Effects of Three Different Alternate Wetting and Drying Regimes in Rice Cultivation on Yield, Water Use, and Water Use Efficiency in a Clay Soil During a Wet Year

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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, pure-line cultivar (Roy J) 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 2015, and unknown factors contributing to low yields even in the conventionally flooded treatments. Even with these complications, the trends in the data indicated that AWD is a feasible water management practice for rice in Arkansas. For both cultivars, all AWD regimes tested in this experiment were associated with a loss in yield, the hybrid cultivar had a higher yield than the conventional cultivar in all treatments. Water-use efficiency for the wettest AWD treatment was higher than the conventional flood treatments and the dryer AWD treatments. Difference in WUE between cultivars was significant and suggests that the hybrid may have a higher WUE than the conventional.

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.,

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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). At the same time 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 to 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, pure-line cultivar (Roy J) and a hybrid cultivar (XL753) grown on Sharkey silty clay soils in the northeast corner of the Mississippi delta rice-growing region in Arkansas.

PROCEDURE

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 (Saxton et al., 1986) using pesudotransfer functions to determine saturation, field capacity and wilting points of 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 12 June 2015 and plants emerged 19 June 2015. No irrigations were applied until the initial flood 20 July 2015, rainfall was sufficient for stand establishment. Plot sizes were 30 ft × 52 ft (1560 sq ft), separated by dual packed levees to prevent water movement between plots. Plots were planted half with a conventional, pure-line cultivar (Roy J) and half with a hybrid (XL753) of which 260 sq ft of each cultivar in each plot was harvested on 20 October 2015.

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/21.6% VWC, 3) AWD/25.4% VWC, and 4) AWD/30.2% VWC. The AWD represents alternate wetting and drying followed by the volumetric soil water content at which subsequent irrigations were triggered. The available water holding capacity of this soil is 21.5% VWC (difference between field capacity and wilting point). The actual deficits the trigger levels represent correspond to 20%, 42.3%, and 60% managed allowable depletions (MAD). These deficits resulted in soil moisture trigger points of 30.2% VWC, 25.4% VWC, and 21.6% VWC respectively.

All treatments were flooded to a 2- to 3-inch depth for 10 days (20 to 30 July) after the preflood nitrogen (N; i.e., urea) fertilizer application of 120 lb N/acre (20 July). In the flooded treatments, this flood depth was maintained throughout the growing season. After the initial 10 day flood, the AWD treatments were allowed to dry until the soil moisture reached the critical VWC triggers for each respective treatment (21.6%, 25.4%, and 30.2% VWC at a soil 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. 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. Weather data was also obtained from the Northeast Research and Extension Center onsite weather station. At harvest, grain was harvested, weighed, and moisture readings were obtained for 260 sq ft from each cultivar within each plot using an Almaco SPC40 small plot research combine with 5-foot header width. All yields in bushels per acre (bu/acre) were corrected to 12% moisture.

Data Analysis

All data were analyzed using SYSTAT 13, the treatment and cultivar effects on yield and water-use efficiency were evaluated with an analysis of variance. Normality of all data was confirmed using a Kolmogorov-Smirnov normality test and both models passed homogeneity of variances. Significant treatment effects were further analyzed using a Tukey test method of mean comparison.

In order to compare the differences in yields and relative yields (% relative to the flooded yield average of each respective cultivar) among treatments, an analysis of variance was used with a response variable, yield (bu/acre), and two factors, water treatment (four factor levels: flood, AWD/21.6% VWC, AWD/25.4% VWC, and AWD/30.2% VWC), cultivar (two factor levels: XL753 and Roy J), and a water treatment/cultivar interaction term. Water-use efficiency, bushels per acre-inch of water applied (bu/acre-inch), was calculated for all replicates in each treatment and each cultivar by dividing yield per acre (bu/acre) by the average inches of water applied (acre-inch/acre) for each respective treatment. In order to compare the differences in WUE between water treatments and across cultivars, a balanced analysis of variances with a response variable of WUE and two factors: water treatment (four factor levels: flood, AWD/21.6% VWC, AWD/25.4% VWC, and AWD/30.2% VWC), cultivar (two factor levels, XL753 and Roy J), and a water treatment/cultivar interaction term.

