The Economic Viability of Alternative Wetting and Drying Irrigation in Arkansas Rice Production

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ABSTRACT

As water becomes scarcer in rice (*Oryza sativa* L.) production regions throughout the world, producers are becoming aware of the importance of increasing water use efficiency. Thus, new rice production methods which increase water use efficiency (WUE) are beginning to be adopted. This study analyzes one such alternative production method and its economic feasibility in Arkansas. Alternate wetting and drying (AWD) irrigation has the potential to address the concerns of groundwater depletion as well as greenhouse gas emissions (GHG) associated with rice production. Field experiments were conducted in 2012 and 2013 in the Arkansas Delta for three different AWD irrigation regimes and compared to continuous flooded rice. Data collection included CH_4 and N_2O emissions, grain yields, and irrigation total water use. Relative to continuous flooding WUE increased by 21 to 56% with the adoption of AWD irrigation and global warming potential (GWP) decreased by 45 to 90%. One common criticism of AWD is the potential for reduced yields and subsequent reductions in producer profits. Our results indicate that some AWD regimes are currently economically competitive even without incentives such as GHG reduction payments or water conservation payments. These results suggest that there is currently an economic rationale for adoption of some AWD regimes and those AWD regimes that are not currently economically competitive may be in the future as groundwater levels recede. A county-level break-even analysis indicates an additional depth to ground water of only 5 to 10 m will result in other AWD practices evaluated here becoming profitable.

Agriculture in many parts of the world is faced with increasing water scarcity which is predicted to get worse (Jacob et al., 2014), threatening the sustainability of agricultural systems and food security. Rice is a major consumer of water relative to many other crops but is the staple food for almost half of the world's seven billion people and the staple of nearly 560 million impoverished consumers in Asia alone (IRRI 2013). This study focuses on Arkansas which produces approximately half of the total U.S. rice production. In Arkansas, groundwater depletion in the rice-producing region is a pressing concern. The current irrigation level is unsustainable because water use exceeds recharge. In 2004, the Arkansas Natural Resources Commission (ANRC) estimated groundwater withdrawals at 24.6 billion liters per year, a 70% increase from the amount used in 1985 and over 12 times that of 1945 (ANRC, 2013). To reach sustainable pumping levels, the U.S. Geological Survey's 2013 estimates that certain rice growing counties in the Arkansas Delta will need to reduce irrigation pumping rates by as much as 74% (USGS, 2013) (Fig. 1). With

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Copyright © 2015 by the American Society of Agronomy, 5585 Guilford Road, Madison, WI 53711. All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. water supplies declining at these rates, the long-run viability of water-intensive agriculture such as rice production is at risk. Irrigation techniques that are more water efficient have the potential to sustain the current crop cultivation over a longer time. This will give the agricultural economy more time to adjust to rising cost of water.

Alternate wetting and drying irrigation of rice is a practice where the producer allows the rice field soils to drain intermittently (either intentionally or naturally through evapotranspiration and percolation) during the rice life-cycle rather than having the field continuously flooded. The rate and timing of water applications is a function of rainfall, soil moisture, soil type, and rice growth stage. Previous studies have shown that AWD can increase water use efficiency by reducing seepage and percolation during production as well as making full use of rainfall during the growing season (Linquist et al., 2014). Several studies (Guerra et al., 1998; Bouman et al., 2007) have shown that water-saving irrigation techniques such as AWD have the potential to reduce total water usage by 20 to 70% without causing yield losses. However, in a comprehensive review of 31 published articles, Bouman and Toung (2001) reported that 92% of the AWD studies resulted in yield reductions, as much as a 70% lower yield relative to flooded rice. The large range in yield reductions was due to the differences in "severity" of AWD treatments in terms of water stress. Previous studies in the mid-South concluded that rice produced under non-flooded conditions using furrow and sprinkler irrigation

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



Fig. I. County level percentage of 2009 water use sustainable for the Alluvial Aquifer based on 1997 pumping rates.

were not economically viable due to large yield penalties (Van der Hoek et al., 2001). However, until recently, AWD had not been evaluated in U.S. rice production systems.

Rice production has also been identified as a significant source of atmospheric methane (CH₄) emissions globally (Linquist et al., 2012). Flooded-rice production accounts for 11% of total agricultural methane emissions in the United States, ranking third behind enteric fermentation and manure management (Rosegrant et al., 2008; USEPA, 2009a, 2009b). Furthermore, yield-scaled global warming potential (GWP), a metric that accesses the GWP per unit of yield (Van Groenigen et al., 2010) is much higher for rice systems than other cereal systems (Linquist et al., 2012). Flooding the soil is a prerequisite for sustained emissions of methane. Periodic aeration of flooded soils inhibits methane-producing bacteria; as such AWD can substantially reduce methane emissions (Xiaoyuan et al., 2005). The Intergovernmental Panel on Climate Change (IPCC, 2006) recognizes the effects of aeration on CH₄ emissions with an average of 40% reduction in CH₄ emissions for single aeration events and 48% for multiple aeration events. Previous studies have shown that AWD can also promote N₂O production. Wassmann et al. (2009) concluded that while there were conflicting reports on the net GWP of AWD, but there is a growing consensus that this practice decreases the net GWP of paddy fields.

