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Reducing greenhouse gas emissions, water use, and grain arsenic levels in rice systems

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Abstract

Agriculture is faced with the challenge of providing healthy food for a growing population at minimal environmental cost. Rice (*Oryza sativa*), the staple crop for the largest number of people on earth, is grown under flooded soil conditions and uses more water and has higher greenhouse gas (GHG) emissions than most crops. The objective of this study was to test the hypothesis that alternate wetting and drying (AWD – flooding the soil and then allowing to dry down before being reflooded) water management practices will maintain grain yields and concurrently reduce water use, greenhouse gas emissions and arsenic (As) levels in rice. Various treatments ranging in frequency and duration of AWD practices were evaluated at three locations over 2 years. Relative to the flooded control treatment and depending on the AWD treatment, yields were reduced by <1–13%; water-use efficiency was improved by 18–63%, global warming potential (GWP of CH_4 and N_2O emissions) reduced by 45–90%, and grain As concentrations reduced by up to 64%. In general, as the severity of AWD increased by allowing the soil to dry out more between flood events, yields declined while the other benefits increased. The reduction in GWP was mostly attributed to a reduction in CH_4 emissions as changes in N_2O emissions were minimal among treatments. When AWD was practiced early in the growing season followed by flooding for remainder of season, similar yields as the flooded control were obtained but reduced water use (18%), GWP (45%) and yield-scaled GWP (45%); although grain As concentrations were similar or higher. This highlights that multiple environmental benefits can be realized without sacrificing yield but there may be trade-offs to consider. Importantly, adoption of these practices will require that they are economically attractive and can be adapted to field scales.

Keywords: alternate wetting and drying, arsenic, greenhouse gas emissions, irrigation management, *Oryza sativa*, sustainable intensification, water-use efficiency

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Introduction

Agriculture faces the tremendous challenge in the coming decades of providing healthy food for a growing population while minimizing environmental consequences. Some estimate that crop production will need to double (2.4% annual increase) by the year 2050 to meet global demand (Ray *et al*., 2013); however, an analysis of crop yield trends show that these needs will not be met at the current rate of increase (Grassini *et al*., 2013; Ray *et al*., 2013). Agricultural intensification, whereby higher yields per unit of land area are realized, is considered necessary to achieve this goal (Burney *et al*., 2010; Godfray *et al*., 2011; Godfray & Garnett, 2014); however, intensification can have environmental costs such as nonpoint source pollution and increased greenhouse gas (GHG) emissions (Matson *et al*., 1997; Vitousek *et al*., 1997; Tilman, 1999). This has lead the push for sustainable intensification (Godfray *et al*., 2011) whereby higher yields are achieved without (or with reduced) damage to the environment – meeting the dual goals of protecting natural resources while ensuring global food security. Increased production also implies increased demand for water. Irrigation is by far the largest component of anthropogenic demand for fresh water (Haddeland *et al*., 2014). Drought, along with high water use, is depleting water reserves in many parts of the world and water scarcity problems will only increase due to climate change (Schewe *et al*., 2014).

Rice is the staple crop for the largest number of people on earth (Maclean *et al*., 2002). Because rice is usually grown under flooded conditions it uses more

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water than most crops and has higher global warming potential (GWP) of GHG emissions – particularly due to high CH_4 emissions (Linquist *et al.*, 2012). Yield-scaled GWP (GWP_Y) is a metric that assesses the GWP per unit of yield (van Groenigen *et al.*, 2010). It is useful for accessing a system's ability to address the dual goals of sustainable intensification: protecting natural resources while ensuring global food security (e.g., Pittelkow *et al.*, 2014 in rice systems). Accounting for both CH_4 and N_2O, rice systems also have higher GWP_Y than other cereals (Linquist *et al.*, 2012) indicating they emit more GHG emissions per unit of yield. Furthermore, there have been recent health concerns related to grain arsenic (As) concentrations (Mandal & Suzuki, 2002; Banerjee *et al.*, 2013). Under the flooded, anaerobic soil conditions As is reduced from As (V) to As (III) (Takahashi *et al.*, 2004) which increases its phytoavailability and uptake by rice (Ma *et al.*, 2008; Zhao *et al.*, 2010). In certain parts of the world, grain As concentrations are high and have been shown to have adverse health effects (Mandal & Suzuki, 2002)

These concerns related to rice can be addressed by changing water management from continuously flooded anaerobic systems to those in which aerobic cycles are introduced periodically during the growing season. This is often referred to as alternate wetting and drying (AWD), and involves flooding fields followed by allowing them drying down to the desired moisture content through evapotranspiration and percolation before reflooding. Altering soil chemistry and flooding practices through the introduction of aerobic periods during the growing season can lead to reduced water use (Belder *et al.*, 2004; De Vries *et al.*, 2010; Yao *et al.*, 2012; Liu *et al.*, 2013), reduced GWP of GHG fluxes (Yan *et al.*, 2005; Feng *et al.*, 2013) and reduced As concentrations in rice grain (Takahashi *et al.*, 2004; Xu *et al.*, 2008; Talukder *et al.*, 2012). Key to addressing food security needs, some have reported that yields can be maintained in these AWD systems (Belder *et al.*, 2004; De Vries *et al.*, 2010; Yao *et al.*, 2012).

Various studies have investigated benefits associated with AWD management in rice systems separately; however, our objective was to evaluate these multiple benefits of AWD in a single study. It is important that AWD is effective in high yielding environments; however, AWD has not been evaluated in the US where average yields are higher than in most other regions of the world (e.g., 2012 US rice yields averaged 8.35 Mg ha^{-1} compared to 4.49 Mg ha^{-1} for Asia; FAO http://faostat3.fao.org/faostat-gateway/go/to/download/Q/QC/E) and cultural practices are different (e.g., direct-seeded as opposed to transplanted as is common in Asia). To accomplish this objective three field studies were conducted to test the hypothesis that AWD water management practices will maintain rice yields while reducing water use, GWP and grain As levels.

Materials and methods

Site description

In 2012 and 2013 experiments were carried out at the University of Arkansas Rice Research and Extension Center near Stuttgart (N 34°27′ latitude; W 091°24′ longitude). The experiments were conducted in separate fields with different crop rotations: rice–rice (RR) and rice-soybean (RS). Experiments in RS rotations were evaluated in 2012 and 2013 and a RR rotation (in rice cultivation since 2011) in 2013. The experiments were conducted on adjacent fields, comprised of the same treatments and managed similarly. In all experiments the residues from the preceding rice or soybean crop were disked into the soil. During the winter, fields were not intentionally flooded and no effort was made to retain rainfall within the field. The soil on all fields was a Dewitt silt loam (fine, smectitic, thermic, Typic Albaqualfs; USDA, 2006) with a total C content of 0.67%, total N content of 0.075%, a pH of 5.6 (1:2 soil/water), and a total As content of 4.2 mg kg^{-1}.

Crop management

At all sites the rice crop was established by drill-seeding rice (hybrid CLXL745) on April 10 and 23 in 2012 and 2013, respectively. Following tillage and planting, no irrigation water was applied as rainfall was sufficient for crop establishment. After 1 month the fields were flooded and treatments were imposed. All P and K fertilizer (29 and 84 kg P and K ha^{-1}, respectively) was applied before the last tillage operation, while the N fertilizer (144 kg urea-N ha^{-1}) was applied just prior to the initial flood. At the end of the season, when rice reached physiological maturity, no additional water was applied and remaining water in the plots was drained. Drain dates were August 12 (2012) and August 25 (2013 RS) and September 2 (RR). Plot sizes were 244 m^2 and a 91.5 m^2 area from middle of each experimental plot was harvested at maturity with a small plot combine to determine grain yield and obtain grain samples for analysis.

