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Evaluation of alternate wetting and drying irrigation management in rice

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Water level declines in the Mississippi River Valley Alluvial Aquifer (MRVAA) are attributed largely to withdrawals for rice (*Oryza sativa* L.) irrigation. This study was performed to determine if alternative irrigation strategies for rice could reduce withdrawal from the MRVAA without having an adverse effect on grain yield, grain quality, control of barnyardgrass, and profitability. Research was conducted in Stoneville, MS and 19 on-farm locations across the Delta region of Mississippi from 2014 through 2017 to determine the irrigation threshold for alternate wetting and drying (AWD) rice irrigation, the effect of AWD management on barnyardgrass control, and effects of irrigation water management practice, i.e., conventional flood via cascade (CONV), multiple side inlet (MSI), and MSI coupled with AWD, on aquifer withdrawal, rough rice grain yield, irrigation water use efficiency (IWUE), and net returns above irrigation costs. An AWD threshold of -20 cm below the soil surface had no adverse effect on grain yield or grain quality, reduced irrigation applied by 50%, and improved IWUE by 45% compared to a continuous flood (CF). Control of barnyardgrass in AWD was either maintained or improved compared to CF for both Clearfield and conventional rice production systems. At the production scale, up to 39% less water was applied to AWD compared to CONV and MSI. Rice grain yield for AWD was not different from either CONV or MSI, despite substantial

reductions in water use. Relative to standard irrigation strategies, AWD maintained or increased net returns up to \$238 ha^{-1} for pumping depths from 5.5 m to 122 m and diesel prices from \$0.42 L^{-1} to \$0.98 L^{-1}. Irrigation water use efficiency was up to 59% greater for AWD relative to conventional systems due to the positive effects of the former on water use while maintaining yield. These data demonstrate that AWD can reduce withdrawal from the MRVAA while maintaining or improving yield and net returns relative to irrigation strategies currently employed across the midsouthern USA rice belt.

DEDICATION

I would like to dedicate this work to:

My wife, Abbey Atwill,

My daughter, June Evelyn Atwill,

My parents, Richard & Amanda Atwill and Curt & Lisa Dunlap,

My siblings, Abby & Alexis Atwill, Hannah Beth & Cody Hearyman,

My grandfather, Richard Lee Atwill.

I want to thank each of you for your support and encouragement throughout this process.

Further, I will never be able to thank my wife enough for her encouragement

and patience through this experience and beyond.

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I owe a substantial part of my success to my major professor, Dr. Jason Krutz. I wish to express my greatest appreciation to you for introducing me to the world of agriculture and Mississippi State University. Thank you for your honesty, guidance, and friendship both professionally and personally. I am forever grateful, thank you.

To my committee members, Dr. Jason Bond, Dr. Tim Walker, Dr. Mike Phillips, Dr. Drew Gholson, and Dr. Bobby Golden, I appreciate your willingness to guide me through my research and further develop me to become a valuable resource for our southern rice producers. I hope to have an opportunity to work with each of you again in the future.

To Dave Spencer, Corey Bryant, Stephen Leininger, and Dan Roach, I appreciate your friendship and hard work walking rice fields and laying pipe in the Mississippi heat. Additionally, I would like to thank the rest of the staff and faculty at Delta Research and Extension Center for their support.

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CHAPTER I

ESTABLISHMENT OF THRESHOLDS FOR ALTERNATE WETTING AND DRYING IRRIGATION MANAGEMENT IN RICE

Abstract

The long-term viability of rice production in the midsouthern USA could be affected by irrigation management strategy. This study was conducted to determine if rice sustainability can be improved through manipulation of the irrigation threshold. The effects of an alternate wetting and drying (AWD) irrigation threshold and cultivar on water applied, rice grain yield, seed quality, irrigation water use efficiency, and net returns were investigated at Stoneville, MS on a Sharkey clay (very fine, smectitic, thermic Chromic Epiaquert). Water applied increased exponentially from 316 mm for the AWD threshold of -40 cm to 1061 mm for the conventional flood. For both hybrid and inbred lines, rice grain yield decreased linearly at a rate of 14 kg ha^{-1} for each cm decrease in irrigation threshold. Alternate wetting and drying irrigation threshold had no effect on seed quality parameters including chalk, milling total, and milling whole. Net returns decreased in the order \$2076 ha^{-1} for XL753 > \$1706 ha^{-1} for Rex > \$1535 ha^{-1} for CL151; however, net returns were not affected by AWD irrigation threshold. Our analysis of these data indicates that converting from a conventional flood to an AWD irrigation threshold ranging from 0 to -20 cm will likely improve the sustainability of rice production in the midsouthern USA.