In 2012 and 2013, three AWD practices that varied in severity were evaluated in Arkansas. This experiment showed that, relative to the flooded control and depending on the AWD treatment, yields were reduced by <1 to 13%; water use efficiency was improved by 18 to 63%, and GWP reduced by 45 to 90% (Table 1). In general, as the aeration duration resulting from the AWD increased, yields declined while the other benefits of decreased water usage and GWP increased. The reduction in GWP was mostly attributed to a reduction in CH₄ emissions as changes in N₂O emissions were minimal among treatments.

Following up on that experiment in which the agronomic and environmental benefits were evaluated, the purpose of this study is to (i) compare profits of three AWD practices to traditional flooding (ii) introduce a C payment from an offset market for GHG reduction and estimate profitability between AWD and traditional flooding (iii) introduce a water payment equivalent to the social value of water and use this criterion to re-estimate profitability of AWD and traditional flooding. The data used in this study consist of total water usage, methane and nitrous oxide emissions, and yields across 2 yr (3 site-years total), and three AWD treatments.

[able 1. Mean (2012 and 2013) yields, CH4 and №	2O emissions, global warming potential (GWP) and water usage for each water	management practice.
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Irrigation type	Yield	CH ₄ emission	N ₂ O emission	GWP†	Water use
	kg ha ⁻¹	kg CH₄–C ha ^{−I}	kg N₂O−N ha ^{−I}	kg CO₂eq ha ^{−I}	m ³ ha ⁻¹
Flood‡	10,260A	105A	0.03A	3520A	7939A
AWD/40-Flood	10,170AB	55.IA	0.17A	1922B	6512AB
AWD/60	9730B	6.88 A	0.28A	359C	5452BC
AWD/40	8970C	7.73B	0.51A	494C	4438C
ANOVA					
Year (Y)	§	***	ns¶	***	ns
Rotation (R)	***	*	*	*	na
Treatment (T)	*	§	ns	§	*
R×T	ns	ns	ns	*	na
Υ×Τ	ns	ns	ns	ns	ns

* Significance at 0.05.

*** Significance at 0.001.

 \dagger Global Warming Potential (GWP) is the summation of N₂O and CH₄ in CO₂ equivalents (CO₂ eq).

 \ddagger Means followed by the same letter are not different at P < 0.05 using adjusted Tukey mean comparison.

§ Significance at 0.0001.

 \P ns, not significant. na, not applicable as rotational effects were not considered in this analysis due to limited replication.

MATERIALS AND METHODS

Field experiments were conducted in 2012 and 2013 at the University of Arkansas' Rice Research and Extension Center near Stuttgart (34°27′ N, 091°24′ W) to evaluate three AWD treatments relative to a continuously flooded control. Details and results of this study are reported by Linquist et al. (2014); however, below we provide some background information on this study. The experiments were conducted in separate fields with different crop rotations common to Arkansas: rice–rice and rice–soybean. The experiments were all conducted on adjacent fields, had the same treatments and were managed similarly. The soils on all fields were Dewitt silt loam (fine, smectitic, thermic, Typic Albaqualf) with total C content of 0.67%, total N content of 0.075%, and a pH of 5.6 (1:2 soil/water).

In both years the study contained four replications and the following four water treatments: (i) Flood, (ii) AWD/40-Flood, (iii) AWD/60, and (iv) AWD/40 where AWD represents alternate wetting and drying followed after the backslash by the percent of saturated soil water holding capacity at which fields were re-flooded to a depth of 10 cm. Thus AWD/60 would indicate an alternate wetting and drying regime where water was applied when the saturated soil water holding capacity was under 60% at a depth of 10 cm. The flood treatment was managed according to traditional practices for drill-seeded rice with a permanent flood being established about 30 d after planting. For the AWD/40-Flood treatment the AWD/40 management was maintained from initial flood (about 30 d after planting) until the plants reached the R0–R1 growth stage (start of panicle development and formation of panicle branches) (Counce et al., 2000), after which a 10-cm flood was maintained until the field was drained. All rice (hybrid CLXL745, released by RiceTec, Houston, TX) plantings were dry seeded. For the AWD water treatments, the initial floods were maintained for 10 d after which they were allowed to dry via evapotranspiration. When any treatment reached the R7 (at least one grain on the main stem panicle has a yellow hull) growth stage (Counce et al., 2000), no further water was applied, and the plots containing water were drained. A 3.0 by 30.5-m area of each plot was harvested to determine grain yield and samples for further analysis.