Treatments and experimental design

Four water management treatments were laid out in a randomized complete block design, replicated three times. Treatments were: (i) Flood (continuously flooded control), (ii) AWD/40F (flood), (iii) AWD/60, and (iv) AWD/40, where AWD represents alternate wetting and drying followed by the percent of saturated volumetric water when fields were re-flooded. For the AWD/40F treatment water was managed the same as the AWD/40 management until the plants reached the reproductive growth stage; after which a flood was maintained until the field was drained for harvest. Plots were separated by packed levees to prevent water movement between plots. For the AWD water treatments, the plots were irrigated to a flood depth of 10 cm and the water was allowed to subside via evapotranspiration and percolation until soil moisture reached the critical moisture level for that treatment (60 and 40% of saturated volumetric water – measured at 5 cm depth) when the plots were reflooded. In the Flood treatment, water was maintained at 10-cm. Across sites and years in the AWD/40F, AWD/60 and AWD/40 treatments there were 2–3, 4–5, and 3–4 flooding events, respectively (Fig. 1). In 2013, the first flood was maintained for 7–10 days in all AWD treatments to ensure maximum fertilizer N uptake before draining and reflooding.

Water input/output measurements

To determine water use, the inlets of two replications in the RS experiment (in both years) and a single replication in the RR experiment were equipped with McCrometer flow meters. The irrigation was managed in a manner that the only drainage occurred at the end of season in preparation for harvest. At this time the water height in each plot was measured before drainage to estimate the amount of water drained from the plot. This drainage water was not deducted from the total amount of water applied. Seasonal rainfall was determined from planting until the final drain from a weather station located on site.

Soil moisture determination

Soil moisture measurements were carried out using a Dynamax TH300 soil moisture probe which measured the soil volumetric water content to a depth of 5 cm. At saturation, soil volumetric water content was 0.40 m^3 m^{-3}. The targeted soil moisture reflood period for the AWD/60 treatment was

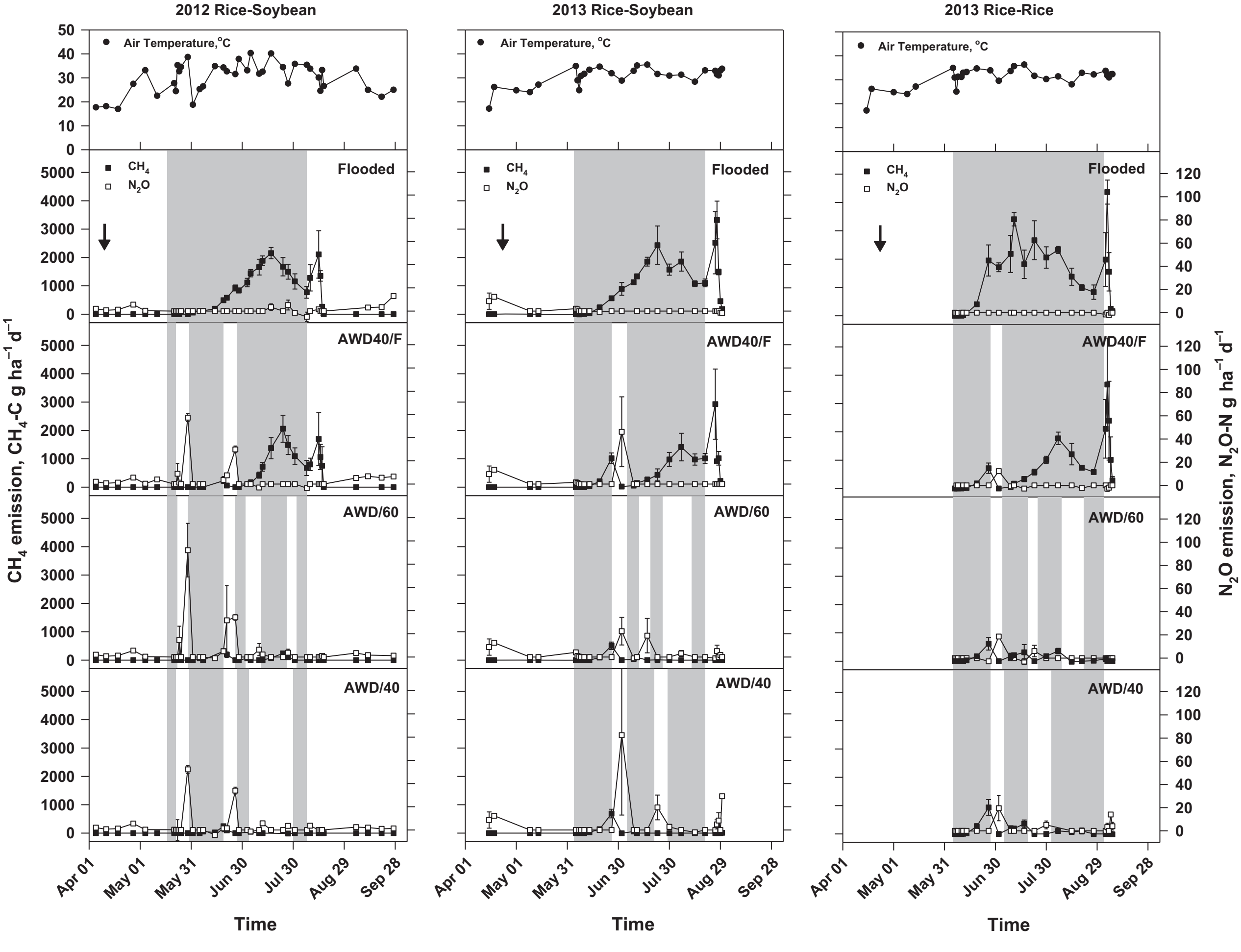

Fig. 1 Greenhouse gas fluxes and mean daily temperature for the three experimental sites in 2012 and 2013 as affected by AWD treatment. The 60 and 40 in the treatment legend indicate the percent of saturated volumetric water when the field was reflooded (40% being the driest). The shaded bars represent the approximate time the soil was flooded or saturated. The left hand side of each shaded bar is the known data of flooding; however, the right hand side is an estimate of when soils dropped below saturation. Refer to Fig. 2 for the relationship between soil moisture and GHG emissions. The arrow indicates the planting date for each experiment. In the 2013 Rice–Rice experiment gas measurements were not taken until permanent flood (approximately 1 month after planting).

60% of this value (0.24 m^3 m^{-3}) and 40% for the AWD/40 treatment (0.16 m^3 m^{-3}). When the average value of the treatment replications reached the target value, all plots of that treatment were flooded. In addition to the Dynamax TH300 soil moisture probe, a Campbell Scientific CS655 water content reflectometer was also used in the 2013 RR experiment in three of the treatments (Flooded, AWD/40 and AWD/60) which measured volumetric soil water content to a depth of 12 cm every hour.