Introduction

The sustainability of irrigated agriculture in the Lower Mississippi River Basin (LMRB) is questionable as extraction of water from the Mississippi River Valley Alluvial Aquifer (MRVAA) exceeds long-term recharge rates. Approximately 98% of the total withdrawals from the MRVAA is applied to row-crops including cotton (Gossypium hirsutum L.), corn (Zea mays L.), soybean (Glycine max (L). Merr.), and rice (Oryza sativa L.). Seventeen percent of the row-crop hectarage in the LMRB is rice, yet rice accounts for 38% of all withdrawal from the MRVAA (USDA-NASS, 2015). Clearly, means to reduce the use of water in rice are required to ensure the sustainability of irrigated agriculture in the LMRB.

Producers in the LMRB have adjusted land preparation and modified irrigation delivery techniques to reduce the amount of water applied to rice. Land leveling on rice production fields allows for levees to be constructed straight and perpendicular to the slope of the field, and allows for a more uniform flood depth, decreases tillage and harvest cost, and allows for better drainage and weed control compared to the traditional, contour-levee system. The adoption of straight-levee rice production during the 1980's decreased water use by 17%, compared with contour-levee production (Smith et al., 2007). Fields that are precision leveled with no slope are referred to as zero-grade. No levees are needed to maintain uniform flood depth on zero-grade production fields, and water use is reduced 60% compared with contour levee fields (Watkins, 2007). Using low pressure, thin-walled (225 to 255 μm) disposable irrigation tubing to deliver water independently to each paddy, referred to as Multiple Side-Inlet (MSI) reduces irrigation inputs up to 21% compared with single-point, cascade distribution system with a continuous flood (Atwill et al., 2020). Additional reductions in the amount of water applied to rice may be attained by adjusting irrigation thresholds.

Currently, in the midsouthern USA, the majority of rice hectares are grown in a drill-seeded, delayed flood production system on contour-levee and/or precision-leveled, straight-levee production fields under a continuous flood (CF; Street and Bollich, 2003). Rice is grown upland until the four- to five-leaf rice growth stage, at which time a 5- to 10-cm flood is established and maintained until 2 weeks prior to harvest. Historically, the flood was established for weed control and fertility management. Research from developing countries indicate that alternative, low-water-use production systems may reduce the amount of water applied relative to CF.

Alternate wetting and drying, which began in India, is a water management strategy wherein the field is not continuously flooded (Lampayan et al., 2015). Currently, AWD is the recommended water management practice for rice in Bangladesh, the Philippines, Myanmar, Vietnam, Taiwan, China, Nepal, and India (Lampayan et al., 2014, 2015; Rejesus et al., 2011; Kima et al., 2015; Howell et al., 2015; Yao et al., 2012; Sudhir et al., 2011). Reduction of supplemental irrigation under AWD ranges from 25 – 60% compared to CF and varies based on rice growing region, soil texture, and environmental conditions (Lampayan et al., 2014, 2015; Rejesus et al., 2011; Kima et al., 2015; Howell et al., 2015; Yao et al., 2012; Sudhir et al., 2011; Carrijo et al., 2017). Alternate wetting and drying in rice that does not result in a loss of grain yield is considered “safe” AWD. The degree to which a paddy subjected to the drying portion, or threshold, is determined experimentally for each region based on soil texture, environmental conditions, and cultivar, crop growth stage, and depth of groundwater table (Lampayan et al., 2014, 2015; Zhou et al., 2017). “Safe” AWD consists of three key elements: (1) shallow flooding for the first 2 weeks after planting, (2) shallow flooding from heading to the end of flowering, and (3) AWD during all other periods, with irrigation water applied whenever the perched water table falls to about 15cm (Bouman et al., 2007; Lampayan et al., 2015). The threshold established by Bouman et al. (2007) for “safe” AWD was determined experimentally for rice production in the Philippines, and varies among rice producing regions. “Safe” AWD guidelines have been established for most of the rice growing regions of the world (Lampayan et al., 2015), however, the majority of the rice grown with cultural practices that are not used in the midsouthern USA.

It has been shown that the field water tube used for AWD works well in conditions where there is a perched water table as a result of rain and/or irrigation, as is the case in heavy clay soils with low permeability, and in puddled soils because of the relatively impermeable hardpan that usually develops at 15-25cm (Bouman et al., 2007; Lampayan et al., 2014). In light textured soils where there is not a hardpan and water tables are deep, such as fields under direct dry-seeded rice on light-textured soils, the field water tube may not be effective, and farmer-friendly methods for scheduling irrigation still needs to be developed.

In addition to rice grain yield, the effect of AWD threshold on USA rice grain quality have not been evaluated. Rice grain dimensions (Length:Width ratio) and chalkiness determine rice grain market classes and are important for assuring high grain quality and market value (Edwards et al., 2017). United states rice export markets depend on long grain rice with a high L:W ratio and translucent grains (chalk < 5%). Chalkiness in rice kernels is affected by cultivar genetics and environmental factors, particularly high nighttime temperatures and relative humidity during flowering. High nighttime temperature and relative humidity during the period of 2 weeks prior to flowering through 100% heading increase rice grain chalk directly. In CF irrigation, rice plants are exposed to minimal drought stress during this period, and the effect of AWD on rice grain quality is unknown.