All data were analyzed for normality using the Shapiro-Wilk approach and data that did not pass the test (total CH_4 and N₂O emissions) were log transformed (P = 0.00-0.05). Yield, GHG emissions, and GWP due to the main effects of water management, year, rotation, rotation × water management, and year × water management; and block × water management as random effect were analyzed using PROC MIXED (SAS Institute, 2010). Since there were no interaction effects between year and water management treatment, differences in yield, and total CH4 and N2O emissions, data were analyzed using PROC MIXED with Tukey for multiple treatment mean comparisons at P value < 0.05 (SAS Institute, 2010). Rotational effects were not considered for water use due to limited replication (Linquist et al., 2014). Water use due to the main effects of water management, year, and year × water management; and block × water management as random effect were analyzed using PROC MIXED (SAS Institute, 2010). We used the adjusted Tukey to compare means of water treatments based on an unbalanced data set (SAS Institute, 2010).

Fluxes of CH_4 and N_2O were measured (Table 1) using static vented flux chamber technique (Hutchinson and Livingston, 1993). Gas flux measurements were conducted at daily to weekly intervals during the entire growing season. Cumulative seasonal gas emissions were determined by assuming that emissions followed a linear trend on days when gases were not measured. To determine total water use, each inlet was equipped with flow meters. The only drainage occurred at the end of season in preparation for harvest.

Other Greenhouse Gas Emissions

Multiple GHG's associated with global warming, were converted to their CO_2 equivalent (CO_2 eq) to obtain a "carbon footprint" for all inputs used in rice production. Values provided by the U.S. Environmental Protection Agency (USEPA) were used for diesel. EcoInvent's life cycle inventory database through SimaPro 7.1(2009) was used to calculate the upstream emissions from the production of fuel. Typically the life cycle inventory (LCI) includes both direct and indirect emissions were those that came from on-farm operations. Examples are CO_2

emissions from diesel used by tractors and irrigation equipment and gasoline used by farm trucks. Indirect emissions were generated off farm as a result of manufacturing inputs used on the farm. Examples are GHG emissions from natural gas to produce commercial fertilizer.

The GHG reductions in this study are a result of switching from traditional flooding to an AWD irrigation regime resulting in less methane emissions from a reduced flood and reduced CO_2 emissions from reduced diesel required for irrigation. This study assumes that water for irrigation is pumped from the average depth of the Alluvial aquifer on the Arkansas side of 22.58 m (ANRC, 2013) using a diesel pump which requires 0.0117 L of diesel to raise 1 m³ of water, assuming 75% pump efficiency and 5% drive loss (Slaton 2001). Roughly 50% of irrigation wells in Arkansas are powered by electric motors. That being said, the amount of CO_2 released to raise 1 m³ of water using an electric motor is higher given that the majority of Arkansas electricity is provided by coal burning power plants (USEIA, 2014). Thus, the estimates from this study for irrigation emissions should be slightly conservative.

Carbon Payments

A mitigation price of US\$7.66 Mg⁻¹ of CO₂ equivalent (eq) was used as it was the 2014 May futures price on the European Carbon Futures market on the European Energy Exchange (EEX). Carbon payments for diesel use reduction for irrigation are relatively small compared to those for methane (given methane emissions for flooded rice often exceed a 3 Mg of CO₂ eq ha⁻¹). However, pumping costs, diesel usage, and associated CO₂ eq for pumping will increase as depletion of the Alluival aquifer continues as more fuel is needed to raise water from greater depths. This means that C payments should increase over time with the decreasing groundwater level, all else being equal.

Water Payments

To calculate an appropriate payment for reducing groundwater use, we determined the social value of leaving water in the aquifer, and then set the payment equal to this social value. The value of the aquifer includes the capacity of ground water to (i) buffer against periodic shortages in surface water supplies; (ii) prevent subsidence of the land surface; (iii) protect water quality by maintaining capacity to dilute groundwater contaminants; and (iv) provide discharge to support recreational activities and facilitate ecological diversity. We adopted a conservative estimate by calculating only the value to buffer against periodic shortages in surface water. The buffer value is the economic value of the risk management or stabilization role for agriculture of ground water.

Consider an uncertain supply of surface water, *S*, with a distribution having mean m and the variance σ^2 ; *F*() represents per hectare yield response to water, and *p* is the net unit value of the crop. Tsur (1990) showed that buffer value can be approximated by 0.5 *p*[-*F*"(m)] σ^2 . This indicates that the buffer value depends on the value of marginal productivity of water at m, the degree of concavity of *F* at m, and the variance of surface water supply σ^2 . We assumed that buffer value would remain constant over time although m and σ^2 would be affected by the changing climate and *p* would depend on market conditions.

To determine the values of m and σ^2 , 13 yr (2000–2012) of monthly rainfall data were collected from the Wynne, AR (an available weather station in the major rice-producing area of Arkansas) weather station from June to September when ground water is typically applied to Delta rice (NOAA, 2013). For the 4 mo season over the 13 yr, the average seasonal rainfall was 1234 m³ ha⁻¹ and the variance of the seasonal rainfall was 204,977 (m³)².