Greenhouse gas flux measurements

Fluxes of CH_4 and N_2O were measured using static vented flux chamber technique (Hutchinson & Livingston, 1993). The chamber included a permanent base that was inserted into the soil (with plants growing inside); extensions of varying length to accommodate the growing plants; and a lid which was equipped with vent tube, fan and thermocouple wire. The base was made of PVC pipe (29.5 cm in diameter) and inserted to a depth of 15 cm which left about 10 cm above the soil line. Holes drilled in the base above and below the soil line allowed for relatively free root and water movement. During sampling, holes above the water line were plugged with rubber stoppers when the water level was below the holes to ensure chambers were air-tight. Chambers were positioned at least 1 m inside the plots and sampling locations were connected using board walks to prevent soil disturbance when sampling.

Gas flux measurements were conducted at daily to weekly intervals during the entire growing season (in the 2013 RR experiment sampling began at time of permanent flood instead of planting) between 09:00 and 10:30 hrs. Gas samples (25 ml) were taken from the chamber at four equal time (21 min) intervals using pre-evacuated 12.5 ml glass vials (Labco Ltd., Buckinghamsire, UK). The vials had a rubber septa double sealed with 100% silicon for leak-free storage and transportation before gas analysis. The vials were sent to the University of California in Davis for analysis. To ensure quality assurance, standard concentrations of 1.0 ppm N_2O and 4.99 ppm CH_4 in the same type of vial were included in triplicate with each shipment of field gas samples. We never found significant differences ($P = 0.05$) between the mixed standards and the actual concentrations of the standard used; indicating that the transport and storage of samples did not alter the concentrations of headspace gas.

Samples were all analyzed within 2 weeks of sampling for CH_4 and N_2O on a gas chromatograph (Shimadzu Scientific, Inst, Columbia, MD, USA). Results of GC analyses were accepted when standard gas calibrations produced linear relationships between voltage output and gas concentration with an $r^2 > 0.996$. Quality assurances of gas concentrations were monitored by inserting standard gas samples every 10 samples, and were within 95% of known concentration.

Concentrations were converted to mass per volume units (g N_2O or CH_4 L^{-1}) using the Ideal Gas Law and chamber air temperatures and volumes. Fluxes of N_2O and CH_4 were calculated using linear regression of gas concentration versus chamber closure time and the enclosed soil surface. Individual flux values were set to zero if the change in concentration over time fell below the GC detection limit, and flux values were rejected (i.e., treated as missing data) if they passed the rejection test but had a $r^2 < 0.90$.

Cumulative seasonal gas emissions were determined by successive linear interpolation of gas emissions on the sampling days assuming that emissions followed a linear trend on days when gases were not measured. Gas emissions from flooded control treatment plots prior to the application of different water management were used to calculate cumulative seasonal GHG emissions for all treatment as the treatments were managed identically up to that time point. The GWP of N_2O and CH_4 was calculated in mass of CO_2 equivalents (kg CO_2 eq ha^{-1}) over a 100-yr time horizon. A radiative forcing potential relative to CO_2 of 298 was used for N_2O and 25 for CH_4 (Ramaswamy *et al.*, 2001). GWP_Y was expressed as GWP per unit mass of rice grain (kg CO_2 eq Mg $grain^{-1}$) was obtained from the ratio of GWP (kg CO_2 eq ha^{-1}) and grain yield (Mg ha^{-1}).

Arsenic analysis

Whole grain samples were collected from the harvest plots and dried to 12% moisture. Grain samples were milled for 30 sec using a McGill No. 2 rice miller to achieve white (polished) grain samples. To analyze for total As, grain samples were ground to a fine powder; 2 g DW was weighed into a 100 mL tall form Pyrex beaker; 10 mL of a solution containing 75 g MgO l^{-1} and 105 g $Mg(NO_3)_2{\cdot}6H_2O$ l^{-1} (AOAC, 1965) was added and heated with stirring to dryness; samples were ashed at 450° for at least 16 h; ash was treated with 2 ml water, then 2 ml of concentrated HNO_3 was added and beakers heated to near dryness with stirring. Ash was then dissolved in 3 M HCl with cover glass to support reflux for 2 h, then filtered thru pre-wetted Whatman #40 paper, rinsed and diluted to volume. Solution As was then measured by Inductively coupled Plasma-Atomic Emission Spectrometry using a hydride generation flow injection method. A 4 ml aliquot of sample was transferred to a test tube and was pre-reduced with KI and ascorbic acid in HCl and allowed to stand for 20 min before analysis. Quality assurance was assessed by random duplicate analysis of samples, analysis of NIST (National Institute of Standards and Technology) rice standard reference material 1568B, recovery of spikes to samples before analysis, and analysis of blanks and spiked digested blanks and samples. Using this methodology, the mean total As we measured in the NIST standard was 267 ± 5.4 μg As kg^{-1} dry standard which is within one standard deviation of the certified standard (285 ± 14 μg As kg^{-1} dry weight). The Limit of Quantitation for this methodology is 10 μg kg^{-1} dry weight of rice and none of the samples were below this value.

Data analysis

All data were tested for normal distribution using the Shapiro–Wilk approach and data that did not pass the test were log transformed ($P = 0.01$–0.5). Differences in GHG emissions among treatments were determined using SAS programs for randomized complete block design at P-value < 0.05 (SAS, 2010). Gas emissions, GWP, yield and total As due to main effects like water management, year, rotation, rotation × water management, year × rotation × water management and block × water management as random effect were analyzed using PROC MIXED. Differences in gas emissions and yield data due to water treatments and year by rotation were analyzed using PROC MIXED with Tukey for multiple treatment mean comparisons at P-value < 0.05 (SAS, 2010).

Results

Yields

Across years, rice yields in the continuously flooded control treatment averaged 10.26 Mg ha^{-1} and were 13% higher in the RS rotation compared to the RR system (Table 1). In the AWD/40-F treatment yields were similar to the control. In the AWD/60 treatment yields were similar to the control at two sites but lower in the 2013 RS field (averaged yield decline of 5%). Increasing water stress further (AWD/40) resulted in an average yield decline of 13%.

GHG emissions, GWP, and yield-scaled GWP

Fluxes of CH_4 and N_2O were highly dependent on water management and soil moisture conditions (Figs 1,2). In all treatments CH_4 emissions were detectable after approximately 2 weeks of soil flooding. In the flooded control, CH_4 emissions continued to increase and peaked 1.5–2 months after flooding (up to 2000–3000 g CH_4-C ha^{-1} day^{-1}). Thereafter, fluxes tended to decline until the final drain when there was a short but substantial spike in CH_4 emissions before decreasing to zero emissions. In the AWD/40F, CH_4 fluxes increased once the soil was reflooded to values similar to the flooded treatment in 2012 but less than in 2013. The AWD/40F also had a large post drain spike in CH_4 emissions similar to the control. The AWD/40 and AWD/60 treatments emitted some CH_4 – especially when soils remained saturated for a longer period of time; however, emissions never exceeded 1000 g CH_4-C ha^{-1} day^{-1} and decreased to zero when the soil was allowed to dry. These treatments also did not have a post drain spike in CH_4 emissions as was observed in the other treatments.

Table 1 Rice (CLXL 745) grain yields in each year and cropping system. The ANOVA for the mean was based on data across years and rotations as there was no significant interaction

	Rice grain yields* (Mg ha^{-1})			
Water treatment	2012-RS	2013-RS	2013-RR	Mean
Flood	9.78 a	11.15 a	9.84 a	10.26 a
AWD/40–Flood	9.27 a	11.15 a	10.33 a	10.17 ab
AWD/60	9.22 a	10.37 b	9.61 a	9.73 b
AWD/40	9.03 a	9.58 c	8.31 b	8.97 c

*Rice grain yields within each column followed by same letter are not significantly different at $P < 0.05$.

