of variance without transformation. Growing season GWP, fallow season GWP, and annual GWP were calculated for a 100-yr time horizon using radiative forcing potentials with climate-carbon feedbacks relative to CO_2 of 34 and 298 for CH_4 and N_2O respectively (Myhre et al., 2013). Yield-scaled GWP (GWP_Y) was calculated as the ratio of growing season GWP (kg CO_2-eq ha^{-1}) to grain yield (Mg ha^{-1}). We used PROC MIXED in SAS® software Version 9.4 for analysis of variance on cumulative growing season, fallow season, and annual CH_4 emissions, N_2O emissions, and GWP with an adjusted Tukey means separation (SAS Institute Inc., 2013). The year was included as a repeated effect as the treatment layout was maintained over the course of this experiment. The same model was used for analysis of variance and means separation on grain total As concentrations, rice grain yield, and yield-scaled GWP, though grain yield was analyzed separately for each year due to a significant year by treatment interaction. The water management treatment (DS-AWD, WS-AWD, WS-C) was included as a fixed effect, block and the block by treatment interaction were included as random effects, and other interactions were included to the degree that it minimized the corrected Akaike Information Criteria (AICC).

3. Results and discussion

3.1. Water management and grain yield

The yield potential was the same for all water management treatments (10–11 Mg ha^{-1}) in both years that the yield response to N rate was evaluated (Fig. 2). Rice grain yields at the conventional N rate of 180 kg N ha^{-1} were similar for all water management

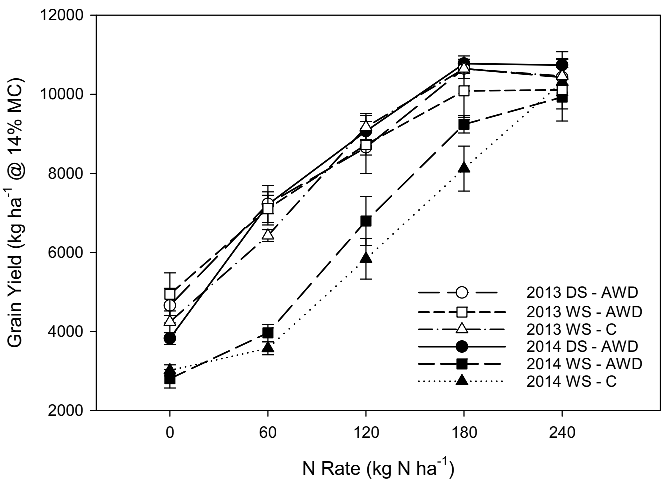

Fig. 2. Nitrogen response curves for the three water management treatments (water-seeded with conventional continuous flood irrigation (WS-C), water-seeded with alternate wetting and drying (WS-AWD), and drill-seeded with alternate wetting and drying (DS-AWD)) during the 2013 and 2014 growing seasons. Grain yields are standardized to 14 percent moisture content and error bars represent the standard error of the mean grain yield at each N application rate.

treatments in 2012 and 2013 (average = 9.86 and 10.46 Mg ha^{-1} respectively), whereas in 2014 the grain yield in the DS-AWD treatment was significantly higher (10.78 Mg ha^{-1}) than in the WS-C treatment (8.12 Mg ha^{-1}; Table 2). The reported effect of AWD on grain yield is highly variable: while some studies have shown that AWD can decrease rice grain yield (Linquist et al., 2015a; Xu et al., 2015), many other studies have shown no change in yield (Belder et al., 2004; Dong et al., 2012; Pandey et al., 2014; Yao et al., 2012) or even an increase in yield with AWD (Liu et al., 2013). This variable yield response to AWD is not surprising given the wide range of water management regimes that are classified as AWD, and the importance of AWD severity and timing in determining grain yields (Boonjung and Fukai, 1996). For example, a field experiment in China showed that allowing sandy loam soils to dry to −15 kPa prior to rewetting increased grain yield by 11%, but yield was reduced by 32% when fields were allowed to dry to −30 kPa before rewetting (Zhang et al., 2009). Similarly, the practice of "safe AWD" promoted by the International Rice Research Institute uses a water level of −15 cm (>−10 kPa) in perforated field water tubes as the threshold for rewetting in order to avoid a yield penalty (Bouman et al., 2007). This threshold has been supported by many field observations (Dong et al., 2012; Pandey et al., 2014; Yao et al., 2012), though in rare cases yield reductions have been observed with even less severe drying regimes (Lagomarsino et al., 2016). Yield reductions have frequently been observed with more severe drying regimes (Bouman and Tuong, 2001; Linquist et al., 2015a; Xu et al., 2015).