Data on rice yield for varying levels of water input came from field observations of alternate wet–dry and flood irrigation treatments. Several functional forms were estimated for the response of rice yield to water input, and the natural log form was chosen based on fit to determine the concavity of rice yield response to water input at the average rainfall for the season, [-F"(m)], estimated to be 3.39×10^{-4} kg (m³)². The net unit value of rice is the price of a kg of rice from the 5-yr average of December futures prices for harvest time contracts (GPTC, 2014) at US\$0.31 kg⁻¹ less the costs of production for a kilogram of rice based on production budgets¹ (University of Arkansas–CES, 2014) of \$0.161 kg⁻¹, making the net unit value of rice equal to \$0.15 kg⁻¹.

The buffer value for 1131 m³ of ground water which is roughly the difference of the water applied for conventionally grown and AWD rice is: $0.5 p[-F"(m)]\sigma^2 = 0.5 \times 0.149 \times$ $3.39 \times 10^{-4} \times 204,977 = 5.18 . The estimate for the buffer value per m³ is then: \$5.18/1,131 m³ = \$0.00458 per m³.

Comparison of the Profitability of the Irrigation Regimes

Profit for irrigation regime *j* can be written as:

$$\prod_{j=(PY_{j})-C_{j}+(P_{CO_{2}}X_{CO_{2}j})+(P_{H_{2}O}X_{H_{2}Oj}) \qquad [1]$$

where *P* is the March 2014 price for a kilogram of rice, Y_i is yield of under irrigation regime j, C_i is the cost of irrigation for régime j. Other costs of production (seed, fertilizer, herbicide, fungicide, etc.) were assumed fixed because the same variety was used for all trials and thus dropped out of our relative comparison. Thus, profit in *absolute* terms estimated in Eq. [1] was high but the relative differences among profits were unbiased. Differences across other fixed costs (soil moisture meter, etc.) warrant further research. P_{CO2} is the price of a tonne of CO₂ and X_{CO2i} is the amount of total GHG (CH₄ and N₂O) reduction from irrigation regime j compared with traditional flooding. P_{H2O} is the payment for 1 m³ of water and X_{H2Oi} is the reduced amount of ground water (m^3) from implementing AWD irrigation regime jinstead of traditional flooding. Thus, $(P_{CO2}X_{CO2i})$ can be viewed as a GHG offset or abatement payment for irrigation regime j and $(P_{H20}X_{H20i})$ can be viewed as a water abatement payment for switching from traditional flooding to AWD irrigation regime j. Comparing profits across regimes and incentives (GHG and water payments) can give producers, purchasers of rice, consumers, and industry a better idea of what type of incentives would be needed to produce rice under AWD.

RESULTS AND DISCUSSION

On average, yield loss (although not significant) from AWD/40-Flood was 90 kg ha⁻¹ and with the March 2014 rice futures price of 0.337 kg^{-1} this equates to a revenue loss of

¹The production costs include operating expenses, chemical and fertilizer applications, machinery and equipment, and post-harvest expenses.

Table 2. Water and	greenhouse ga	s (GHG) use efficiency	y b	y flooding	regime
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Irrigation treatment	Water use efficiency	GHG use efficiency†
	kg rice m ⁻³ water	kg rice kg ⁻¹ CO ₂ e
Flood	1.29	2.91
AWD/40-Flood	1.56	5.29
AWD/60	1.78	27.13
AWD/40	2.02	18.15

 \dagger Denotes total global warming potential (GWP) (CH₄ and N₂O) from Table I. CO₂e is all GHG (N₂0, CH₄ and CO₂) in their CO₂ equivalence.

\$30.37 ha⁻¹. While there is not a statistical difference between the observed yields of AWD/40-Flood and traditional flooding, calculations in this paper were derived using the actual observed yields for both. Yield losses associated with AWD/60 and AWD/40 were 530 and 1290 kg ha⁻¹, respectively (Table 1). Given the March 2014 futures market price for rice, switching from traditional flooding to AWD/60 and AWD/40 resulted in a revenue loss of \$178.83 and \$435.27 ha⁻¹, respectively. To put these numbers in perspective, the estimated revenue from traditional flooding was \$3,384.91 ha⁻¹. Thus, based on revenue generated by the rice harvest there would be a disincentive to adopt AWD/40 and AWD/60 flooding unless there were additional revenue incentives (i.e., the potential payments for reductions in GHG emissions and payments associated with water savings) or cost reduction incentives (i.e., reduced diesel usage for pumping ground water).

The average amount of water used to produce 1 kg of rice under traditional flooding was 1.29 m³ (Table 2). Switching from traditional flooding to AWD/40 increased water use efficiency (WUE) by 57%. The AWD/60 treatment increased WUE by 38% and that of AWD/40-Flood increased by 21% compared with traditional flooding. Thus, from a water conservation efficiency standpoint, all forms of AWD were superior to traditional flooding. That being said, there is often a divergence between environmental (GHG and water use) efficiency and profit maximization. Because the value of a stable climate or abundant aquifer are not internalized in the private marketplace, incentives in the form of abatement payments may need to be put in place to encourage efficient use of these resources.