Nitrous oxide emissions were observed at low levels during the first month before the field was flooded. In the flooded control treatment, N_2O levels were not detectable during the growing season (Figs 1,2). In all

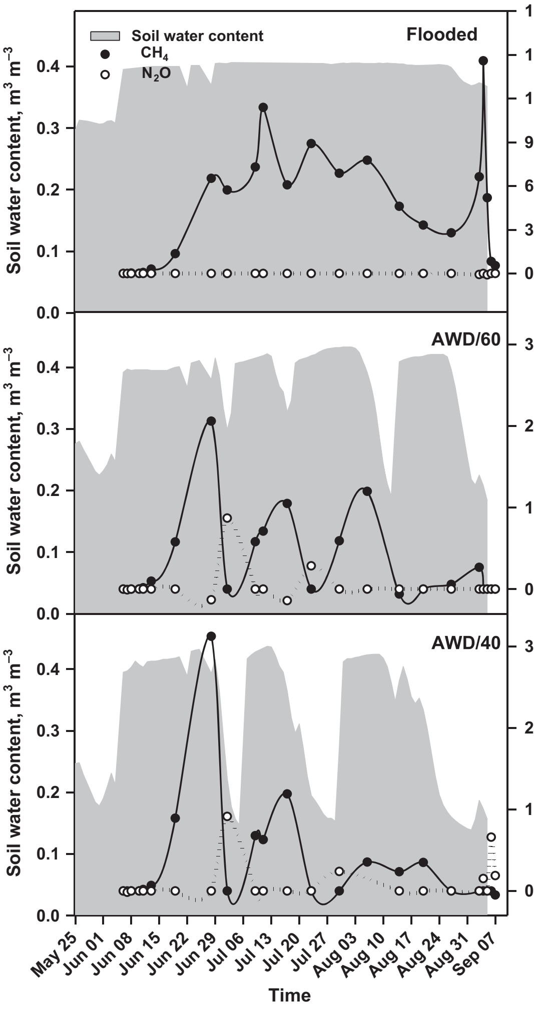

Fig. 2 CH_4 and N_2O fluxes in relation to soil water content and AWD management for the 2013 rice–rice experiment. The 60 and 40 in the treatment legend indicate the percent of saturated volumetric water when the field was reflooded (40% being the driest). In this experiment, measurement of GHG emissions began at the onset of flooding (June 6). Note different scale of the right Y axis.

other treatments N_2O emissions were detected during periods when the soil was drained; however, peak emissions were less than 100 g N_2O-N ha^{-1} day^{-1}.

Cumulative seasonal CH_4 and N_2O gas fluxes varied across the growing seasons and fields but in all treatments were higher in the 2013 RR rotation compared to the RS rotation. In the flooded control, CH_4 and N_2O emissions averaged 105 kg CH_4-C ha^{-1} and 0.031 kg N_2O-N ha^{-1} (Table 2). Methane emissions were reduced by 48, 93 and 93% in the AWD/40F, AWD/60 and AWD/40 treatments, respectively. In contrast, implementation of AWD increased N_2O emissions by 0.143, 0.245, and 0.474 kg N_2O-N ha^{-1}, respectively. While the relative increase in N_2O emissions was large, the GWP was dominated by CH_4 emissions and GWP decreased relative to the control by 45, 90, and 86% in the AWD/40F, AWD/60 and AWD/40 treatments, respectively. In the 2013 RR experiment GHG measurements only began with the onset of the first flooding event and thus emissions from planting to the first flood are not included in the cumulative emission value. During this period there were no CH_4 emissions as the field was not flooded and N_2O emissions were likely low. For example, at the two sites (2012 and 2013 RS) where gas measurements were taken during this period, cumulative N_2O emissions were only 0.007 and 0.076 kg N_2O-N ha^{-1}, respectively.

Yield-scaled GWP, a measure of the amount of GHG emitted per unit of yield, was highest in the flooded control treatment, averaging 347 kg CO_2 eq Mg^{-1} across years and sites. Introducing AWD practices reduced GWP_Y by 45, 89, and 84% in the AWD/40F, AWD/60 and AWD/40 treatments, respectively.

Water use and water-use efficiency

Irrigation water use in the control treatment averaged 7939 m^3 ha^{-1} (Table 3). Water reductions relative to the control treatment of 18, 31 and 44% were observed in the AWD/40F, AWD/60 and AWD/40 treatments, respectively; and irrigation water-use efficiency which was 1.30 kg rice m^{-3} in the control, increased by 22, 43 and 63%, respectively. The amount of rainfall received from planting until draining for harvest was 182, 212, and 219 mm in 2012, 2013 RS and 2013 RR, respectively. Thus, rainfall contributed on average 2043 m^3 ha^{-1} to total water use and in the flooded treatment an average total of 9982 m^3 ha^{-1} was used.

Rice grain arsenic

Total grain As levels ranged from 114 to 433 μg kg^{-1} across years and treatments (Table 4). Arsenic levels were highest in the Flood and AWD40/F treatments

Table 2 Seasonal GHG emissions and GWP under different water management and crop rotations

	CH_4*	N_2O†	GWP*	
Water management	kg CH_4-C ha^{-1}	kg N_2O-N ha^{-1}	kg CO_2 eq ha^{-1}	kg CO_2 eq Mg^{-1}
2012 Rice-soybean (RS)				
Flood	71.0 a	0.031	2385 a	249 a
AWD/40–flood	37.2 b	0.104	1292 b	145 b
AWD/60	2.8 c	0.229	201 c	23 c
AWD/40	1.7 c	0.137	120 c	14 c
2013 Rice-soybean (RS)				
Flood	100 a	0.07 b	3371 a	303 a
AWD/40–flood	56.7 b	0.39 a	2076 b	187 ab
AWD/60	6.04 c	0.40 a	389 c	38 c
AWD/40	7.80 c	1.05 a	751 c	78 bc
2013 Rice–rice‡ (RR)				
Flood	144 a	−0.008 b	4804 a	489 a
AWD/40–flood	71.4 b	0.028 b	2397 b	239 b
AWD/60	11.8 c	0.198 ab	486 c	51 c
AWD/40	13.7 c	0.329 a	611 c	73 c

*CH_4 emissions and GWP followed by same letter are not significantly different at $P < 0.05$.

†N_2O emissions followed by same letter are not significantly different at $P < 0.10$ (were not significant at 0.05).

‡In the 2013 rice–rice experiment measurement of GHG emissions began at the onset of permanent flooding (about 1 month after planting).This likely resulted in slightly lower cumulative N_2O emissions.