RESULTS AND DISCUSSION

The yields regardless of treatment suffered greatly this season likely due to several factors. First due to the prolonged rain, planting this year was delayed till mid-June and also the plot combine is not a rice machine and the operator expressed that a good percentage of grain was lost through the combine (estimated 20-25%). Onset of irrigation and preflood N fertilizer applications was also delayed due to rain rendering the plots inaccessible as well as warm minimum temperatures could also have contributed to the lower yields this year (Fig. 1). It is likely that other factors (such as possibility of drift) also played into the low yields obtained, however, we have little to no evidence that can help us speculate on other possible factors contributing to the low yields experienced across all water treatments including the conventional flooded treatment. The highest deficit treatment of 60%, AWD/21.6%VWC was far too much of a deficit for use in AWD studies or applications in Sharkey silt clay soils, experiencing on average a 59.6% reduction in yield relative to the average of the conventional flooded treatment, and the average 21.6% VWC treatment yield was 58.4% less than the average flooded yield. This is similar to last years results (Gaspar et al., 2015), that show the AWD 24%VWC treatment resulted in a 73.5% reduction in yield from the conventional flooded treatment.

Yields

The interaction effect between water treatment and cultivar was not significant for yield ($P = 0.691$) and relative yield ($P = 0.504$). This indicated that cultivar effects on yield and water treatment effects on yield are consistent across all water treatments and cultivars, respectively. Significant effects of water treatment ($P < 0.001$) and cultivar ($P < 0.001$) on yield were observed. The mean comparison for water treatment indicated that the flooded treatment and the AWD/30.2% VWC were significantly similar and had the highest yields (Table 1). The flood treatment average yield (48.8 bu/acre) was 23.4%, 36.7%, and 58.4% greater than the average yield of the AWD/30.2% VWC, AWD/25.4% VWC, and AWD/21.6% VWC treatments, respectively, independent of cultivar. The mean comparison between cultivars indicated that XL753 yielded on average 40.4% more yield than Roy J, irrespective of water treatments.

The relative yield analysis similarly shows that significant effects of water treatment ($P < 0.001$) and cultivar ($P = 0.030$) on yield were observed. The AWD/30.2% VWC, AWD/25.4% VWC, and AWD/21.6% VWC treatment replicates experienced an average reduction in grain production of 24.5%, 38.9%, and 59.6% relative to the flooded treatment average yield, respectively (Table 1).

Water Use Efficiency

The interaction effect between water treatment and cultivar was not significant ($P = 0.154$). This indicated that cultivar effects on WUE and water treatment effects on WUE are consistent across all water treatments and cultivars, respectively. Significant effect of water treatment ($P < 0.001$) on WUE was also observed. The AWD/30.2% VWC (1.77 bu/ac-in) and AWD/25.4% VWC (1.27 bu/ac-in) treatments had the highest grain to water use ratio (Table 2). The data indicate that on average AWD/30.2% VWC yielded 1.1 and 1.25 more bushels of grain/acre-inch of water applied, than AWD/21.6% VWC and flood treatment, respectively. The cultivar difference in WUE was significant ($P < 0.001$), indicating that XL753 on average yielded 0.63 bu of grain more per ac-in of water used than Roy J across all irrigation treatments.

The deviation between cultivar WUE means can be explained from examining the overall mean difference in in WUE between cultivars (Table 2) as well as the least square mean for WUE and yield for each cultivar within each water treatment (data not shown). Despite the fact that both cultivars were planted in each treatment replication and they experienced the same amount of irrigation within each replication, Roy J had consistent lower yields and WUE than XL753 which ultimately lowered the average yield and WUE for each irrigation treatment considerably.

Observational Results

The average water used in each water treatment was greatest for the flood, followed by AWD/21.6% VWC, AWD/25.4% VWC and AWD/30.2% VWC (Table 2). The AWD/21.6% VWC reached trigger point once 54 days after termination of the initial flood, AWD/25.4% VWC reached trigger point once 40 days after termination of the initial flood, and the AWD/30.2% VWC trigger was met twice 32 days after termination of the initial flood, then again 54 days later (Fig. 1). This year had substantial amounts of rain totaling 14.47 inches during the growing season and 9.42 inches during the irrigation period. The dates of the reflood for the treatments was a considerable length of time and is likely due to the high amount of rain during and post initial flood (Fig. 1). Aside from the amount of rainfall this year, the water applied to all treatments was extremely high (Table 2); due to the difficulties establishing the initial flood (Table 2) and in pulling levees in this soil, the levee ditch depth ranged 8 to 9 inches, which could have also contributed to the high water usage. It is also probable that seepage from the levees can also explain the high water use, such was observed in the previous study in 2014 (Gaspar et al., 2015). 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 and depth data across the levees after a flooding event would be needed to determine if leakage across the levees was occurring. Similarly soil moisture and depth measurement readings across the soil profile could indicate the amount of deep percolation occurring in each plot.