Importantly the AWD/40-Flood treatment was economically viable without adding benefits of C and water payments. Since the yield difference between it and traditional flooding was not statistically significant, profitability should be higher (assuming a frictionless transition) due to lower input costs. However, AWD adoption has been slow, regardless of the increased estimated profitably, as producers lack the information on proper management techniques and are reluctant to adopt until certain of best management practices. Below we explore other incentives that could increase the rate at which AWD is adopted.

Alternate Wetting and Drying vs. Traditional Flooding

By switching from traditional flooding to AWD/40-Flood, a producer could reduce water usage by 1427 m³ ha⁻¹ resulting in a 16.69 L reduction in diesel fuel needed (Table 1). Given an off-road diesel price (January 2014) of \$0.831 L⁻¹ a producer would save \$13.86 ha⁻¹ on diesel costs by switching to AWD/40-Flood from traditional flooding. It requires 0.0117 L to lift 1 m³ of water assuming a 75% pump efficiency and 5% drive loss from a depth of 22.58 m ($0.83 \times 0.0117 \times$ 1,427 = \$13.86). From the example above it was shown that switching from traditional flooding to AWD/40-Flood would on average cost a producer \$30.37 ha⁻¹ in perceived associated yield loss resulting in a net loss of \$16.51 ha⁻¹. This is the same methodology which was used to create Table 3 which indicates from the observed data that by switching to AWD/40-Flood, producers would expect to lose 0.49% of their profits compared with traditional flooding. However, because there is not a statistical difference in the yields between AWD/40-Flood and traditional flooding, producers would experience a gain in profitability from reduced input costs.

Using the same calculations, AWD/60 saves 2487 m³ of water resulting in a diesel cost savings of \$24.15 ha⁻¹. The estimated yield loss with AWD/60 is 530kg ha⁻¹ which equates to a \$178.83 loss ha⁻¹, resulting in a net loss of \$154.68 ha⁻¹, which is equivalent to a 4.57% loss (Table 3). The estimated yield loss for AWD/40 is 1290 kg ha⁻¹ which would equate to a revenue reduction of \$435.27. Based on savings of \$34.00 (3501 m³ difference between traditional flood water usage and AWD/40) in diesel costs, AWD/40 would have a net loss of \$401.27 ha⁻¹, or a loss in revenue of 11.85%. Therefore, with the exception of AWD/40-Flood, which had nearly equivalent profit margins without additional incentives it would not be profitable for producers in Arkansas to adopt any of the other AWD treatments.

The largest historical driver of AWD not being competitive and widely adopted is the risk of yield loss. There was no statistical difference in yield between AWD/40-Flood and traditional flooding which would mean that AWD/40-Flood should be more attractive to a producer because it has similar yields and lower diesel costs. Both AWD/40 and AWD/60 are associated with too large of a yield loss for diesel savings alone to make them competitive. Given the relative prices of diesel and rice, the largest driver is yield loss not cost savings via diesel reduction. Thus, as the incentive structure stands now, there would be little to no incentive to adopt AWD/40 and AWD/60 in Arkansas. If the local/state/federal governments were to impose taxes or offer incentives for GHG emissions and water usage, these irrigation strategies could become more palatable to producers.

Table 3. Profit differences dollars I	u ^{–I} between various a	lternate wetting and dr	ying (AWD) irrigatio	on regimes and traditional flooding
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Irrigation type	Relative to traditional flooding	With CO ₂ Payments†	With H ₂ O Payments/Tax‡	CO ₂ and H ₂ O Payments
AWD/40-Flood	-16.51§	-2.61	-9.97	3.23
	[–0.49]¶	[-0.08]	[-0.29]	[0.12]
AWD/60	-154.68	-127.28	-143.29	-115.89
	[-4.57]	[-3.76]	[-4.23]	[-3.42]
AWD/40	-401.27	-378.10	-385.23	-358.69
	[-11.85]	[-11.07]	[-11.38]	[-10.60]

 $+ CO_2$ eq price of \$7.66 Mg⁻¹.

 \ddagger Social value of water of estimated at \$0.00458 m⁻³ and diesel cost of \$0.83 L⁻¹ with water use differences calculated from Table I.

§ Denotes dollar per hectare difference from switching from traditional flooding.

¶ Number in brackets denote percentage difference from switching from traditional flooding.