Table 3 Irrigation water use ($m^3\ ha^{-1}$) and irrigation water-use efficiency (WUE = kg rice m^{-3}). In the rice-soybean (RS) rotation water meters were put in two replications and the standard deviation of the water use is in '()'. In the rice–rice (RR) a water meter was only placed in one replication. These calculations do not include rainfall which was 182, 212, and 219 mm in 2012, 2013 RS and 2013 RR, respectively

	2012-RS		2013-RS		2013-RR		Mean	
Water treatment	Use	WUE	Use	WUE	Use	WUE	Use	WUE
Flood	7617 (718)	1.28	7617 (1077)	1.46	8582	1.15	7939	1.30
AWD/40 – Flood	6602 (359)	1.40	6475 (538)	1.72	6459	1.60	6512	1.58
AWD/60	6475 (180)	1.42	5840 (0)	1.78	4040	2.38	5452	1.86
AWD/40	5078 (359)	1.78	5205 (180)	1.84	3030	2.74	4438	2.12

Table 4 Rice grain total arsenic concentrations of polished white rice. There was not a significant difference between the rice-soybean (RS) rotation in 2012 and 2013 so means are provided. The rice–rice (RR) rotation had significantly higher ($P < 0.05$) As concentrations and are provided separately

	Rice grain arsenic concentration* ($\mu g\ kg^{-1}$)	
Water treatment	2012/13-RS	2013-RR
Flood	343 a	370 b
AWD/40 – Flood	334 a	433 a
AWD/60	165 b	199 c
AWD/40	114 b	149 c

*Rice grain arsenic within each column followed by same letter are not significantly different at $P < 0.05$.

followed by AWD/60 and AWD/40. On average, total grain As concentrations were 56% less in the AWD/60 and AWD/40 than in the Flood treatment. The As levels were on average 20% higher ($P < 0.05$) in the RR rotation than the RS rotation.

Discussion

While other studies have evaluated AWD, this is the first study where multiple benefits (yields, GHG emissions, water use, and grain As) have been accessed in a single study. It is also the first study in the US where rice yields are typically higher than most regions of the world. Our results demonstrate that there are trade-offs to consider between the AWD strategies tested and the desired sustainable intensification goals we evaluated for rice systems. No single AWD strategy was able to maintain yields, while reducing water use, GHG emissions and grain As concentrations. Yields of over 10 Mg ha^{-1} were attained in the control and AWD40/F treatments which are typical of well managed rice fields in this region (Walker *et al.*, 2008). Similarly, the 14% increase in rice yields when rice is grown in rotation with soybean is commonly observed (Olk *et al.*, 2009). While the AWD40/F maintained yields and lowered water use and GHG emissions; As grain concentrations remained unchanged or increased. Using AWD/60 and AWD/40 strategies, reductions in water use, GHG emissions, and grain As concentrations were all realized, but this was accompanied by a 5 and 13% reduction in grain yields, respectively. These points are further elaborated on below.

GHG and GWP

The average GWP of GHG emissions from rice systems are about three fold higher than for other cereal crops (Linquist *et al.*, 2012). The high GWP is due primarily to high CH_4 emissions under flooded soils which create an anaerobic environment favorable for methanogenesis (Yan *et al.*, 2005). Therefore, to reduce GWP in rice systems, efforts need to concentrate on CH_4 emissions. The reduction in CH_4 emissions of 48% in the AWD/40F and 93% in both the AWD/60 and AWD/40 treatments are larger than has typically been observed. The IPCC Tier 1 methodology assumes a 40% reduction for a single drain (similar to AWD/40F) and a 48% reduction for multiple drainages (Yan *et al.*, 2005; Lasco *et al.*, 2006). The cause for the greater reduction in CH_4 emissions in our study is not clear but it may be that the soils in our study dried out to a greater degree between flood events than other studies; however, this is hard to verify because many studies do not report soil moisture. Another reason for lower CH_4 emissions is that in the AWD/60 and AWD/40 treatments, daily CH_4 fluxes never reached the levels observed for the continuously flooded treatment (Figs 1,2). Finally, in continuously flooded systems there is often a spike in CH_4 emissions at the end of the season as was observed in the Flood and AWD/40F treatments in this study (Fig. 1). This spike, which can contribute up to 18% of total seasonal emissions (Denier van der Gon *et al.*, 1996; Wassmann *et al.*, 2000; Adviento-Borbe *et al.*, 2013; Pittelkow *et al.*, 2013), is thought to be the physical release of entrapped CH_4 when the soil changes from saturated to unsaturated conditions during drying

(Wassmann *et al.*, 2002). In the AWD/60 and AWD/40 treatments, this spike was not observed, possibly as there was not a sufficiently long period of time when the soil was flooded prior to the drain for methanogenesis to occur.

Flooded rice systems generally emit less N_2O than dryland crops because flooding results in most N being lost as N_2 rather than N_2O (Firestone & Davidson, 1989). Due to the introduction of aerobic cycles, AWD practices often lead to increased N_2O emissions (Akiyama *et al.*, 2005; Zou *et al.*, 2007) as was observed in this study (Figs 1,2). Nitrous oxide emissions were measurable when the soils were drying out between flood events and were close to zero when soils were flooded. In nonrice soils, others have reported that N_2O emissions are highest when the soil water-filled pore space is >60% (Del Pradao *et al.*, 2006). While we did not measure the water-filled pore space in this study, it is likely that as the soil dried between flooding events the soil water-filled pore space was in this range for at least part of the drying period. Also in our study, N_2O emissions tended to be highest during drain events early in the season as opposed to later in the season – possibly due to more residual fertilizer N in the soil early in the season than later in the season (Linquist *et al.*, 2006). Despite this, seasonal N_2O emissions remained low in all treatments; i.e., less than 1.05 kg N_2O-N ha^{-1} and in most cases below 0.4 kg N_2O-N ha^{-1} (Table 2). These values are also lower than the average seasonal N_2O emissions that Linquist *et al.* (2012) reported for wheat and maize (1.44 and 3.01 kg N_2O-N ha^{-1}, respectively). Due to the ability to achieve both low CH_4 and N_2O emissions from rice systems through careful water and N management the GWP can be lower in rice than for dryland crops. Overall, the GWP (CH_4 and N_2O) of the AWD/60 and AWD/40 treatments averaged 426 kg CO_2 eq ha^{-1} $season^{-1}$, which is significantly lower than the average that Linquist *et al.* (2012) reported for wheat (662 kg CO_2 eq ha^{-1} $season^{-1}$) and maize (1399 kg CO_2 eq ha^{-1} $season^{-1}$). These results were in part made possible by applying all the N fertilizer just before flooding (about 1 month after planting) and maintaining the initial flood for a longer period (only in 2013) to ensure adequate time for plant uptake and low soil mineral soil N before the second flooding (Linquist *et al.*, 2006). This reduced the possibility for nitrification and denitrification as both processes can result in N_2O losses (Bateman & Baggs, 2005). While this initial prolonged flood period resulted in CH_4 fluxes in 2013, these fluxes were never as high as in the continuously flooded treatment (Fig. 1).

Yield-scaled GWP (GWP_Y), the GWP per unit of grain yield, was reduced by almost half in the AWD/40F treatment (Table 2). This result is especially encouraging as it was not associated with a yield reduction (Table 1) but had significant water savings (Table 3); and highlights the potential for sustainable intensification with appropriate management. The GWP_Y in the other treatments which experienced more severe AWD (more frequent drying events) was reduced even further (85–89%); however, this was accompanied by yield reductions. There clearly is no benefit of the most severe AWD treatment (AWD/40) compared to AWD/60 as CH_4 emissions were similar, but AWD/60 had higher yields and lower N_2O emissions than the AWD/40 resulting in the lowest GWP_Y being in the AWD/60 treatment. The yield decline between the Flood and AWD/60 is small (5%) but significant. Further research needs to test to see if soils can be reflooded sooner (at higher moisture content) so yields do not decline but large reductions in GWP and water use are still achieved.