The MRVAA is relied on for irrigating intensively managed crops in the Mississippi River Delta region of Mississippi (Powers, 2006). Therefore, irrigation of crops, including rice, should be done in the most efficient manner. Continuous flooding has been the common irrigation scheme used for most rice producers in the USA, yet several other established practices exist (Street and Bollich, 2003). Alternate irrigation strategies may reduce irrigation costs; however, producers have expressed concerns regarding the potential negative impacts of AWD rice irrigation (Massey et al., 2014).

The primary and immediate concern of growers is the establishment of an AWD threshold used to determine when irrigation events should occur that reduce water use and maintain grain yield compared to CF. Additionally, labor associated with changing an irrigation management practice is of concern to rice producers in the midsouthern USA. Before adoption of alternate irrigation strategies in the midsouthern USA, examining effects on popular rice varieties and hybrids is a priority. The objective of this study was to determine an AWD irrigation threshold for midsouthern USA rice production that maintains grain yield, improves IWUE, reduces irrigation amounts, and improves on-farm profitability.

Materials and Methods

Study Site and Experimental Design

A study to evaluate the response of three rice cultivars to six irrigation regimes was conducted in 2015 (33.40ºN, 90.93ºW), 2016 (33. 40ºN, 90.92ºW), and 2017 ((33. 40ºN, 90.93ºW) at the Mississippi State University Delta Research and Extension Center in Stoneville, Mississippi. The experimental design was a split-plot design with irrigation regime (I) as the main plot and cultivar (C) as the subplot. Four replicates of water regime were included with four replicates of cultivar within each main plot unit. The irrigation regimes were continuously flooded (CF); AWD at the soil surface threshold level for irrigation (AWD-SS); AWD at -10 cm (AWD10); AWD at -20 cm (AWD20); AWD at -30 cm (AWD30); and AWD at -40 cm (AWD40). Within the main plot irrigation, two inbred long-grain cultivars: 'CL151' and 'Rex', and one hybrid long-grain cultivar, 'XL753' (RiceTec, Inc. Alvin, TX) were evaluated.

The soil was a Sharkey clay (very fine, smectitic, thermic Chromic Epiaquert) with a pH ranging from 8.0 to 8.2 and organic matter content ranging from 1.9 to 2.1%. Experimental sites were in a 1:1 soybean to rice rotation. Field preparation each year consisted of disking and field cultivation in the fall, followed by light field cultivation prior to planting. Emerged spring vegetation was controlled using glyphosate (Roundup® Weathermax® 4.5 L, Monsanto Company, 800 N. Lindburgh Blvd., St. Louis, MO 63167) at 1,120 g ae ha^{-1} prior to planting.

The main plot irrigation regime consisted of 0.15 ha rice paddies 28 m x 54 m wide. Main plot units were surrounded by two 2.3-m levees, and adjacent plots were separated by a 16 m buffer zone of non-irrigated rice. Irrigation water was applied to main plots via layflat polyethylene tubing, and irrigation amount was monitored using McCrometer flowmeters.

Experimental sublots were 4.6-m in length, seeded at 80 and 30 kg ha^{-1} for inbred and hybrid cultivars, respectively. Rice was seeded to a depth of 2 cm with an eight-row small-plot grain drill (Great Plains Mfg. Inc. Salina, KS) equipped with double disk openers and press wheels spaced 20-cm apart. Nitrogen fertilizer was applied immediately before flood establishment as urea (46-0-0) at approximately 165 kg ha^{-1}. Experimental plots were managed according to University recommendations for each respective state to minimize weed and insect pest pressure (Buehring et al. 2008).

Rice plots were harvested when the grain moisture reached a range of 150 to 180 g kg^{-1} H2O with a Wintersteiger Delta (Wintersteiger USA, Salt Lake City, UT) small-plot combine equipped with a Harvest Master Grain Gauge (Juniper Systems, Inc. Logan, UT). Yields were adjusted to a kg ha^{-1} basis at a moisture content of 120 g kg^{-1} H2O for analysis.

Rough rice was dried to approximately 12% moisture using a forced air drier at 28C, and grain aspirated (Air Blast Seed Cleaner, Almaco, Nevada, IA) prior to milling. Head rice yield was estimated rom 125-g samples of cleaned rough rice using the procedure outlined by Adair et al (1972). Rough rice was mechanically hulled, milled in a McGill no. 2 miller for 30 s, and size separated with a no. 12 (4.76-mm) screen. Head rice yield was calculated as a mass fraction of the original 125-g sample of rough rice. Rice grain chalk (% of total area) and grain dimensions were determined using a WinSEEDLE Pro 2012a (Regent Instruments Inc., Canada) and an EPSON Expression 10000XL Flatbed Scanner (Epson America Inc., Long Beach, CA) using approximately 150 whole milled grain rice kernels.