In this study the AWD treatments involved rewetting when the θ_V dropped to 0.35 $m^3 m^{-3}$; in contrast, the yield decrease with AWD reported by Linquist et al. (2015a) involved rewetting fields at a θ_V of 0.16–0.24 $m^3 m^{-3}$. No yield decline was observed in our study as a result of this higher minimum soil water content (Table 2). While soil θ_V is a relatively easy measurement for management decisions, soil water potential better describes the soil water status with respect to plant uptake and stress (Hillel, 2004). The soil θ_V at rewetting in our study corresponded to a lower soil water potential (−50 kPa) and thus a more severe AWD regime than that in many studies that reported a yield loss with AWD (Bouman and Tuong, 2001; Xu et al., 2015; Zhang et al., 2009). Differences in varietal response to AWD management may offer one explanation for this contradiction, as observed by Xu et al. (2015) in response to the same intermittent irrigation treatments. Nonetheless, this variable yield response to soil water potential is a significant obstacle to AWD adoption, as it makes it difficult to determine a precise threshold soil water potential for rewetting in order to prevent a yield penalty. Furthermore, soil water status can be highly heterogeneous even within fields at the scale of commercial rice production, which may result in variable yields. Targeted research is needed to adapt AWD regimes to local production environments and field scales in order to reduce risk-related barriers to AWD adoption.

3.2. Nitrogen management

The agronomic and economic performance of an AWD production system is tied not only to optimal grain yields, but also to the N rates required to achieve these yields. The N response curves were similar for all treatments in 2013, with yield increases observed until 180 kg N ha^{-1}, and no further increase in yield at higher N rates (Fig. 2). In 2014 however, both WS treatments showed yield increases up to 240 kg N ha^{-1}, while the DS-AWD treatment obtained its maximum yield at 180 kg N ha^{-1} (Fig. 2). Although the yield potential was the same for all treatments in each year, in 2014 the WS treatments thus required approximately 60 kg N ha^{-1} more fertilizer to achieve this yield (Fig. 2; Table 2). Bufogle et al. (1997) reported increased fertilizer N recovery in DS systems, but more recent work in California with similar early-maturing medium grain varieties (M-202, M206) has shown no significant differences in optimal N rates between DS and WS systems (Pittelkow et al., 2012; Pittelkow et al., 2014a). Lower grain yields in the WS treatments were observed even in the zero N subplots (Fig. 2), suggesting that indigenous soil N may have been lost from the WS treatments by denitrification or by nitrate leaching with deep percolation. Denitrification can be a significant

Table 2
Rice grain yield, growing season GWP, and yield-scaled GWP at the conventional N rate of 180 kg N ha^{-1} for the 2012–2014 growing seasons.

Treatment[b]	Yield[a] (Mg ha^{-1})			Growing Season GWP (kg CO_2-eq ha^{-1})			GWP-Y (kg CO_2-eq Mg^{-1})		
	2012	2013	2014	2013	2014	Mean	2013	2014	Mean
WS–C	9.94[c] a (0.919)	10.7 *a* (0.241)	8.12 *b* (0.568)	5518 (1143)	6553 (884)	6035 *a*	516 (101)	818 (137)	667 *a*
WS–AWD	10.6 *a* (0.409)	10.1 *a* (0.670)	9.24 *ab* (0.219)	2387 (574)	2334 (797)	2361 *b*	245 (67.6)	257 (94.1)	251 *b*
DS–AWD	9.04 *a* (1.02)	10.7 *a* (0.123)	10.8 *a* (0.195)	819 (67.1)	987 (231)	903 *b*	77.0 (6.63)	91.5 (20.9)	84.3 *b*

[a] Grain yield was analyzed separately for each year due to a significant year by treatment interaction.
[b] The treatments are: water-seeded with conventional continuous flood irrigation (WS-C), water-seeded with alternate wetting and drying (WS-AWD), and drill-seeded with alternate wetting and drying (DS-AWD).
[c] The standard error of the mean for each value is indicated in parentheses and values followed by the same letter are not significantly different at $p < 0.05$.