Water-use efficiency

Water availability is a global concern (Haddeland *et al.*, 2014; Schewe *et al.*, 2014) and in the US it is an issue in all regions where rice is grown (California, Gulf Coast and Mississippi Valley). In Arkansas much of the water is pumped from the Sparta aquifer which is receding, requiring irrigation from increasing depths and resulting in producers having to install on-farm reservoirs to capture and store winter rainfall to supplement irrigation water use (Reba *et al.*, 2013). Therefore, water savings are particularly attractive for rice producers in this region. In the continuously flooded treatment 7939 m^3 ha^{-1} of irrigation water was used which is typical (7600–9000 m^3 ha^{-1}) for this region (Smith *et al.*, 2006). In the AWD/40F similar yields were achieved with an overall reduction in water use of 18%, and such reductions due to AWD have been reported elsewhere (Belder *et al.*, 2004; De Vries *et al.*, 2010; Yao *et al.*, 2012; Liu *et al.*, 2013). Water savings, however, can be highly variable depending on water table depth and the plow pan which affects percolation rates (De Vries *et al.*, 2010). In fact, in some cases AWD can lead to increased water use because the drying can lead to soil shrinkage and cracking resulting in increased water use due to preferential flow of water to the subsoil (Bouman & Tuong, 2001).

Water-use efficiency increased with increasing severity of AWD from 1.30 (control) to 2.12 kg rice m^{-3} (Table 3) despite declining yields (Table 1). From an economic stand point, assuming an average well depth of 22.6 meters (average depth of the alluvial aquifer), that a diesel pump requires 0.012 l of diesel to raise 1 m^{-3} of water (Slaton, 2001), diesel costs of $0.83 per liter, the water use and yield losses associated with AWD (Tables 1,3) and a rice price of \$0.337 kg^{-1} (Mar 2014 futures price) there is a net loss of \$16.51, \$154.68, and \$401.27 ha^{-1} compared to conventional flooding for AWD/40F, AWD/60 and AWD/40, respectively. At these input and output prices, the maximum yield loss associated with AWD that would make producers indifferent between AWD and conventional flooding would be less than 1% for all AWD treatments. While we recognize that the yield loss reported for the AWD/40F was small and not significant in this study (Table 1), this analysis suggests that cost savings from reduced pumping will not drive adoption of AWD and other incentives may be necessary. Furthermore, given the risk of yield loss, research and extension efforts are needed so that risk can be minimized. This economic analysis assumes that water is available; however, some forecast increasing water shortages due to climate change (Schewe *et al*., 2014) and under those conditions, systems that require less water should be more attractive in adapting to climate change.

Sensitivity to moisture stress

This study demonstrates the sensitivity of rice yield to small changes in soil moisture which further increases risk and can limit adoption. Similarly, Bouman & Tuong (2001) in a review found that that even when rice soils were allowed to dry to the point where there was no longer any flood water on the soil surface but the soil remained saturated, the overall yield reduction averaged 6%. In this study, the average yield difference between the AWD/60 and AWD/40 was 0.73 Mg ha^{-1} – a significant yield reduction of about 8%. In practical terms, the time required for a soil to dry from 60 to 40% of saturated volumetric water is a few days depending on climate and crop factors; therefore a short delay in irrigation can have serious impacts on yield. However, recent findings have reported that high yields can be maintained, or even increased, with AWD water management (Belder *et al*., 2004; De Vries *et al*., 2010; Yao *et al*., 2012; Liu *et al*., 2013). It is not clear from all of these studies how dry the soil became between each flooding event without sacrificing yield; however, in our study, it appear that 60% of saturated volumetric water was close to the critical value as yields declined by only 5% on average. Certainly, further research needs to be directed toward identifying critical soil moisture levels that rice can withstand without yield loss. Importantly, improved response to increased water stress may be related to varietal choice, as in this study and in most cases just mentioned (Belder *et al*., 2004; Yao *et al*., 2012; Liu *et al*., 2013) hybrid rice varieties were used.

Arsenic

Arsenic in rice grain has recently been mentioned as a human health concern especially for populations where rice makes up a relatively high percentage of the diet (Williams *et al*., 2007; Banerjee *et al*., 2013). In anaerobic soils, the reductive mobilization of As increases the phytoavailability and uptake of As in rice (Meharg & Zhao, 2012). Rice, grown aerobically or with introduced aerobic cycles such as with AWD can have lower As uptake. For example, Somenahally *et al*. (2011) reported a 41% reduction in total grain As from rice grown on intermittently flooded fields. In this study, grain As concentrations in the continuously flooded systems averaged about 350 μg kg^{-1} (Table 4), which is similar to the variety average reported in the Mississippi Valley and lower than in Bangladesh, China and Texas (Williams *et al*., 2007; Norton *et al*., 2012). The 20% increase in grain As concentration in the RR rotation may be due to a couple of reasons. First, in the RR rotation there is a greater amount of residues being incorporated compared to the RS rotation (soybeans produce less residue than rice). Addition of organic residues increases microbial activity, As release to the soil solution, and subsequent As uptake by the plant (Norton *et al*., 2013; Jia *et al*., 2014). Second, the rice residues in the RR rotation likely contain higher As concentrations than the soybean residues that are incorporated in the RS rotation (Xu *et al*., 2008).

Introduction of aerobic cycles during the growing season in both the AWD/60 and AWD/40 treatments reduced As levels by 56% on average and, in all cases, were less than 200 μg kg^{-1}. This study also suggests that the timing and or number of aerobic periods remain important. Grain As levels in the AWD/40F (a single drain period early in the season) were not lower and in the RR rotation were actually higher by 17%, for reasons not immediately clear. It appears that As accumulated later in the growing season is translocated to the grain and that the introduction of aerobic cycles during this period can reduce grain As concentrations. However, a number of different As species are accumulated by the crop and these species exhibit differences in mobility within the plant (Meharg & Zhao, 2012).

Considerations and challenges

In this study, only CH_4 and N_2O fluxes are considered – not CO_2. Soil CO_2 fluxes are a source of GHG emissions; however, on a global scale they are estimated to contribute less than 1% to the GWP of agriculture

(Smith *et al.*, 2007). The net balance between C respiration and fixation in a cropping system is reflected by changes in soil organic C over time (West & Post, 2002; Stewart *et al.*, 2007) which is difficult to detect in short-term experiments due to the relatively small change and high degree of spatial variability of soil organic C (Post *et al.*, 2001; Conant *et al.*, 2011). Continuous flooded rice monoculture promotes soil C sequestration (Witt *et al.*, 2000; Pan *et al.*, 2010; Wu, 2011), therefore, conversion from such a system to AWD may result in a loss of soil C. In the southern US where rice is often rotated with soybean a change to AWD may not alter soil organic C as soil C stocks are already degraded in these systems (Scott & Wood, 1989); however, in other parts of the world where rice is routinely monocropped, loss of soil C needs to be considered.

