Effects of Water-Saving Rice Cultivation Methods on Yield, Water Use, and Water-Use Efficiency

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ABSTRACT

Water available for irrigation is declining in many rice-growing regions around the world. Global populations continue to rise increasing crop production demand. Rice production systems must face the dilemma of maintaining or increasing yields with less water available to irrigate. Alternate wetting and drying (AWD) has shown to be an effective tool for water conservation in irrigated rice systems. Research on AWD practices is lacking and more information is needed to verify the success of AWD across varying soil types. More work is needed to develop clear recommendations for AWD irrigation practices in Arkansas. In this study we compared the effects of three different AWD regimes and a continuous flood management on rice yields and water-use efficiency (WUE) from a conventional variety (RoyJ) and a hybrid (XL753). The study was located in the northeast corner of the Mississippi delta rice-growing region in Arkansas and results were complicated by a high rainfall pattern in 2014; even with this complication, results indicated that AWD is a feasible water management practice for rice in Arkansas. For both varieties, all AWD regimes tested in this experiment were associated with a loss in yield, the hybrid cultivar had a higher yield than the conventional variety in all treatments. Water-use efficiency for the wettest AWD treatment was higher than the conventional flood treatments and the dryer AWD treatments. Differences in WUE between varieties approached significance differences, and suggests that the hybrid may have a higher WUE than the conventional cultivar.

INTRODUCTION

Water available for irrigation is declining in the main crop-growing regions. Irrigation is the largest component of fresh water use (Haddeland et al., 2014). High water use and drought are depleting water available for human use (Schewe et al., 2014). The alluvial aquifer in the east-central region of Arkansas is being depleted at unsustainable rates (ANRC, 2012). It has been estimated that 1.8 billion people will be living in regions with absolute water shortages and as much as two-thirds of the global population may be under water stress conditions by 2025 (FAO, 2013). Global populations continue to rise increasing crop production demand. Ray et al. (2013) estimates that global crop production needs will double by 2050 with an increase of 2.4% annually. Agricultural production systems must face the dilemma of maintaining or increasing yields with less water available to irrigate. Globally, rice production systems account for one-third of the total fresh water use (Bouman, 2009). Although rice and other crops have similar transpiration rates, substantially more water loss is associated with anaerobic rice cultivation practices than aerobic crop production systems due to soil percolation losses and evapotranspiration (Bouman, 2009). Water shortages coupled with the high costs associated with irrigation create the need to research alternate production methods that minimize water use while maximizing/maintaining yields. This can also be referred as water-use efficiency (WUE) measured as unit of grain per area divided by the volume of water applied per area. Such information will help guide rice producers that face the dilemma of water shortages first hand and provide viable alternative methods to minimize profit losses.

One such method that has been receiving increased attention in recent years is a rice production method referred to as alternate wetting and drying (AWD). Alternate wetting and drying combines the beneficial side effects of anaerobic rice cultivation (nematode and weed control), and aerobic cultivation practices (reduction in water use, grain toxin builds, and greenhouse gas emissions; Price et al., 2013). Alternate wetting and drying has shown to be an effective tool for water conservation in rice production systems. Zhang et al. (2009) found that AWD can lower water use in rice production by ~35%, while maintaining and even increasing rice yields relative to continual flood methods. Not only does this method reduce water use, but also it has been shown to be very effective in reducing greenhouse gas emissions that result from the brief aerobic periods (Yan et al.,2005; Feng et al., 2013), and at reducing buildup of arsenic in rice grains (Takahashi et al., 2004;Talukder et al., 2012).

In the literature, AWD methods in comparison to anaerobic rice cultivation have a range of results: no difference in yields, yield increases, and yield decreases. Davies et al. (2011) reviewed existing literature and found that mixed results on yield differences is likely dependent on severity of the soil moisture deficit during the dry-down events. This implies that target deficits will vary with differences in soil characteristics. An extensive study has been conducted in the Grand Prairie rice-growing region near Stuttgart, Ark. Linquist et al. (2015) found that in Dewitt silt loam soils, although yields were reduced less than 1% to 13%, the WUE was improved by 18% to 63% and AWD (early season) followed by flooding practices (late season) reduced water use by 18% while maintaining similar yields to that of flooded controls. Research on AWD practices is lacking in other regions of the state and across varying soil types, more work is needed in order to develop clear recommendations for AWD irrigation practices in the state of Arkansas. In this study we compared the effects of three different AWD regimes and a continuous flood management, on rice yields from a conventional variety (Roy J) and a hybrid variety (XL753) grown on Sharkey silty clay soils in the northeast corner of the Mississippi delta rice-growing region in Arkansas.