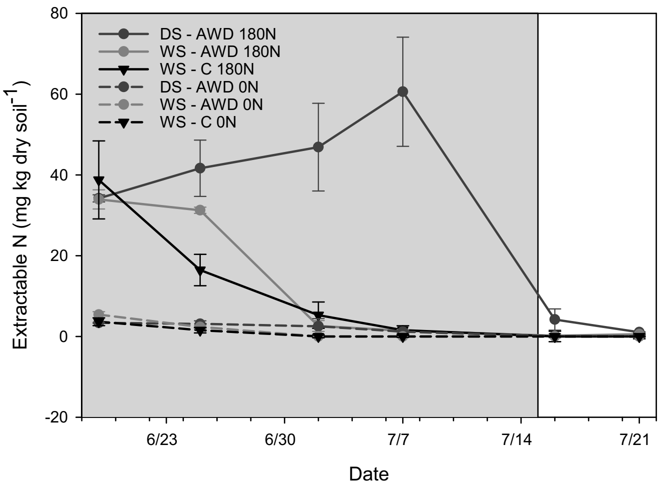

Fig. 3. Total soil extractable N content (NH_4^+–N and NO_3^-–N) during the 2014 growing season in the 0 N and 180 N subplots for all three main plot treatments. Error bars represent the standard error of the mean. The treatments are: water-seeded with conventional continuous flood irrigation (WS-C), water-seeded with alternate wetting and drying (WS-AWD), and drill-seeded with alternate wetting and drying (DS-AWD). Fertilizer N application was done on 6/16 in the drill-seeded plots and on 5/19 in the water-seeded plots. Gray or white shading indicate dates during which the AWD plots were flooded or drained respectively.

loss pathway under flooded conditions if relatively high nitrate concentrations are present before flooding (Buresh et al., 2008). Nitrate leaching can also be an important loss pathway in rice fields where high water losses from deep percolation are observed (Chowdary et al., 2004), though previous studies in conventionally irrigated California rice systems have shown that nitrate leaching is minimal and that combined losses from deep percolation and lateral seepage represent less than 15 percent of total water inputs (Liang et al., 2014; Linquist et al., 2015b).

The introduction of aerobic cycles with AWD has the potential to increase N losses due to increased nitrification and subsequent denitrification (Cai et al., 1997; Cai et al., 1999). It is therefore critical that soil inorganic N levels are low prior to initiating AWD water management in order to avoid these types of losses. Soil extractable N levels were measured in the 0 N and 180 N subplots of all treatments during the 2014 growing season (Fig. 3). Soil N levels in the 180 N subplots dropped to almost zero before the floodwater completely subsided (approximately 49 and 29 days after N fertilization in the WS and DS treatments respectively). This synchronization of water management with soil N levels resulted in minimal N losses during the aerobic drying cycles, as evidenced by negligible N_2O emissions during the drying cycles (Fig. 4). Importantly, neither AWD system (DS or WS) required increased N rates to achieve optimal yields relative to the conventional (WS-C) treatment.

3.3. Greenhouse gas emissions and global warming potential

Methane dominated the annual GWP of all three water management treatments during both years (94% on average), with its contribution ranging from 86% (DS-AWD) to 99% (WS-C; Table 3). During the growing season, daily CH_4 emissions in the WS-C plots increased to 87 kg CO_2-eq. ha^{-1} by August 5th in 2013 and to 80 kg CO_2-eq. ha^{-1} by July 16th in 2014, after which point emissions began to decline (Fig. 4 A–B). Growing season CH_4 emissions in the WS-C treatment were 133 kg CH_4-C ha^{-1} when averaged between years (Table 3), which is in good agreement with the global 100 kg CH_4-C ha^{-1} average reported in a meta-analysis by Linquist et al. (2012). Growing season CH_4 emissions ranging from 11 to 338 kg CH_4-C ha^{-1} have been reported for California rice systems (Pittelkow et al., 2013; Pittelkow et al., 2014a; Simmonds et al., 2015).