Alternate Wetting and Drying with Carbon Payments vs. Traditional Flooding

One option that may make AWD more attractive is to provide producers a GHG payment (\$7.66 Mg⁻¹ CO₂) as compensation for practices that reduce emissions compared with traditional baseline production. While AWD/40 is the largest benefactor of C payments (in the form of GWP reductions), AWD/40-Flood is the most economically attractive alternative, because the observed yield loss associated with AWD/40-Flood (0.88%) which was not statistically different from traditional flooding, is substantially less than that of AWD/40 and AWD/60, 5.45% and 14.38%, respectively (Table 3). The C payment is calculated by taking the difference in GWP and multiplying that by the price of Mg⁻¹ of CO₂ eq. As an example, the GWP of flooding was estimated at 3520 kg CO2e ha⁻¹ (Table 1), by switching to AWD/40 a producer would reduce that to 494 kg ha⁻¹ or a difference of 3026 kg ha⁻¹ which is divided by $1000 (\text{kg Mg}^{-1})$ to obtain a reduction of 3.03 t CO₂ eq ha⁻¹. Using the May 2014 European Carbon exchange price for Mg⁻¹ of CO₂ eq at \$7.66 this would result in a GHG abatement payment of 23.17 ha⁻¹. Added to the revenue loss of \$401.27 ha⁻¹ (calculated above), this would indicate that net loss would be equivalent to \$378.10 ha⁻¹ (column 2 in Table 3 is created in this manner). Given the same methodology a GHG abatement payment would result in a \$2.61 ha⁻¹ profit loss for AWD/40-Flood and \$127.28 loss ha⁻¹ for AWD/60 compared with traditional flooding.

Alternate Wetting and Drying with Water Payments vs. Traditional Flooding

When payments are made to producers who adopt AWD (or taxes are applied to those who use traditional flooding) equivalent to the social value of ground water (\$0.00458 m⁻³) the economic impacts are smaller compared with GHG abatement payments. Here, AWD/40 appears to have the most to gain economically because of its small water footprint compared with traditional flooding, a reduction of 44.1%. However; large water savings and their subsequent social value payment cannot overcome the large yield reduction associated with AWD/40 and thus it still is the least attractive of the three alternative irrigation methods in terms of profitability. To calculate the total social value of water the model derives total water savings and multiplies it by the social value of water. Thus, by switching from flooding to AWD/40, a producer would receive a payment of \$16.03 ha⁻¹ for 3501 m³ of water saved at a price of 0.00458 m^{-3} . Alternatively, instead of a payment to a producer who adopts AWD/40, this could be a tax on a producer who implements traditional flooding, which in the end results in the same economic outcome. As calculated above, revenue lost from yield reductions for AWD/40 was \$435.27 ha⁻¹. Adopting AWD/40 saves \$34.00 ha⁻¹ in pumping costs due to the reduced amount of diesel needed to irrigate. Given the \$16.03 ha⁻¹ payment for the social value of water plus the \$34.00 ha⁻¹ cost reductions, their profit would be estimated as \$385.23 ha⁻¹ less (Table 3 column 3). Using the same methodology, switching to AWD/40-Flood would lose \$9.97 ha⁻¹ (0.29%) and \$143.29 ha⁻¹ (4.23%) by switching to AWD/60. Again, it appears that profits with AWD/40-Flood and traditional flooding are similar, but payments made to

producers equivalent to the social value of water for adopting AWD/60 and /40 are not enough of an economic incentive to entice a switch from traditional flooding.

Alternate Wetting and Drying with Carbon and Water Payments vs. Traditional Flooding

If a payment for ground water and CO_2 reductions were both implemented, then the changes in revenue compared with traditional flooding would range from 0.12 to -10.60% (Table 3). Switching from traditional flooding to AWD/40 results in a loss of \$358.69 (10.6%) ha⁻¹ and \$115.89 (3.42%) ha⁻¹ by switching to AWD/60. Conversely, AWD/40-Flood, which was shown to be more profitable than traditional flooding due to lower input costs and equivalent yields, becomes even more profitable than traditional flooding with water and GHG abatement payments. Estimates indicate that profits would increase by \$3.23 (0.12%) ha⁻¹ (Table 3).

A sensitivity analysis was conducted to indicate the robustness of the model under varying input and output prices, and relative rankings of profitability only switched under nonsensical C and diesel prices. Currently, C markets are thinly traded in the United States and thus few places to purchase offsets exist which was the rationale for using the higher volume European C price of EU\$7.66 Mg⁻¹. The EPA predicted a U.S. C price between \$10 and \$30 per tonne if the Waxman–Markey Bill would have passed in 2011 (USEPA, 2011). Other caveats about this study are the pumping depth used of 22.58 m. This will probably increase if the Alluvial aquifer continues to fall. In many places in the aquifer, 30+ m wells are common and thus AWD would look more attractive. Again, the largest driver of AWD not currently being competitive is the associated yield loss or risk thereof. Adoption has been minimal even though research has shown some AWD regimes can maintain the yield of traditional flooding. As aquifer levels continue to fall, scientists, policymakers, and producers will need to conceive and improve water use efficiency in production agriculture. Regardless of potential C markets or water taxes, if production methods like AWD/40-Flood can maintain current yields and reduce input costs and water requirements, producers will likely increase adoption rates.