PROCEDURES

This study was conducted at the University of Arkansas System Division of Agriculture's Northeast Research and Extension Center near Keiser, Ark., in 2014. The soil type was a Sharkey silty clay with 3% sand, 33.1% silt, and 63.9 % clay (USDA-NRCS, 2013). Saturation, field capacity, and wilting point were calculated using Soil-Plant-Atmosphere-Water (SPAW) software's (USDA-ARS, Washington State University, Pullman Wash.) soil water characteristics with the soil equation of Saxton et al. (1986) and were determined to be 45.1%, 34.5%, and 13% volumetric soil water content (VWC), respectively. Rice was drill-seeded at a rate of 90 lb/acre for the conventional and 30 lb/acre for the hybrid on 8 May 2014 and plants emerged 18 May 2014. No irrigations were applied until the initial flood 11 July 2014, rainfall was sufficient for stand establishment. Plot sizes were 30 ft × 100 ft (3,000 sq ft), separated by dual packed levees to prevent water movement between plots. Plots were planted half with a conventional variety (RoyJ) and half with a hybrid (XL753) of which 800 sq ft of each variety in each plot was harvested on 9 October 2014.

The study involved four water management treatments replicated four times in a randomized complete block design. Treatments were: 1) flood (continuously flooded control), 2) AWD/16% VWC, 3) AWD/24% VWC, and 4) AWD/32% VWC. The AWD represents alternate wetting and drying followed by the volumetric soil water content. Thresholds and fields in each treatment were allowed to dry until a reflood was applied. Note: thresholds were selected based off previous studies, which had this soil type with a saturation point of 40.0% with triggers at 60% saturation (24% VWC) and 40% saturation (16% VWC) (Linquist et al., 2015); 32% VWC was selected based off of 80% saturation of the soil type with a saturation point of 40%. The plant available water of this soil is 21.5% VWC (difference between field capacity and wilting point). The actual deficits the trigger levels represent are deficits corresponding to 12% (32% VWC trigger), 49% (24% VWC trigger), and 86% (16% trigger). The highest deficit of 86% (or lowest VWC trigger of 16%) is near the wilting point, so it should be noted that this is a trigger level that is far too extreme for rice AWD. The authors caution other researchers to evaluate the available water-holding capacity of their soil types and use a managed allowable depletion that is reasonable for the soil type. Using the percent of field capacity, as has been done in other studies may not be appropriate to represent plant available water in different soil types.

All treatments were flooded to a 2- to 3-inch depth for 10 days (11-21 July) after the preflood nitrogen (i.e., urea) fertilizer application of 145 lb N/acre (8 July). In the flooded treatments, this flood depth was maintained throughout the growing season. After the initial ten day flood, the AWD treatments were allowed to dry until the soil moisture reached critical VWC for each respective treatment (16%, 24%, and 32% VWC at a depth of 2.5 inches) at which time the plots were re-flooded. Critical VWC thresholds were determined using a Dynamax TH300 soil moisture probe. Three measurements were collected from each replication in each treatment if the overall average of all the reps in that treatment reached the threshold or lower; a flood was applied to all plots of that treatment. Campbell Scientific CS655 water content reflectometer (Campbell Scientific, Inc., Logan, Utah) was also used in one of each AWD treatment's plots to track volumetric soil water content throughout the growing season at a depth of about 4.7 inches (12 cm). In the same three replicates, a Campbell Scientific CS451 pressure transducer (placed at the bottom of an 8- to 9-inch levee ditch) was also used to track the depth of the floods in the AWD treatments. Water inputs were also measured with 4-inch McCrometer propeller flowmeters in three out of the four replicates to determine the average total water usage for each water management treatment. Rain data was also collected using a Texas Electronics rain gage TE525 (Dallas, Texas). All logging sensor's inputs were processed and stored using a Campbell Scientific CR3000 data logger. At harvest, 800 sq ft were harvested with a small plot research combine with 4-foot header from each variety within each plot. The grain was weighed and moisture readings were taken and recorded. Yields in bushels per acre were calculated with a 12% moisture correction for each variety in water treatment plot and across all replicates.