The DS-AWD and WS-AWD treatments reduced growing season CH_4 emissions by 87% and 60% respectively (Table 3), due to the introduction of aerobic conditions by the first AWD drain event and negligible subsequent CH_4 emissions (Fig. 4 C–F). A significant portion of growing season CH_4 emissions, 10% on average, comes from a spike in CH_4 emissions during the end-of-season drain (Adviento-Borbe et al., 2015). While this was observed both years in the WS-C treatment, minimal CH_4 emission spikes were observed in the AWD treatments (Fig. 4). The reduction in growing season CH_4 emissions in the AWD treatments can therefore be attributed to negligible CH_4 emissions following the first drying event and greatly reduced end-of-season CH_4 spikes (Fig. 4; Table 3). The 66% reduction in growing season CH_4 emissions observed in the DS-AWD treatment relative to the WS-AWD treatment can likely be attributed to intermittent aerobic conditions in the DS plots during flush irrigation for crop establishment (Fig. 4; Table 3); a similar 47% reduction in growing season CH_4 emissions over WS systems was seen in continuously flooded DS California rice systems (Pittelkow et al., 2014a).

While AWD consistently decreases growing season CH_4 emissions, N_2O emissions usually increase and can negate the reduction in GWP from reduced CH_4 emissions (Akiyama et al., 2005; Lagomarsino et al., 2016). Although nitrification is normally minimal in conventionally flooded fields, limiting N_2O loss as a by-product of both nitrification and denitrification, the introduction of aerobic periods could allow for nitrification of fertilizer NH_4^+ and thus greater denitrification losses (Buresh et al., 2008). Coordination of water management and N application timing is therefore required to prevent high N_2O emissions from offsetting reductions in GWP. In this experiment, all plots were flooded after N application and remained flooded until soil extractable N levels dropped to approximately zero (Fig. 3); as a result subsequent N_2O emissions were negligible (Fig. 4A–F). Some N_2O peaks were observed after the first two flush irrigation events for crop establishment in the DS-AWD treatment in 2014 (Fig. 4F), though these peaks accounted for only 11% of growing season GWP (Table 3). In contrast, N_2O fluxes were negligible (with the system possibly acting as a sink) during the growing season in the WS-AWD and WS-C treatments (Table 3).

Fallow season emissions can account for a significant fraction of annual GHG emissions from rice systems. No significant differences in fallow season CH_4 emissions were observed among treatments in this study, indicating that the effects of AWD on CH_4 emissions do not extend beyond the growing season (Table 3). Although CH_4 emissions during this flooded winter fallow period were generally low and relatively constant, spikes were observed during the spring drain for most treatment-year combinations (Fig. 4 G–H). Fallow season CH_4 emissions accounted for 22% of annual CH_4 emissions in the WS-C treatment; this compares to an average of 20% and a 5–55% range reported in similar California rice systems (Adviento-Borbe et al., 2013; Fitzgerald et al., 2000; Pittelkow et al., 2013; Pittelkow et al., 2014a). Due to lower growing season CH_4 emissions, fallow season emissions accounted for 27% and 53% of annual CH_4 emissions in the WS-AWD and DS-AWD treatments respectively (Table 3). Fallow season N_2O emissions peaked after floodwater was drained in the spring and were similar between treatments, comprising 68% of annual N_2O emissions in the DS-AWD treatment and 100% of annual N_2O emissions in the WS treatments (Fig. 4 G–H; Table 3). Fallow season emissions comprised 36% of annual GWP on average, ranging from 22% in the WS-C treatment to 55% in the DS-AWD treatment. In comparison, Adviento-Borbe et al. (2013) reported