Economic Analysis

The model used to project irrigation costs in this research incorporates irrigation enterprise budgets developed utilizing the Mississippi State University Budget Generator. Irrigation costs and rice grain yield were derived from pumping amounts and relative yield, respectively, for each irrigation threshold. The model develops estimates of total receipts, total direct expenses, total fixed expenses, total specified expenses, and net returns above total specified expenses on a per-hectare basis. Diesel costs were estimated for each observation based on the amount of water pumped at a baseline diesel cost of \$0.70 L^{-1}, the average diesel price used in developing MSU budgets for 2015, 2016, and 2017 crop years (Mississippi State University, 2016, 2017, 2018). The rice price was held constant at \$0.27 kg^{-1}, the average price reported by USDA at Greenville, MS for the August, September, and October harvest periods for the 2015, 2016, and 2017 crop years (see Mississippi portal for rice at https://www.ers.usda.gov/data-products/commodity-costs-and-returns/commodity-costs-and-returns/#Recent Costs and Returns: Rice).

Assumptions related to equipment used in each enterprise budget are based on recent analysis in the same region (Atwill et al., 2020; Bryant et al., 2017). The values for purchase price and fuel consumption are based on personal communications with Mississippi Delta-region irrigation equipment input and service providers. Irrigation is assumed to be supplied from a 42.6-m Standard Depth well equipped with a 100-hp stationary diesel engine pumping at 454 m^3 hr^{-1}.

Irrigation set up includes costs for labor, fuel, repair and maintenance of equipment, supplies and interest associated with surveying and marking levees, building levees, installing gates, removing gates, removing levees along with capital recovery costs associated with land forming, well, pump and engine. Irrigation setup includes costs for poly-pipe, labor to install and remove the poly-pipe as well as repair and maintenance costs on machinery associated with installing and removing the Polypipe. Water lifting costs include irrigation labor to apply water in addition to fuel cost associated with pumping. Water lifting costs are expressed as dollars per hectare-mm pumped and vary between treatments with the total amount applied for each treatment.

Statistical Analysis

This experiment was a split-plot with irrigation threshold (I, fixed effect) as the whole plot and cultivar (C, fixed effect) as the sub-plot. Initially, treatment means for grain yield, plant height, grain chalk %, L:W ratio, and milling yield were calculated across replicates of cultivar for each irrigation threshold treatment replication (within each year). Treatment means for grain yield and water applied were used to calculate irrigation water use efficiency (IWUE). Means for rice grain yield, plant height, grain chalk, milling yield, and IWUE for irrigation threshold, cultivar, and the interaction among I x C were separated using the Mixed Procedure (Littell et al. 2006) in SAS 9.4 (SAS Institute Inc. Cary, NC) at the 0.05 significance level. Outlier detection for all parameters was performed using studentized residuals and Cook's D-values using PROC GLM in SAS.

Rice grain yield, plant height, grain chalk, milling yield, and IWUE were regressed on irrigation threshold, allowing for both linear and quadratic terms with coefficients depending on cultivar and year. Nonsignificant ($P>0.05$) parameters were removed sequentially and the model was refit until a satisfactory model was obtained. Differences among all remaining coefficients, which varied by cultivar, year, or both, were determined using single-degree-of-freedom contrasts.

All data were subjected to ANOVA using the Mixed Procedure (Littell et al. 2006) in SAS 9.4. Type III statistics were used to test all possible fixed effects or interactions among the fixed effects. Each year, replication of cultivar were averaged for each cultivar within each irrigation treatment replication for rice grain yield, plant height, total milling yield, head rice yield, and grain chalk each replication of irrigation treatment. Irrigation replication and irrigation replication nested within year) were considered random effects. Considering site-year an environmental or random effect permits inferences about treatments to be made over a range of environments (Blouin et al. 2011; Carmer et al. 1989). Fixed effects for these parameters were cultivar and irrigation treatment and interaction of cultivar*irrigaiton. Least-square means were calculated, and mean separation ($P \leq 0.05$) was produced using PDMIX800 in SAS software, which is a macro for converting mean-separation output letter groupings (Saxton, 1998).

Results and Discussion

This study was conducted to determine if rice sustainability can be improved through manipulation of the irrigation threshold. Water applied increased exponentially from 316 mm for the AWD threshold of -40 cm to 1061 mm for the conventional flood (Figure 1.2). For both hybrid and inbred lines, rice grain yield decreased linearly at a rate of 14 kg ha^{-1} for each cm decrease in irrigation threshold (Figure 1.2). The range of AWD thresholds had no effect on seed quality parameters including chalk, milling total, and milling whole (Table 1.4). Net returns decreased in the order XL753 > Rex > CL151; however, net returns were not affected by AWD irrigation threshold (Table 1.4, 1.5).