While this study and others show that rice yields can be maintained with AWD/40F, AWD practices have not been widely adopted in the US or globally. There are a number of potential reasons for this – both economical (briefly discussed above) and physical. First, in many parts of the world rice is grown in the wet season in low-lying areas where it is not possible to drain fields and fields do not dry out because of rainfall. In other areas rice is grown in flooded but rainfed conditions and farmers are not likely to drain fields intentionally due to risk of drought. Finally, in many irrigated rice systems surface water is used and fields and farmers within the irrigation scheme may be hydrological connected making it difficult, if not impossible, for a famer to manage a field independently. It is critical to be able to manage water independently and have enough water to rapidly flood a field when needed due to the sensitivity of rice to even mild water stress (Bouman & Tuong, 2001). For example, the critical time to irrigate the AWD/40 was only a few days later than the AWD/60 treatment; however, due to the size of many rice fields in the US and how fields are irrigated, it can take five to 10 days to reflood a field. Therefore, depending on how the irrigation is managed, critical soil moisture contents in the soils in parts of the field may decrease considerably below the targeted level resulting in yield declines.

Finally, this study demonstrates the potential to achieve multiple environmental goals through AWD. However, there are trade-offs to consider in that some AWD strategies lower yields while others maintain or even increase grain As levels. Plant breeding to develop varieties that can achieve some or all of these goals is an avenue to consider. It has already been demonstrated that there are varietal differences in terms of CH_4 emissions (Lindau *et al.*, 1995; Wassmann *et al.*, 2002) and grain As concentrations (Hu *et al.*, 2013). While efforts may continue in this area, this study suggest that with limited resources efforts should focus on breeding varieties that are less sensitive to yield reductions under nonsaturated soil conditions. By achieving this outcome of no yield reduction, the other benefits can be realized through field management practices. For example, by breeding for rice that can withstand water conditions similar to AWD/60 without a yield loss as our study shows, the other goals of reducing GWP (90%), water use (31%) and grain As (49%) can be achieved.

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References

Adviento-Borbe MA, Pittelkow CM, Anders M *et al.* (2013) Optimal fertilizer nitrogen rates and yield-scaled global warming potential in drill seeded rice. *Journal of Environmental Quality*, **42**, 1623–1634.

Akiyama H, Yagi K, Yan X (2005) Direct N_2O emissions from rice paddy fields: summary of available data. *Global Biogeochemical Cycles*, **19**, GB1005.

AOAC (1965) Official methods of analysis of the association of official agricultural chemists. In: *Method for Arsenic in Feeds*, 10th edn, Section 33.003 (ed. Horwitz, W), pp. 632–633. Assoc. Offic. Agric. Chem., Washington, DC.

Banerjee M, Baerjee N, Bhattacharjee P *et al.* (2013) High arsenic in rice is associated with elevated genotoxic effects in humans. *Scientific Reports* **3**, 2195; doi:10.1038/srep02195.

Bateman EG, Baggs EM (2005) Contributions of nitrification and denitrification to N_2O emissions from soils at different water-filled pore space. *Biology and Fertility of Soils*, **41**, 379–388.

Belder P, Bouman BAM, Cabangon R *et al.* (2004) Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia. *Agricultural Water Management*, **65**, 193–210.

Bouman BAM, Tuong TP (2001) Field water management to save water and increase its productivity in irrigated lowland rice. *Agricultural Water Management*, **49**, 11–30.

Burney JA, Davis SJ, Lobell DB (2010) Greenhouse gas mitigation by agricultural intensification. *Proceedings of the National Academy of Sciences of the United States of America*, **107**, 12052–12057.

Conant RT, Ogle SM, Paul EA, Paustian K (2011) Measuring and monitoring soil organic carbon stocks in agricultural lands for climate mitigation. *Frontiers in Ecology and the Environment*, **9**, 169–173.

De Vries ME, Rodenburg J, Bado BV *et al.* (2010) Rice production with less irrigation water is possible in a Sahelian environment. *Field Crops Research*, **116**, 154–164.

Del Pradao A, Merino P, Estavillo JM, Pinto M, Gonzalez-Murua C (2006) N2O and NO emissions from different N sources and under a range of soil water contents. *Nutrient Cycling in Agroecosystems*, **74**, 229–243.

Denier van der Gon HAC, van Breeman N, Neue H-U, Lantin RS, Aduna JB, Alberto MCR, Wassman R (1996) Release of entrapped methane from wetland rice fields upon soil drying. *Global Biogeochemical Cycles*, **10**, 1–7.

Feng J, Chen CQ, Zhang Y *et al.* (2013) Impacts of cropping practices on yield-scaled greenhouse gas emissions from rice fields in China: a meta-analysis. *Agriculture Ecosystems & Environment*, **164**, 220–228.

Firestone MK, Davidson EA (1989) Microbial basis of NO and N_2O production and consumption in soils. In: *Exchange of trace gases between terrestrial ecosystems and the atmosphere* (eds Andreae MO, Schimel DS), pp. 7–21. John Wiley & Sons, New York, NY, USA.

Godfray HCJ, Garnett T (2014) Food security and sustainable intensification. *Philosophical Transactions of the Royal Society B – Biological Sciences*, **369**, 20120273. doi:10.1098/rstb.2012.0273.

Godfray HCJ, Pretty J, Thomas SM, Warham EJ, Beddington JR (2011) Linking policy on climate and food. *Science*, **331**, 1013–1014.

Grassini P, Eskridge KM, Cassman KG (2013) Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nature Communications*, **4**, 2918.

van Groenigen JW, Velthof GL, Oenema O, van Groenigen KJ, van Kessel C (2010) Towards an agronomic assessment of N_2O emissions: a case study for arable crops. *European Journal of Soil Science*, **61**, 903–913.

Haddeland I, Heinke J, Biemans H *et al.* (2014) Global water resources affected by human interventions and climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **111**, 3251–3256.

Hu P, Huang J, Ouyang Y *et al.* (2013) Water management affects arsenic and cadmium accumulation in different rice cultivars. *Environmental Geochemistry and Health*, **35**, 767–778.

Hutchinson GL, Livingston GP (1993) Use of chamber systems to measure trace gas fluxesIn: *Agricultural Ecosystem Effects on Trace Gases and Global Climate Change* (eds Harper LA , Mosier AR, Duxbury JM, Rolston DE), pp. 63–78. ASA, CSSA, SSSA, Madison, WI, USA.

Jia Y, Huang H, Chen Z, Zhu Y (2014) Arsenic uptake by rice is influenced by microbe-mediated arsenic redox changes in rhizosphere. *Environmental Science & Technology*, **48**, 1001–1007.

Lasco RD, Ogle S, Raison J *et al.* (2006) Chapter 5: cropland. In: *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (eds Eggleston S, Buendia L, Miwa K, Ngara T, Tanabe K), pp. 5.1–5.66. IGES, IPCC National Greenhouse Gas Inventories Program, Japan.

Lindau CW, Bollich PK, DeLaune RD (1995) Effect of rice variety on methane emission from Louisiana rice. *Agriculture, Ecosystems and Environment*, **54**, 109–114.

Linquist BA, Brouder SM, Hill JE (2006) Winter straw and water management effects on soil nitrogen dynamics in California rice systems. *Agronomy Journal*, **98**, 1050–1059.

Linquist B, van Groenigen KJ, Adviento-Borbe MA, Pittelkow C, van Kessel C (2012) An agronomic assessment of greenhouse gas emissions from major cereal crops. *Global Change Biology*, **18**, 194–209.

Liu L, Chen T, Wang Z *et al.* (2013) Combination of site-specific nitrogen management and alternate wetting and drying irrigation increases grain yield and nitrogen and water use efficiency in super rice. *Field Crops Research*, **154**, 226–235.

Ma JF, Yamaji N, Mitani N *et al.* (2008) Transporters of arsenite in rice and their role in arsenic accumulation in rice grain. *Proceedings of the National Academy of Sciences of the United States of America*, **105**, 9931–9935.