Aggregate Level Breakeven Analysis

In this study, yields of 10,159, 10,188, and 10,219 kg ha⁻¹ are required for AWD/40, AWD/60 and AWD/40-Flood, respectively to make producers indifferent (in a profitability sense) to

Table 4. Breakeven values for yield (kg ha ⁻¹), CO ₂ (dollars Mg ⁻¹) and
water (dollars per m ³) at which three alternate wetting and drying
(AWD) irrigation regimes would have profits equal to the profits of
producing rice under traditional flooding.

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Irrigation type	Breakeven yield†	Breakeven CO ₂ price‡	Breakeven social value of water§
	kg ha ⁻¹	\$ Mg ⁻¹	\$ m ³
AWD/40	10,159	\$115.82	\$1.26
AWD/60	10,188	\$43.25	\$0.68
AWD/40-Flood	10,219	\$9.09	\$0.12

† Traditional flood was associated with a yield of 10,260 (kg ha⁻¹)
‡ Current May 2014 European Climate Exchange CO₂ eq price of \$7.66 Mg⁻¹.
Assumes yields as reported on Table I.

 $\$ Estimated current social value of water in Eq. [1] is \$0.00458 per cubic meter. Assumes yields as reported on Table 1.

traditional flooding which yielded 10,260 (Table 4). Thus, if there were not additional benefits to AWD, then yield reduction of AWD would need to be <1% compared to traditional irrigation for AWD to be competitive. However, when looking at the introduction of a C market and analyzing the C price necessary to equalize profits between these AWD systems and traditional flooding, AWD/40-Flood requires a price of \$9.09 Mg⁻¹of CO₂, or an 18% increase from its current European price of EU\$7.66 Mg⁻¹. In the same respect, AWD/40 and AWD/60 would require CO₂ prices of \$115.82 and \$43.25 Mg⁻¹ of CO₂ which appear unreasonable at current levels of C trading. When looking at a water payment equal to the groundwater buffer value of water, none of the AWD options are able to breakeven due to the fact that the break-even payment would have to be so much higher than the social value of water. A pumping tax of \$0.12 m³ (or a 2620% increase from the current estimate of the social value of water) would be required for AWD/40-Flood to break even with traditional flooding. The AWD/40 and AWD/60 would need a tax of \$1.26 and \$0.68 m³ to breakeven.

While the average depth of the Arkansas portion of the Alluvial is 22.59 m there is a large variation across the Delta. Depth to water ranges from 6.71 m (Independence County) to 44.17 (Lonoke County) (Fig. 2a). These differences would affect the adoption of AWD given the different pumping costs and GHG emissions (associated with pumping) and warrant further discussion. Given the analysis above it appears that AWD/40-Flood would be the first of the AWD alternatives to be adopted, so it will be used as the reference flooding regime. For example, in Lonoke County, if the water table dropped 4.59 m then profits would be equivalent between AWD/40-Flood and traditional flooding without GHG or water payments (Fig. 2b). Figure 2b can be viewed as a potential adoption map for AWD regimes as it shows the relative "distance" to profit equivalence.

There are currently nine counties for which, the introduction of a C market trading at \$7.66 Mg⁻¹ of CO₂, are estimated to make more money with AWD/40-Flood than traditional flooding, all else equal. The top five rice-producing counties in Arkansas in 2012 (Poinsett, Arkansas, Lonoke, Cross, and Prairie) are



Fig. 2. Arkansas Alluvial Aquifer study area, (a) current depth to water for the study area, and (b) aquifer reduction, and (c) CO_2 price required for alternate wetting-drying (AWD)/40-Flood to breakeven with profits of traditional flooding.

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Table 5. Average percent reduction in yield, water usage, and CH_4 and N_2O emissions from converting from traditional flooding to various alternate wetting and drying (AWD) irrigation regimes.[†]

Irrigation type	Average yield difference	Average water usage difference	Average CH ₄ difference	Average N ₂ O difference	Average GWP difference
AWD/40-Flood	-0.88%	-17.97%	-47.52%	461.29%	-45.41%
AWD/60	-5.45%	-31.33%	-93.45%	789.25%	-89.81%
AWD/40	-14.38%	-44.10%	-93.62%	1530.11%	-85.97%

† Based on data presented in Table I.

among the nine, indicating that the major rice-producing areas could be the first to adopt AWD, driven by their water-level situations. There are costs with monitoring CO₂ reductions, but some counties have a breakeven CO₂ price as low as \$1.47 Mg⁻¹ of CO₂ which means that even with lower CO₂ prices, some counties could find AWD/40-Flood more profitable than traditional flooding given the introduction of a C market.