Data Analysis

All data were analyzed using SYSTAT 13 and normality of all data was confirmed using a Shapiro-Wilk normality test. The water-use efficiency analysis of variance model assumption of homogeneity of variance was violated so a natural log transformation was conducted on the WUE response variables. Significant treatment effects were further analyzed using a Holm-Sidak method of mean comparison. Note: AWD/16%VWC was not included in the analysis because of lack of grain fill. In order to compare the differences in yields among treatments, an analysis of variance was used with a response variable, yield (bu/acre), and two treatments, Water treatment (three factor levels: flood, AWD/24% VWC, and AWD/32% VWC), Variety (two factor levels, XL753 and RoyJ), and a water treatment/variety interaction term. One of the AWD/24% VWC replicates also did not reach grain fill or maturity and so was not harvested. This replicate was treated as a missing value in the model. Water-use efficiency, bushels per acre-inch of water applied (bu/acre-inch), was calculated for all water treatments and varieties in plots that had flowmeters (three of the four replicates) by dividing yield per acre (bu/acre) by the inches of water applied per acre (acre-inch/acre). In order to compare the differences in WUE among water treatments and across varieties, a balanced analysis of variances was used in SYSTAT 13 with a response variable of WUE and two treatments: water treatment [three factor levels (three replicates each): flood, AWD/24% VWC, and AWD/32% VWC] and variety (two factor levels, XL753 and RoyJ).

RESULTS AND DISCUSSION

None of the AWD/16%VWC water treatment plots reached maturity indicating that a 16% VWC trigger point is far too low for use in AWD studies or applications in Sharkey silt clay soils. One of the AWD/24%VWC replicates also did not reach maturity suggesting that this replicate experienced more stress than the others in the 24%VWC treatment. However this replicate was one that did not have a flowmeter and water use was not recorded making it difficult to speculate the cause of the added stress to this replicate (only two of the three replicates had meters).

Yields

The interaction effect between water treatment and variety was not significant ($P = 0.905$). This indicated that varietal effects on yields and water treatment effects on yields are consistent across all water treatments and varieties, respectively. Significant effects of water treatment ($P < 0.001$) and variety ($P = 0.015$) on yield were observed. The mean comparison for water treatment indicated that all three treatments were significantly different from one another. The flood treatment (129.6 bu/acre) yielded on average 35.1 bu/acre more grain than AWD/32%VWC and 95.2 bu/acre more than AWD/24%VWC treatments independent of variety (Table 1). The AWD/32%VWC treatment (94.5 bu/acre) produced on average 60.1 bu/acre more grain than AWD/24%VWC (34.4 bu/acre). The mean comparison between varieties indicated that XL753 yielded on average 22.4 bu/acre more than RoyJ.

Water Use Efficiency

The interaction effect between water treatment and variety was not significant ($P = 0.330$). This indicated that varietal effects on WUE and water treatment effects on WUE are consistent across all water treatments and varieties, respectively. The varietal difference in WUE approached significance, $P = 0.052$, so the authors consider this supportive of a difference in WUE efficiency between varieties. Significant effect of water treatment ($P = 0.002$) on WUE was observed. The mean comparison indicates that AWD/32%VWC treatment had the higher grain to water use ratio than both of the other AWD water treatments (Table 2). There was no significant difference in WUE between the Flood and AWD/24% VWC treatments (Table 2). The data indicate that on average AWD/32%VWC's grain to water use ratio was 1.28 to 0.98 bushels of grain/acre-inch of water applied, greater than AWD/24%VWC and flood treatment, respectively. The deviation between varieties WUE means can be explained from examining the least square mean WUE for each variety within each water treatment. Despite having similar amounts of water applied across replicates (data not shown), RoyJ in the AWD/24%VWC treatment had a considerably low WUE relative to XL753 due to the very low average yields for RoyJ in that treatment. More evidence explaining the approaching significant difference in WUE between varieties can be seen from the overall difference in yield observed, across all water treatments, between RoyJ and XL753 as well as in the varietal yields between each treatment (Table 3). The drop in varietal yields from the flooded control to the AWD/32%VWC within variety was the same for XL753 and RoyJ at 27% yield loss from flood control average for each respective variety (Table 3). The drop in varietal yields from the flooded control to the AWD/24%VWC within variety was 67% for XL753 and 81% for RoyJ.