Irrigation Water Applied

A hypothesis of this study was that as water level threshold decreased, irrigation applied would decrease. The response of irrigation water applied to irrigation threshold is exponential in nature and is described by the equation:

$$827 \times exp^{0.025x}$$

where *x* is irrigation threshold in cm relative to the soil surface. Rainfall captured in AWD treatments results in decreased water use when compared to a continuous flood. Reduction in irrigation water applied is attributed to rainfall capture in AWD treatments and is well documented (Chlapecka et al., 2021; Massey et al., 2014; Lampayan et al., 2014; Atwill et al., 2020). Allowing paddy water level to subside increases the amount of ‘freeboard,’ or available water volume that can be captured prior to reaching full water holding capacity and subsequent loss of water. Maintaining a continuous flood with no ‘freeboard’ inhibits capture of water from precipitation: rainfall entering a full paddy overflows and exits the field (Chlapecka et al., 2021; Massey et al., 2014). Cumulative rainfall for June and July were 63mm, 254mm, and 209mm for

2015, 2016, and 2017, respectively (Figure 1.1; Table 1.3). The trend of irrigation water applied remains over a variation in rainfall amounts and suggests that reductions in water use can be achieved for a range of environmental conditions.

Rice Grain Yield

The adoption of an AWD irrigation threshold between 0 and -40 cm will have to maintain or improve effect on rice grain yield for either hybrid or inbred cultivars in the midsouthern USA. Depending on cultivar, AWD either maintained or improved rice grain yield up to 9% relative to a conventional flood for small-plot research conducted in Mississippi and Arkansas (LaHue et al., 2016; Linquist et al., 2015; Massey et al., 2014). A multi-year, on-farm study in Mississippi demonstrated that an AWD irrigation threshold of -10 cm had no effect on rice grain yield relative to the producer standard for soil textures ranging from silt loam to clay (Atwill et al., 2020). Grain yield for rice grown at the -30 to -40 thresholds was less than CF. Grain yield was maintained at and above the -20 cm threshold compared to CF, and these data suggest this is a reasonable threshold for AWD irrigation management on clay textured soils. These reports provide evidence that reasonable AWD will not affect rice grain yield, but questions remain regarding low water use effects on seed quality.

Grain Quality

Milling Yield

Alternate wetting and drying thresholds ranging from 0 to approximately -20 cm will likely have no effect on milling yields and associated premiums. Under the conditions of our experiment, an AWD threshold ranging from 0 to -40 cm had no effect on milled rice and head rice for a hybrid and two inbred cultivars. Similarly, an AWD threshold of 0 cm had no effect on milling yield of XL753 at the field scale in Arkansas (Graham-Acquaah et al., 2019). Yang et al. (2017) reported that head rice yield increased 4 to 5% relative to the conventional flood when AWD was managed with a moderate threshold. Therefore, profitability associated with milling premiums will be similar between AWD and CF.

Grain Dimensions and Chalk

Adoption of AWD thresholds ranging from 0 to -20 cm may impact chalkiness in some rice varieties thereby affecting marketability. Under the conditions of our experiment, an AWD threshold ranging from 0 to -40 cm did not affect grain chalk or L:W ratio. Graham-Acquaah et al. (2019) noted that AWD increased grain chalkiness 0.4% when compared to CF, however, others have suggested that chalkiness is decreased up to 3.4% under moderate AWD (Zhang et al., 2012; Yang et al., 2017). These data suggest that AWD has minimal effect on grain chalk, and is likely dependent on severity of AWD, environment, and cultivar.

Irrigation Water Use Efficiency

Transitioning from CF to AWD will likely increase IWUE, particularly for varieties with exceptional yield potential. Under the conditions of our experiment, the IWUE for all cultivars decreased exponentially as AWD threshold increased, but the IWUE for the high-yielding hybrid was consistently greater than that of the inbred cultivars (Figure 1.3). Similarly, an on-farm study conducted in the Delta region of Mississippi from 2015-2017 demonstrated that AWD increased the IWUE of rice 59% relative to the producer standard (Atwill et al., 2020). Similarly, Chinese researchers noted that AWD increased the IWUE of rice more than 80% relative to that CF (Xue et al., 2013; Ye et al., 2013). Clearly, AWD improves IWUE, but the management strategy must be profitable for producers to adopt the technology.

Net Returns above Irrigation Costs

Converting from CF to AWD irrigation thresholds ranging from -20 cm to 0 cm will likely have a positive effect on net returns. Based on their small plot research, Nalley et al. 2015 concluded that some moderate AWD threshold are economically comparable to that of CF. Moreover, research conducted at the farm scale in Mississippi determined that transitioning from CF to AWD could increase net returns up to \$238 ha^{-1} depending on pumping depth and diesel prices (Atwill et al., 2020). The primary drivers for the economic benefit of AWD included reduced diesel, repair and maintenance, and labor costs. The economic advantage of AWD, coupled with reduced irrigation and no negative effect on rice grain yield, should drive adoption of this technology.