Greenhouse Gas and Water Efficiency

As resources like water become depleted, efficient use of those resources becomes more important in economic decision making. That is, producers will become more attuned to the marginal return they get for the application of every unit of water as water availability decreases. The above results have indicated that while AWD/40 and AWD/60 appear not to have an economic advantage, it does not speak to the efficiency in which water is being used and GHGs are being released. Unfortunately in this context, economic and efficiency optimization diverge given the low relative price of inputs (water and GHG). Table 5 illustrates the GHG and water efficiency gains attributed with converting to AWD irrigation. These results indicate that on average flooding results in 1.29 kg rice m^{-3} water applied. In comparison, AWD/40 produced 2.02 kg of rice m⁻³ of water a 56% increase in efficiency. Similarly, AWD/60 and AWD/40-flood produced 1.78 and 1.56 kg of rice m³, respectively. This is a 38 and 21% increase in efficiency, respectively. Ironically, these increases in efficiency are inversely related to economic profitability, again due to the fact water and GHG are valued so marginally. In terms of GWP, in the traditionally flooded treatment 2.91 kg of rice is produced kg⁻¹ of CO₂e. In comparison, AWD/60 produces 27.13 kg of rice kg⁻¹ of CO₂e, an 832% increase in efficiency. Similarly, AWD/40 and AWD/40-flood produced 18.15 and 5.29 kg of rice m⁻³, a 524 and 82% increase in efficiency, respectively

Perhaps the estimated yield reductions from two of the three AWD regimes (there is no statistical difference between AWD/40-Flood and traditional flooding), are the causes of resistance for some producers to adopt AWD unless water becomes more expensive. That being said, given the decreases in the Alluvial aquifer, producers should look at the marginal value of water, not simply yield ha⁻¹. Using the same amount of water as traditional flooding, a producer could grow 1.22 ha of AWD/40flood rice and produce 21% more rice (Table 6). Using the same notion, a producer could use 1.46 and 1.79 ha and produce 38 and 56% more rice under AWD/60 and AWD/40, respectively, with the same amount of water as traditional flooding. Increasing water limitations are already evident by the fact many producers sacrifice up to 10% of their land for on-farm reservoirs. If, as is likely, profit maximization becomes more heavily influenced by water availability, then producers will most likely increase the adoption of AWD regimes.

Table 6. Standardized water usage and yield comparisons for traditional flood and various alternate wetting and drying (AWD) flooding regimes.

Irrigation type	Actual water usage†	Standardized to flood†	Area planted‡	Weight§
	m	³ ha ⁻¹	ha	kg
Flood	7939	7939	1.00	10,260
AWD/40-Flood	6512	7939	1.22	12,399
AWD/60	5452	7939	1.46	14,168
AWD/40	4438	7939	1.79	16,046

†As derived on Table I.

‡ Flood water divided by actual water used.

§ Hectares multiplied by yield (kg ha⁻¹) as reported on Table 1.

CONCLUSIONS

Relative to traditional flooding, switching to AWD lowers producer profits by 0.88 to 18.58% with profit reductions largely based on duration of flood withdrawal that impact rice yields. That being said, the profit reduction associated with AWD/40-Flood (0.88%) was found not to be statistically different from conventional flooding, meaning that even without incentives it appears to be economically competitive. With the exception of AWD/40-Flood, the optimal environmental (GHG and water) and economic outcomes diverge without further economic incentives such as a C or water conservation payment.

To date, there has been little to no adoption of AWD in Arkansas and the mid-South. This is attributable to a number of factors such as a lack of available information on AWD management, land owner/tenant agreements that do not cover production management changes that could result in lower returns to the land owner, C markets that are not developed, and no statewide programs that either reward the use of AWD or discourage the overuse of water. As producers are made more aware of the potential of AWD to reduce costs (via input reductions) and maintain existing yields, adoption rates are likely to increase. The AWD is one management practices among many (e.g., drought resistant rice cultivars, etc.) that could reduce water use and curtail GHG emissions. Rice producers in the mid-South are beginning to internalize falling aquifer levels as they sacrifice productive land to build on-farm reservoirs. While C markets and water taxes have the potential to make water saving production practices like AWD more attractive, the increasing reality is that water reducing practices may be a necessity in the near future for rice production. The AWD regime AWD/40-Flood examined in this study, was economically competitive with traditional flooding without C markets or water taxes. Those AWD regimes that are not currently competitive look to be in the future as county-level break even analysis indicates an additional depth to ground water of only 5 to 10 m in several Arkansas counties before profits are equivalent between them and traditional flooding regardless of a water tax or C payment.

Given that the cultivar in this study was bred to be produced in flooded environments, it stands to reason that some AWD regimes had yield reductions compared with traditional flooding based on the physiological response of the cultivar. These yield reductions could be mitigated if rice breeders in the United States placed more emphasis on identifying and developing rice cultivars that would respond more favorably to some of the more extreme AWD regimes. Studies such as this, should be seen as only one part of a larger effort to develop sustainable rice production in regions where water is becoming scarcer. Economic studies like this one can be used to help biological scientists conceive research that will improve both environmental sustainability as well as increase economic returns. Achieving sustainable rice production will be through integrated approaches that include agronomic, soils, biological, hydrologic, and other scientific disciplines whose research can be guided by the type of economic analysis presented in this study.

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