SIGNIFICANCE OF FINDINGS

The flood treatment yielded the most grain relative to the AWD treatments across all cultivars. As the deficit increased so did yield reduction. Overall, XL753 yielded significantly more grain than Roy J (Table 1). On average, WUE was greater for the AWD/32% VWC/ 20% deficit treatment (Table 2) than all other treatments. Difference in WUE averages between cultivars was significant, and suggests that XL753 on average had a 46% higher WUE than Roy J across all irrigation treatments. Although the yields this year were extremely low, the yield reduction was expressed in all irrigation treatments and the trends in the data are very similar to the trends observed in the 2014 season (Gaspar et al., 2015). In this study, AWD had considerable water savings and thus additional research is needed to investigate the potential. Small plot research in this soil type is problematic and further work may need larger plots so that the levee seepage influence is reduced and results will be more relevant to what farmers may experience. No significant difference was found in yield between the 20% and 42% deficit thresholds, so more research is needed to better define allowable depletions for re-flooding. 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 cultivar (P < 0.001) revealed by analysis of variance. Relative yield differences between water treatment (P < 0.001) and cultivar (P = 0.030) revealed by analysis of variance. Least square means for rice yields and relative yields for water treatment and cultivar, with Tukey method for mean comparison of significant groupings.

Water treatment	Average yield	Relative yield†
	(bu/acre)	(% of flooded yield)
Flood	48.8 a‡	100 a
20% Deficit/AWD/30.2% VWC§	37.4 ab	75.5 ab
42% Deficit/AWD/25.4% VWC	30.9 bc	61.1 bc
60% Deficit/AWD/21.6% VWC	20.3 c	40.4 c
SEM¶	4.13	8.41
Cultivar		
XL 753	43.1 a	79.0 a
RoyJ	25.7 b	59.6 b
SEM	2.92	5.95

† Relative yield is actual yield divided by the average yields for the flooded treatment reps for each respective cultivar × 100.
‡ 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.
¶ SEM = standard error of the mean.

Table 2. Summary of the water usage (applied) and number of irrigations after the initial 10 day flood cycle. Water use efficiency (WUE) differences revealed by analysis of variance for the factor level differences in WUE for water treatment (P < 0.001) and cultivar (P < 0.001). Least square means for WUE in bushels/acre-inch, for water treatment and cultivar, with Tukey method for mean comparison groupings.

Water treatment	No of refloods post post initial flood	Average total water use	Average water use post initial flood	Water use efficiency
		--------(acre-in./acre)	--------	(bu/acre-in.)
20% Deficit AWD/30.2% VWC†	2	21.1	10.2	1.77 ab
42% Deficit AWD/25.4% VWC	1	24.3	3.9	1.27 a
60% Deficit AWD/21.6% VWC	1	30.3	4.3	0.67 b
Flood	NA	94.1	68.2	0.52‡
SEM§ = 0.147				
Cultivar				
XL753				1.37 a
RoyJ				0.74 b
SEM = 0.104				

† 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.
§ SEM = standard error of the mean.

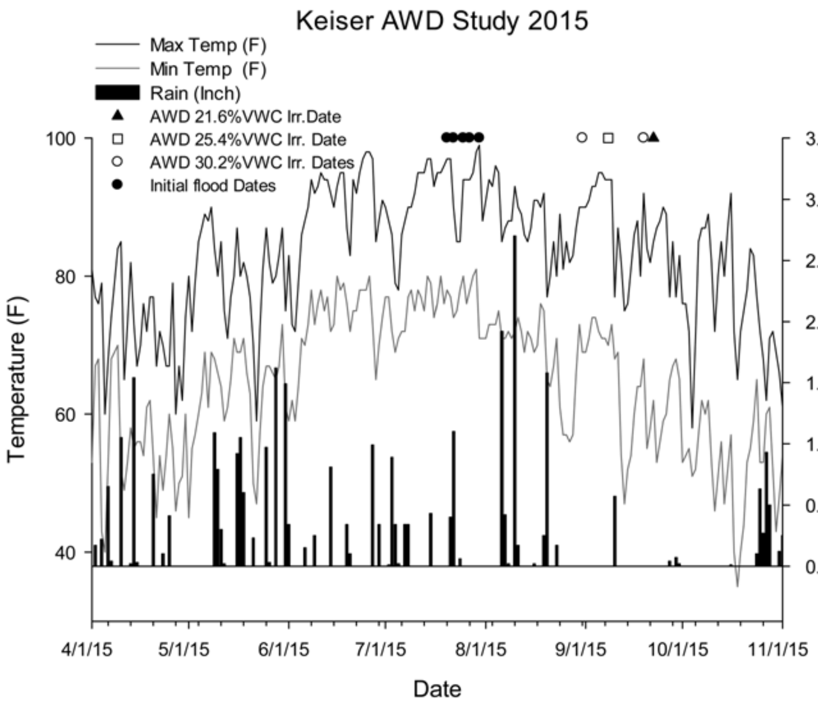

Fig. 1. Minimum and maximum temperature, rainfall, and irrigation dates in the three irrigation treatments [21.6%, 25.4%, and 30.2% volumetric soil water content (VWC)]. AWD = alternate wetting and drying.