Conclusion

This research was conducted to determine if rice sustainability can be improved through manipulation of the irrigation threshold. The data indicate that converting from a conventional 5- to 10-cm flood to AWD water management can reduce water applied up to 45% without affecting yield, seed quality, or net returns. Contrary to conventional wisdom, hybrid and inbred lines responded similarly to AWD irrigation thresholds; however, yield and net returns for the hybrid line were greater than that of the inbred lines. To improve the sustainability of rice production in the midsouthern USA, it appears that growers should plant a high-yielding cultivar and employ AWD water management with thresholds ranging from 0 to -20 cm.

Tables and Figures

Table 1.1 Dates of agronomic management practices and herbicide application dates in an experiment to evaluate barnyardgrass control of conventional rice during 2015, 2016, and 2017 in Stoneville, MS

Management	2015	2016	2017
Planted	14 May	12 May	11 May
Fertilized	24 June	11 June	13 June
Flood Establishment	25 June	12 June	14 June
Flowering	6 Aug.	5 Aug.	29 July
Harvest	12 Sept.	22 Sept.	10 Sept.

Table 1.2 Soil characteristics for an experiment conducted to evaluate six rice irrigation regimes during 2015, 2016, and 2017 in Stoneville, MS

Characteristic	2015	2016	2017
Texture	Sharkey clay	Sharkey/Dowling clay	Sharkey clay
% sand	2.8	17.1	2.8
% silt	29.7	27.8	29.7
% clay	67.5	55	67.5
pH (H_2O) 1:1	6.8	6.7	6.8
Organic Matter (%)	1.8	2	1.8
CEC (cmol kg^{-1})	43	40.5	43

Place all detailed caption, notes, reference, legend information, etc here

Table 1.3 Monthly rainfall, mean maximum temperature, mean minimum temperature, and mean daily radiation during an experiment evaluating six rice irrigation management regimes at Stoneville, MS, in 2015, 2016, and 2017.

Year/Month	Rainfall	T max	T min	Radiation	Accumulated DD50
	mm	---------- ºC	----------	MJ m^{-2} d^{-1}	
2015					
May	150	28.7	17.8	15.8	775
June	61	32.3	21.3	19.5	827
July	2	33.4	23.2	21.4	851
August	17	33.5	20.9	20.4	813
September	22	32.5	18.2	17.2	738
2016					
May	53	28.2	16.4	20.4	716
June	94	32.3	21.9	19.8	844
July	160	33.7	23.1	19.1	858
August	166	33.1	23.1	17.7	829
September	13	33.2	19.6	17.9	746
2017					
May	91	27.5	16.3	17.4	704
June	110	30.0	20.1	15.4	817
July	99	32.9	22.2	18.6	857
August	231	31.6	21.8	15.9	822
September	2	31.1	17.6	18.4	733

Place all detailed caption, notes, reference, legend information, etc here

Table 1.4 Significance of the main effects irrigation and herbicide treatment and interaction among the main effects for rice grain yield, water applied, irrigation water use efficiency (IWUE), plant height, total milling yield, head rice yield, grain chalk and net returns above irrigation costs or an experiment conducted in Stoneville, MS from 2015 – 2017.

Effect	Grain Yield	Water Applied	IWUE	Plant Height	Total Milling	Head Rice	Grain Chalk	Net Returns
Irrigation Threshold	0.0354	<0.0001	<0.0001	0.0306	0.3234	0.5141	0.4458	0.7798
Cultivar	<0.0001	NA[c]	<0.0001	<0.0001	0.0002	0.1744	0.2117	<0.0001
Irrigation x Cultivar	0.8606	NA[c]	<0.0001	0.5730	0.4092	0.4349	0.3731	0.8607

Place all detailed caption, notes, reference, legend information, etc here

Table 1.5 Effects of one hybrid (XL753) cultivar at two pureline inbred cultivars (CL151, Rex) on rice grain yield, grain chalk, total milling yield, head rice yield, plant height, and net returns above irrigation costs for an experiment conducted in Stoneville, MS from 2015 – 2017[a].

Cultivar	Grain Yield	Grain Chalk [b]	Total Milling[c]	Head Rice[c]	Plant Height	Net Returns
	kg ha^{-1}	-------------------	%	-------------------	cm	\$ ha^{-1}
XL753	10771a	10.0	69.8a	58.7	118a	2076a
CL151	7901b	10.9	69.0a	61.8	108c	1535c
Rex	8107b	9.7	67.5b	62.9	114b	1706b

[a] Means within a column followed by the same letter for each parameter are not significantly different at $P \leq 0.05$.

[b] Data are expressed as percent area of chalk vs. translucent in a milled rice sample.