Observational Results

The average water used in each water treatment was highest for the flood, followed by AWD/32%VWC, AWD/24%VWC and AWD/16%VWC (Table 3). After the initial ten day flood, the 16%VWC treatments never reached trigger point and were not re-flooded (Table 3). The AWD/24%VWC reached trigger point once 37 days after termination of the initial flood and the AWD32%VWC trigger was met twice 9 days after termination of the initial flood, then again 26 days later (Figs. 1 and 2). This year had substantial amounts of rain totaling 18 inches during the growing season and 10.3 inches during the irrigation period. In many instances just as plots were drying down toward the trigger point, rains brought the VWC reading back up increasing time between irrigations (Fig. 1). This can also be seen in the water-depth data for several rain events (Fig. 2). Aside from the amount of rainfall this year, the water applied to all treatments was extremely high (Table 3). Due to the difficulties in pulling levees in this soil, the levee ditch depth ranged 8 to 9 inches, which could have contributed to the high water usage. By examining the levee ditch water-depth data it appears as if there were leakage issues seen from the sharp rate of drawdown just following a flooding event (Fig. 2). Speculatively speaking, leakage issues could have been caused by soil cracking resulting in deep percolation losses and/or seepage across the levees; more investigation is needed to explain. Bouman and Tuong (2001) found that AWD methods may lead to increased water use due to drying cycles leading to soil shrinkage and cracking. Data like soil moistures across the levees after a flooding event would be needed to determine if leakage across the levees was occurring.

SIGNIFICANCE OF FINDINGS

The flood treatment yielded the most grain relative to AWD/32%VWC and AWD/24%VWC treatments across both varieties. Overall, XL753 yielded significantly more grain than RoyJ (Table 1). On average WUE for the AWD/32%VWC treatment was greater than AWD/24%VWC and the flood treatments. Difference in WUE averages between varieties approached significance, and suggests that XL753 may have a higher WUE than RoyJ. Overall water use was extremely high and extreme decreases in yield averages between water treatments gives further evidence that AWD methods as well as thresholds will vary depending on soil characteristics in which the practice is implemented. Furthermore, thresholds should be calculated from plant available water characteristics of the soil, and these thresholds have yet to be determined for Arkansas soil types. More AWD research is needed to determine applicable thresholds for AWD methods on a wide variety of soil types in order to establish useful guidelines for farmers that wish to implement this water conservation practice.

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Table 1. Yield differences between water treatment (*P* < 0.001) and variety (*P* = 0.015) revealed by analysis of variance. Least square means for rice yields for water treatment and variety, with Shapiro-Wilk method for mean comparison of significant groupings.

Water treatment	SEM[†]	Average yield
		(bu/acre)
Flood	6.781	129.6 a[§]
AWD/32%VWC[‡]	6.781	94.5 b
AWD/24%VWC	7.83	34.4 c
AWD/16%VWC	NA	0
Variety		
XL 753	5.84	97.4 a
RoyJ	5.84	75 .0 b

[†] SEM = standard error of the mean.

[‡] Indicates treatment not used in the model. VWC = volumetric soil water content.

[§] Means within a column followed by different letters are significantly different at the *P* = 0.05 level.

Table 2. Water-use efficiency (WUE) differences revealed by analysis of variance for the factor level differences in WUE for water treatment ($P < 0.002$) and variety ($P = 0.052$)[†].