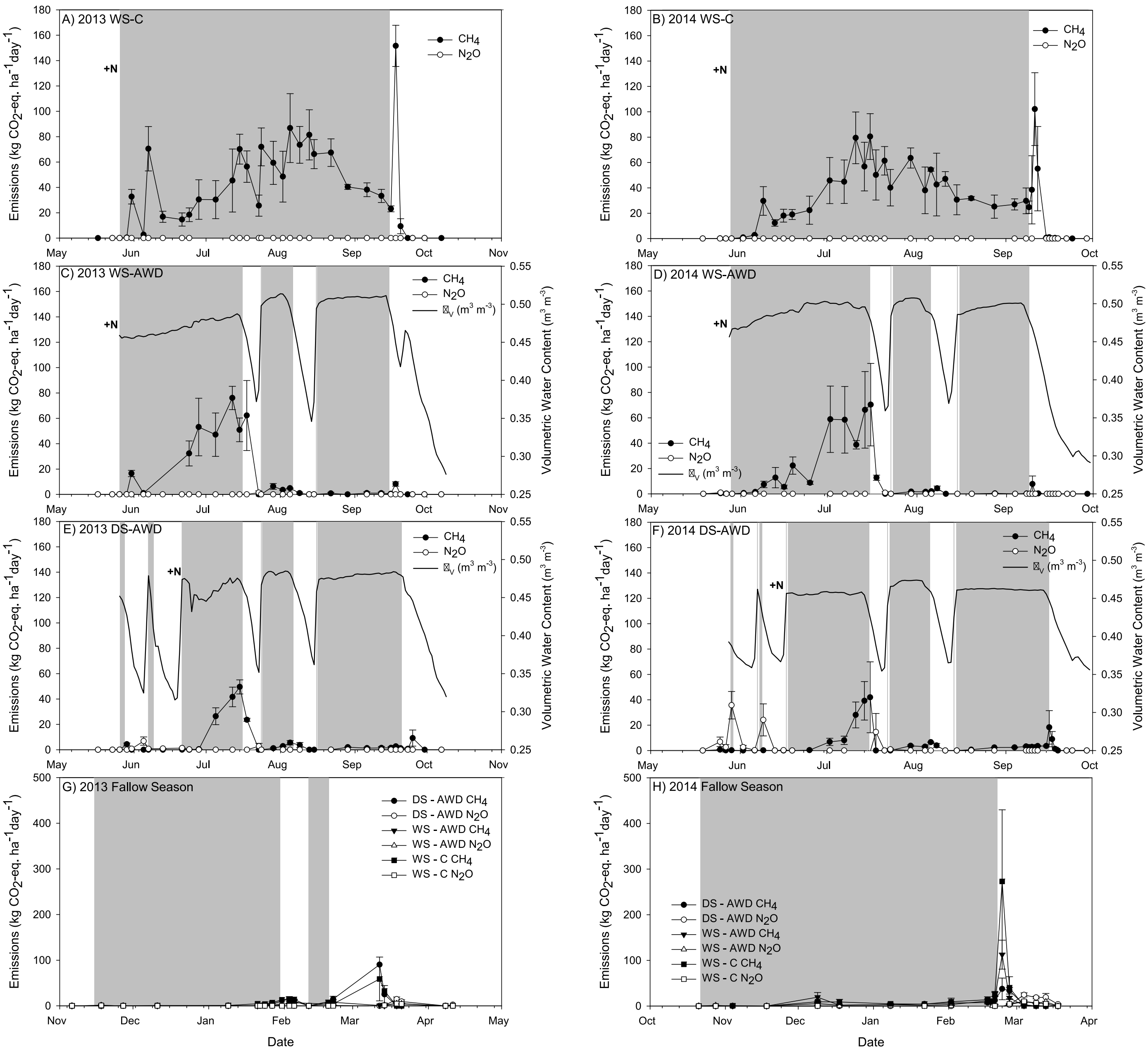

Fig. 4. Methane (CH_4) and nitrous oxide (N_2O) emissions during the growing season (A–F) and winter fallow period (G–H) for 2013–2014 and 2014–2015. Error bars represent the standard error of the mean and “N” indicates fertilization with urea. The treatments are: water-seeded with conventional continuous flood irrigation (WS-C), water-seeded with alternate wetting and drying (WS-AWD), and drill-seeded with alternate wetting and drying (DS-AWD). The average volumetric water content (θ_V) of each AWD treatment is also shown throughout the growing season and gray shading indicates periods during which fields are flooded. Note that the scale for the fallow season plots is different in order to accommodate the spike in CH_4 emissions during the spring drain.

that fallow season emissions accounted for approximately 13% of GWP in conventional flooded California rice systems.