[c] Total milling and head rice yield are expressed as percent yield by weight

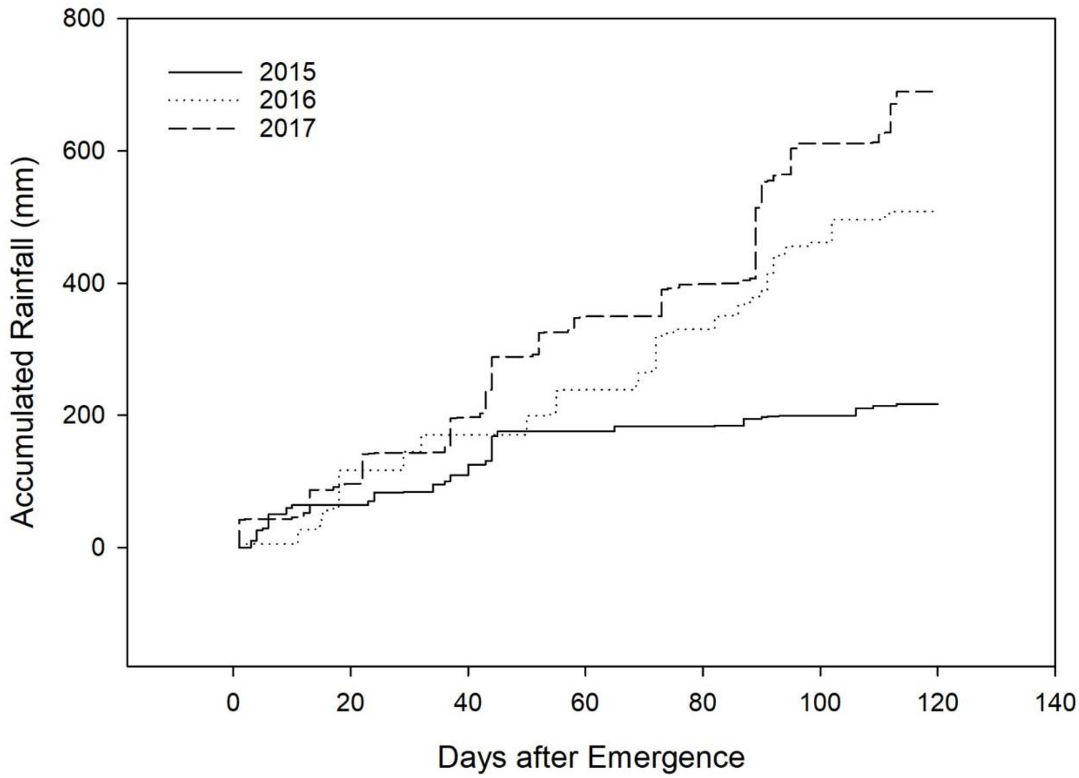

Figure 1.1 Accumulated rainfall amounts (mm) during the 2015 – 2017 growing seasons for an experiment conducted in Stoneville, MS

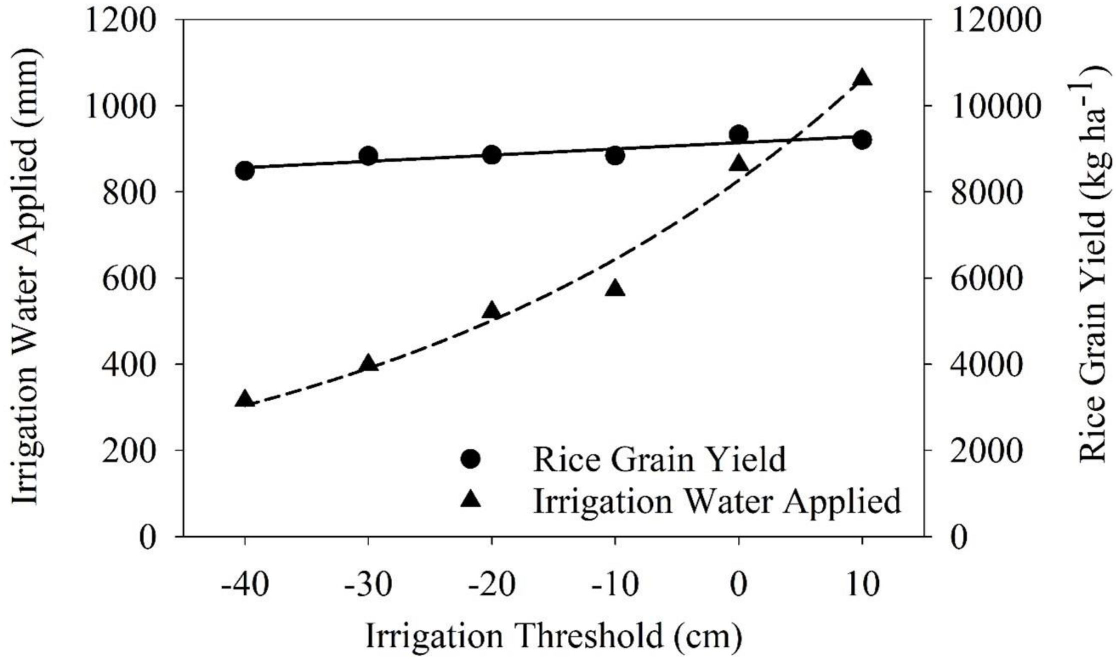

Figure 1.2 Irrigation water applied (mm) and rice grain yield (kg ha^{-1}) of three rice cultivars tested in six irrigation level thresholds for an experiment conducted in Stoneville, MS from 2015 – 2017.