	Water use efficiency
	(bu/acre-inch)
Water treatment	
AWD/32%VWC[‡]	2.00 a[§]
Flood	1.02 b
AWD/24%VWC	0.72 b
AWD/16%VWC[¶]	NA
SEM[#] = 1.17	
Variety	
XL753	1.38 a
RoyJ	0.94 a
SEM = 1.13	

[†] Back-transformed Least square means for WUE in bushels per acre-inch, for water treatment and variety, with Shapiro-Wilk method for mean comparison significant groupings. (Note: varietal WUE means approached significance but no true difference in mean WUE was detected between varieties.)

[‡] AWD = alternate wetting and drying; VWC = volumetric soil water content.

[§] Means within a column followed by different letters are significantly different at the $P = 0.05$ level.

[¶] Indicates treatment not used in the model.

[#] SEM = standard error of the mean.

Table 3. Summary of the water usage (applied) and number of irrigations after the initial 10-day flood cycle[†].

Treatment	No. of reflood after initial flood	Water use	Yield	Varietal WUE
		(acre-inches/acre)	(bu/acre)	(bu/acre-inch)
Flood	13	132.8		
XL753			142.0 a[‡]	1.13 b
RoyJ			117.3 a	0.93 b
AWD/32%VWC[§]	2	45.8		
XL753			103.2 b	2.19 a
RoyJ			85.9 b	1.82 a
AWD/24%VWC	1	42.9		
XL753			47.0 c	1.06 b
RoyJ			21.8 c	0.49 b
AWD/16%VWC	0	21.7		
XL753			NA	NA
RoyJ			NA	NA

[†] The water-use efficiency ratings and varietal yield values came from water treatment by variety interaction term's back-transformed least square means from the analysis of variance of water-use efficiency and yield, respectively. (Note: interaction in both models was not significant so none of the values listed below for yield or efficiency are significantly different between varieties within each water treatment.)

[‡] Means within a column followed by different letters are significantly different at the $P = 0.05$ level.

[§] AWD = alternate wetting and drying; VWC = volumetric soil water content.