Maclean JL, Dawe DC, Hardy B, Hettel GP (eds) (2002) *Rice almanac. Source book for the most important economic activity on earth.* 3rd edn. CABI Publishing, Wallingford, UK. 253 pp.

Mandal BK, Suzuki KT (2002) Arsenic round the world: a review. *Talanta*, **58**, 201–235.

Matson PA, Parton WJ, Power AG, Swift MJ (1997) Agricultural intensification and ecosystem properties. *Science*, **277**, 504–509.

Meharg AA, Zhao F (2012) *Arsenic & Rice*. Springer, Dordrecht.

Norton GJ, Pinson SRM, Alexander J *et al.* (2012) Variation in grain arsenic assessed in a diverse panel of rice (*Oryza sativa*) grown in multiple sites. *New Phytologist*, **193**, 650–664.

Norton GJ, Adomako EE, Deacon CM, Carey A, Price AH, Meharg AA (2013) Effect of organic matter amendment, arsenic amendment and water management on rice grain arsenic species. *Environmental Pollution*, **177**, 38–47.

Olk DC, Anders MM, Filley TR, Isbell C (2009) Crop nitrogen uptake and soil phenols accumulation under continuous rice cropping in Arkansas. *Soil Science Society of America Journal*, **73**, 952–960.

Pan G, Xu X, Smith P, Pan W, Lal R (2010) An increase in topsoil SOC stock of China's croplands between 1985 and 2006 revealed by soil monitoring. *Agriculture Ecosystems & Environment*, **136**, 133–138.

Pittelkow CM, Adviento-Borbe MA, Hill JE, Six J, van Kessel C, Linquist BA (2013) Yield-scaled global warming potential and annual nitrous oxide and methane emissions from continuously flooded rice in response to nitrogen input. *Agriculture Ecosystems & Environment*, **177**, 10–20.

Pittelkow C, Adviento-Borbe MA, van Kessel C, Hill JE, Linquist BA (2014) Optimizing rice yields while minimizing yield-scaled global warming potential. *Global Change Biology*, **20**, 1382–1393.

Post WM, Izaurralde RC, Mann LK, Bliss N (2001) Monitoring and verifying changes of organic carbon in soil. *Climatic Change*, **51**, 73–99.

Ramaswamy V, Boucher O, Haigh J *et al.* (2001) Radiative forcing of climate change. In: *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. (eds Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA), Cambridge University Press, Cambridge, UK.

Ray DK, Mueller ND, West PC, Foley JA (2013) Yield trends are insufficient to double global crop production by 2050. *PLoS ONE*, **8**, e66428.

Reba ML, Daniels M, Chen YS *et al.* (2013) A statewide network for monitoring agricultural water quality and water quantity in Arkansas. *Journal of Soil and Water Conservation*, **68**, 45A–49A.

Schewe J, Heinke J, Gerten D *et al.* (2014) Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **111**, 3245–3250.

Scott HD, Wood LS (1989) Impact of crop production on the physical status of a Typic Albaqualf. *Soil Science Society of America Journal*, **53**, 1819–1825.

Slaton N (2001) *Rice Production Handbook*. The University of Arkansas Cooperative Extension Service, Little Rock, Arkansas.

Smith MC, Massey JH, Branson J *et al.* (2006) Water use estimates for various rice production systems in Mississippi and Arkansas. *Irrigation Science*, **25**, 141–147.

Smith P, Martino D, Cai Z *et al.* (2007) Agriculture. In: *Climate Change 2007: Mitigation. Contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change* (eds Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA) pp. 497–540. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Somenahally AC, Hollister EB, Yan W, Gentry TJ, Loeppert RH (2011) Water management impacts on arsenic speciation and iron-reducing bacteria in contrasting rice-rhizosphere compartments. *Environmental Science & Technology*, **45**, 8328–8335.

Stewart CE, Paustian K, Conant RT, Plante AF, Six J (2007) Soil carbon saturation: concept, evidence and evaluation. *Biogeochemistry*, **86**, 19–31.

Takahashi Y, Minamikawa R, Hattori KH *et al.* (2004) Arsenic behavior in paddy fields during the cycle of flooded and non-flooded periods. *Environmental Science & Technology*, **38**, 1038–1044.

Talukder ASMHM, Meisner CA, Sarkar MAR, Islam MS, Sayre KD, Duxbury JM, Lauren JG (2012) Effect of water management, arsenic and phosphorus levels on rice in a high-arsenic soil-water system: II Arsenic uptake. *Ecotoxicology and Environmental Safety*, **80**, 145–151.

Tilman D (1999) Global environmental impacts of agricultural expansion: the need for sustainable and efficient practices. *Proceedings of the National Academy of Sciences of the United States of America*, **96**, 5995–6000.

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of earth's ecosystems. *Science*, **277**, 494–499.

Walker TW, Bond JA, Ottis BV, Gerard PD, Harrell DL (2008) Hybrid rice response to nitrogen fertilization for midsouthern United States rice production. *Agronomy Journal*, **100**, 381–386.

Wassmann R, Neue HU, Lantin RS, Makarim K, Chareonsilp N, Buendia LV, Rennenberg H (2000) Characterization of methane emissions from rice fields in Asia. II. Differences among irrigated, rainfed and deepwater rice. *Nutrient Cycling in Agroecosystems*, **58**, 13–22.

Wassmann R, Aulakh MS, Lantin RS, Rennenberg H, Aduna JB (2002) Methane emission patterns from rice fields planted to several rice cultivars for nine seasons. *Nutrient Cycling in Agroecosystems*, **64**, 111–124.

West TO, Post WM (2002) Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. *Soil Science Society of America Journal*, **66**, 1930–1946.

Williams PN, Raab A, Feldmann J, Meharg AA (2007) Market basket survey shows elevated levels of as in South Central USA processed rice compared to California: consequences for human dietary exposure. *Environmental Science & Technology*, **41**, 2178–2183.

Witt C, Cassman KG, Olk DC *et al.* (2000) Crop rotation and reside management effects on carbon sequestration, nitrogen cycling, and productivity of irrigated rice systems. *Plant and Soil*, **225**, 263–278.

Wu J (2011) Carbon accumulation in paddy ecosystems in subtropical China: evidence from landscape studies. *European Journal of Soil Science*, **62**, 29–34.

Xu XY, McGrath SP, Meharg AA, Zhao FJ (2008) Growing rice aerobically markedly decreases arsenic accumulation. *Environmental Science & Technology*, **42**, 5574–5579.

Yan X, Yagi K, Akiyama H, Akimoto H (2005) Statistical analysis of the major variables controlling methane emission from rice fields. *Global Change Biology*, **11**, 1131–1141.

Yao F, Huang J, Cui K *et al.* (2012) Agronomic performance of high-yielding rice variety grown under alternate wetting and drying irrigation. *Field Crops Research*, **126**, 16–22.

Zhao FJ, McGrath SP, Meharg AA (2010) Arsenic as a food chain contaminant: mechanism of plant uptake and metabolism and mitigation strategies. *Annual Review of Plant Biology*, **61**, 535–559.

Zou J, Huang Y, Zheng X, Wang Y (2007) Quantifying direct N_2O emissions in paddy fields during rice growing season in mainland China: dependence on water regime. *Atmospheric Environment*, **41**, 8030–8042.