Annual CH_4 emissions were reduced by 57–78% in the AWD treatments, with the greatest reduction corresponding to the DS-AWD treatment (Table 3). Annual N_2O emissions represented only 0.6%, 2.0%, and 14% of annual GWP in the WS-C, WS-AWD, and DS-AWD treatments respectively; except for the DS-AWD treatment, the N_2O emissions as a percent of annual GWP were lower than the 10–18% reported for conventional flooded systems (Linquist et al., 2012; Pittelkow et al., 2014b). As CH_4 was therefore the dominant GHG emitted from all treatments, a 57–74% decrease in annual GWP was observed with AWD (Table 3). Given the growing global food demand, it is increasingly important to evaluate agricultural GHG emissions with respect to crop productivity (Pittelkow et al., 2014b). The yield-scaled GWP was reduced by 59–88% with AWD as a result of similar grain yields among all treatments (Table 2). These reductions in GWP are similar to those reported by other studies, though the magnitude of the reduction depends on the specific AWD regime (Linquist et al., 2015a; Pandey et al., 2014; Xu et al., 2015).

3.4. Rice grain arsenic

Milled rice grain total As concentrations in the WS-C treatment were similar between years (average = 0.114 mg kg^{-1}; Table 4), and comparable to the average grain total As concentration of 0.13 mg kg^{-1} reported for California, but lower than the reported U.S. average of 0.19 mg kg^{-1} (Zavala and Duxbury, 2008). Brown

Table 3
Growing season, fallow season, and annual cumulative CH_4 emissions, N_2O emissions, and GWP for 2013 and 2014, with growing season emissions measured in the 180 kg N ha^{-1} subplots.

Treatment[a]	Growing Season		Fallow Season		Annual		
	CH_4 (kg CH_4-C ha^{-1})	N_2O (kg N_2O-N ha^{-1})	CH_4 (kg CH_4-C ha^{-1})	N_2O (kg N_2O-N ha^{-1})	CH_4 (kg CH_4-C ha^{-1})	N_2O (kg N_2O-N ha^{-1})	GWP (kg CO_2-eq ha^{-1})
2013							
WS–C	122[b]	−0.022	17.1	0.126	139	0.103	6354
	(25.3)	(0.012)	(9.36)	(0.047)	(21.4)	(0.048)	(951)
WS–AWD	53.0	−0.038	7.81	0.199	60.8	0.161	2835
	(12.6)	(0.003)	(1.93)	(0.042)	(13.0)	(0.038)	(572)
DS–AWD	17.0	0.103	15.4	0.387	32.4	0.490	1702
	(2.10)	(0.069)	(8.10)	(0.162)	(6.00)	(0.231)	(373)
2014							
WS–C	145	−0.025	65.7	0.126	210	0.101	9596
	(19.7)	(0.020)	(21.5)	(0.051)	(38.9)	(0.034)	(1783)
WS–AWD	51.7	−0.028	36.6	0.149	88.3	0.122	4067
	(17.6)	(0.001)	(8.12)	(0.013)	(24.8)	(0.012)	(1132)
DS–AWD	18.4	0.320	25.5	0.422	44.0	0.743	2345
	(6.27)	(0.139)	(2.82)	(0.079)	(8.13)	(0.217)	(303)
Means							
WS–C	133[c] *a*	−0.024 *a*	41.4 *a*	0.126 *a*	175 *a*	0.102 *a*	7975 *a*
WS–AWD	52.3 *b*	−0.033 *a*	22.2 *a*	0.174 *a*	74.5 *ab*	0.142 *a*	3451 *ab*
DS–AWD	17.7 *b*	0.212 *a*	20.5 *a*	0.405 *a*	38.2 *b*	0.616 *a*	2023 *b*

[a] The treatments are: water-seeded with conventional continuous flood irrigation (WS-C), water-seeded with alternate wetting and drying (WS-AWD), and drill-seeded with alternate wetting and drying (DS-AWD).
[b] The standard error of the mean for each value is indicated in parentheses.
[c] For each emissions category values followed by the same letter are not significantly different at $p < 0.05$.