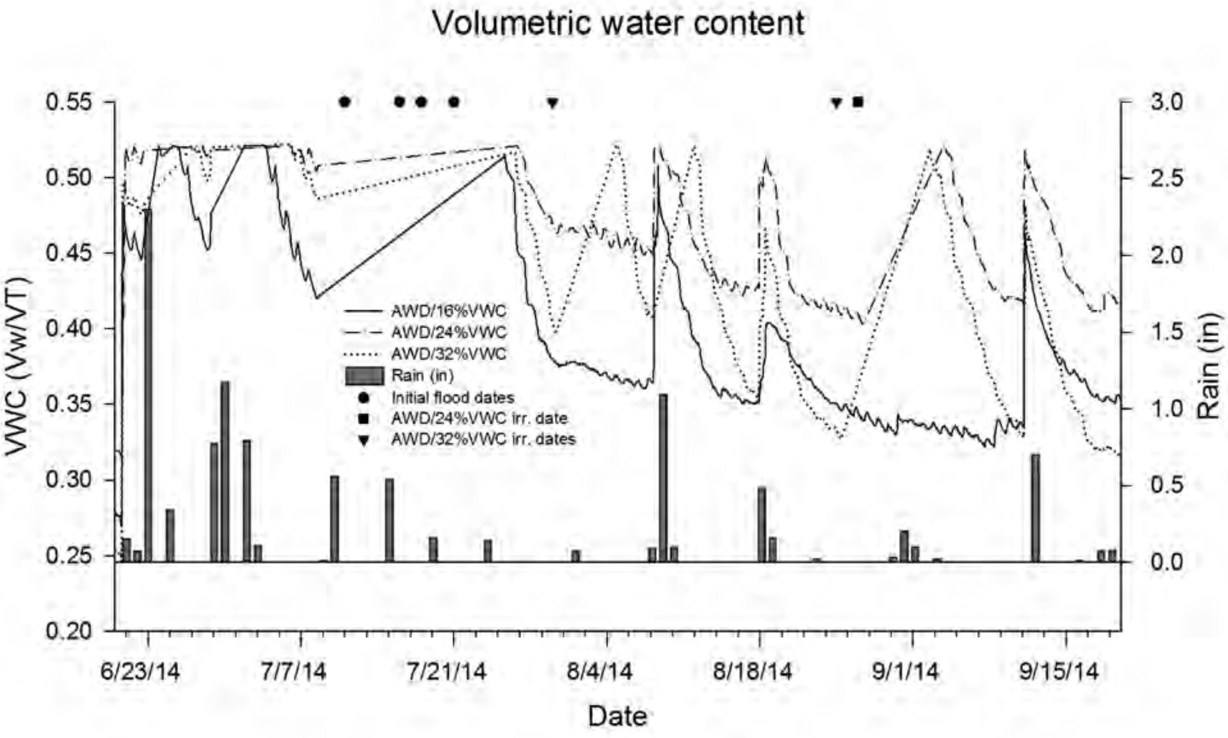

Fig. 1. Mapping volumetric soil water content (VWC) response to rain and irrigation event through a graphical view of volumetric water content for one replicate of each alternate wetting and drying (AWD) water treatment throughout the season with rain amounts/event as well as irrigation dates overlaid.

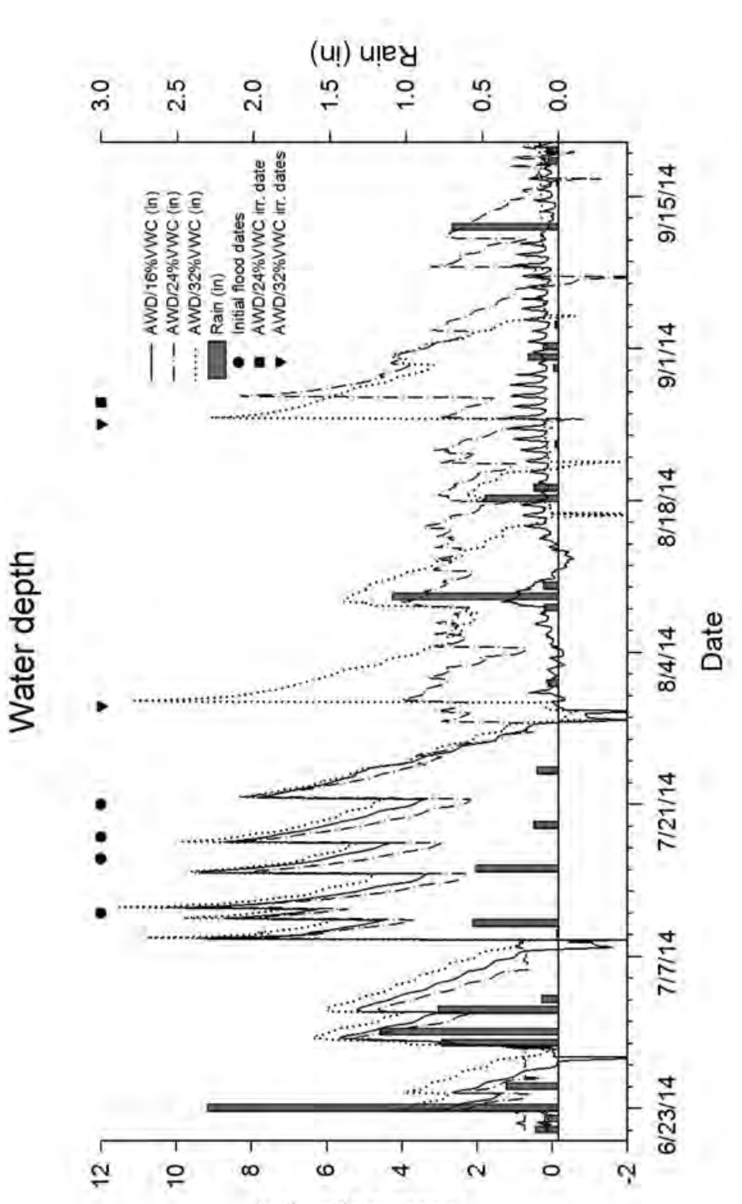

Fig. 2. Mapping bar ditch water depth response to rain and irrigation event through a graphical view of bar ditch depth of one replicate for each alternate wetting and drying (AWD) water treatment throughout the season with rain amounts/ event as well as irrigation dates overlaid. Note levee ditch range is 8 to 9 inches deep.