rice grain total As concentrations were 31% higher on average (WS-C average = 0.143 mg kg^{-1}; Table 4), which is consistent with other studies showing preferential accumulation of As in the rice bran and a higher percentage of inorganic As in brown rice (Meharg et al., 2008; Zhao et al., 2010). Although the U.S. Food and Drug Administration noted that the As levels found in rice samples were too low to cause any short-term adverse health effects, the effects of long-term exposure are less clear (FDA, 2013). The FDA has not yet set regulatory limits for rice grain As, but the Food and Agriculture Organization of the United Nations and the World Health Organization have set voluntary recommended inorganic As limits for polished (milled) rice at 0.2 mg kg^{-1} (Codex Alimentarius Commission, 2014). While the total grain As values in our study are below this limit regardless of the treatment, it is nevertheless important to have agronomic strategies to reduce rice grain As concentrations. Aerobic periods introduced by AWD would favor the oxidation of As(III) to As(V), which is less mobile and thus less bioavailable for uptake and incorporation into the rice grain (Arao et al., 2009; Zhao et al., 2010). The DS-AWD treatment reduced grain total As concentrations by 57% for brown rice and by 59% for milled rice, while the WS-AWD reduced grain total As by 63% and 65% for brown and milled rice respectively (Table 4). This reduction has been confirmed by other studies and suggests that AWD may be a viable option to reduce rice grain As concentrations (Hu et al., 2013; Linquist et al., 2015a).

Results from this study and others indicate that the timing of AWD drain events may have an important effect on grain As concentration. This study suggests that late-season drain events have a greater impact on lowering grain As concentration than early-season drains, as evidenced by the similar grain total As concentrations in the DS-AWD and WS-AWD treatments despite primarily aerobic soils in the DS-AWD treatment during the first month of the season and flooded anaerobic soils in the WS-AWD treatment (Fig. 1; Table 4). Early season AWD followed by continuous flooding similarly resulted in grain total As levels comparable to continuous flooding (Linquist et al., 2015a). Arao et al. (2009) also showed that flooding late in the season (after heading in this case) increased inorganic As levels more than flooding early in the season (before heading). Root and shoot total As generally decrease from early tillering to grain fill, which suggests at least some early season uptake and translocation (Hu et al., 2013). Nevertheless, intermittent irrigation following the

Table 4
Grain total As concentrations for milled and brown rice samples harvested during the 2013 and 2014 growing seasons.

Treatment[a]	Grain total arsenic (mg kg^{-1}) 2013		2014		Means	
	Brown Rice	*Milled Rice*	*Brown Rice*	*Milled Rice*	*Brown Rice*	*Milled Rice*
WS–C	0.136[b]	0.103	0.149	0.125	0.143[c] *a*	0.114 *a*
	(0.016)	(0.018)	(0.017)	(0.015)		
WS–AWD	0.054	0.037	0.051	0.041	0.053 *b*	0.039 *b*
	(0.005)	(0.002)	(0.004)	(0.004)		
DS–AWD	0.056	0.043	0.067	0.050	0.061 *b*	0.046 *b*
	(0.004)	(0.001)	(0.006)	(0.005)		

[a] The treatments are: water-seeded with conventional continuous flood irrigation (WS-C), water-seeded with alternate wetting and drying (WS-AWD), and drill-seeded with alternate wetting and drying (DS-AWD).
[b] The standard error of the mean for each value is indicated in parentheses.
[c] For each category values followed by the same letter are not significantly different at $p < 0.05$.

start of reproductive growth decreased brown rice As concentrations relative to continuous flooding by almost as much as season-long intermittent irrigation (Hu et al., 2013).

4. Conclusions

In this experiment it was found that AWD has the potential to minimize the environmental impacts of rice cultivation while maintaining optimal agronomic performance in high-yielding California rice systems. While other studies have shown that AWD can reduce GHG emissions, water use, and grain As, this has frequently come at the expense of reduced grain yield. In contrast, the AWD treatments in this study significantly reduced GHG emissions and grain total As with no reduction in grain yield. Despite these potential benefits, there are significant obstacles to the adoption of AWD in California and across the U.S.—principally limited information on AWD management at large scales and the risk of yield loss with improper management. With research focused on adapting AWD to field scales, adoption of AWD has the potential to accomplish multiple agronomic and environmental objectives, and should be considered as a viable option for GHG mitigation and rice grain As reduction.

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