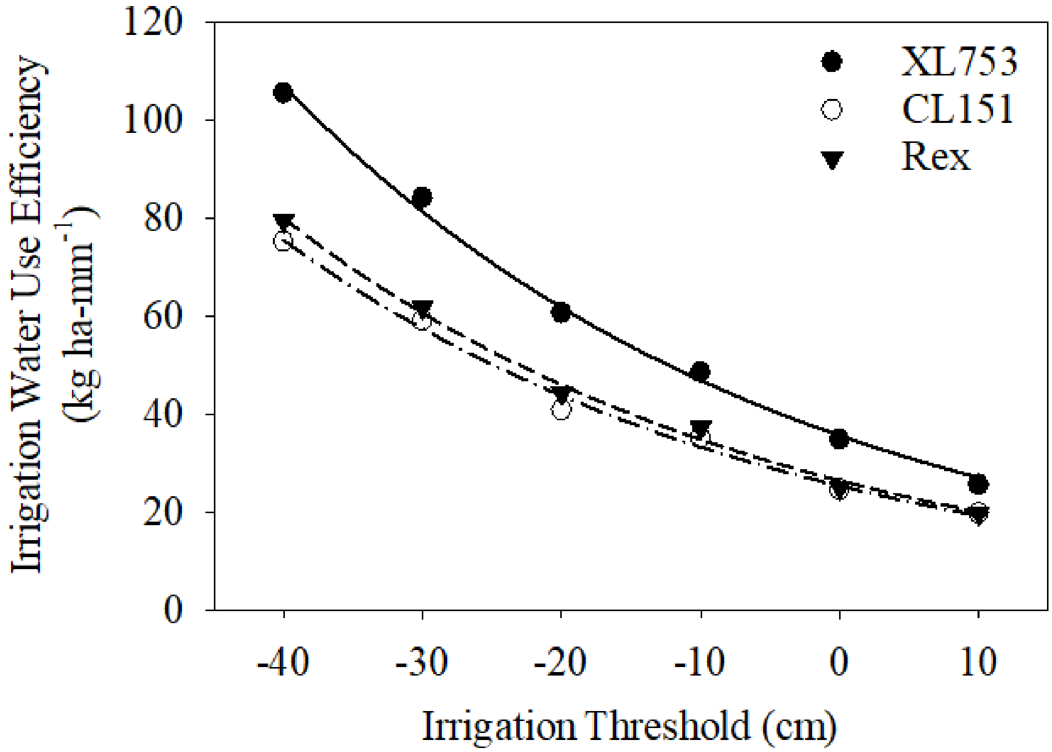

Figure 1.3 Irrigation water use efficiency of three rice cultivars tested in six water level thresholds for an experiment conducted in Stoneville, MS from 2015 – 2017

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CHAPTER II

ALTERNATE WETTING AND DRYING IRRIGATION EFFECTS ON BARNYARDGRASS CONTROL IN CLEARFIELD RICE

Abstract

Reduced control of problematic weeds in rice with herbicides may occur in unsaturated soil conditions. Research was conducted at the Delta Research and Extension Center near Stoneville, MS, to determine whether water management and Clearfield herbicide treatments interact to influence barnyardgrass control and rice yield. Irrigation levels included oscillating water level between 10 cm above to 20 cm below the soil surface (AWD) or maintaining a 5- to 10-cm flood (CONV). Herbicide treatments were combinations of imazethapyr, imazamox, and bispyribac-sodium at rates and timings commonly applied in the Clearfield rice production system. Irrigation level had no effect on barnyardgrass control ($P=0.7197$). With the exception of 80% barnyardgrass control with imazethapyr PRE followed by imazethapyr late-POST (LPOST), control of barnyardgrass was at least 95% for all other herbicide rate and timing combinations ($P=0.0009$). Herbicide treatment had no effect on rice yield ($P=0.9638$), while AWD did reduce rice yield 11% relative to CONV ($P\leq0.0001$). These data indicate that AWD has no adverse effect on barnyardgrass control in the Clearfield rice production system; thus, the water-saving benefits of AWD can be captured by midsouthern USA rice producers.

Introduction

Rice weed control and water management decisions are of utmost importance to producers in the midsouthern USA Prior to introduction of selective herbicides, flooding was the most important management tool for weed control in rice (Chhokar et al. 2014). Consequently, irrigation applied per hectare for rice production is greater than all other crops grown in the midsouthern USA (Massey et al. 2017). Alternate wetting and drying (AWD) water management is effective at reducing irrigation amounts in the midsouthern USA; however, the implications of AWD on Clearfield® rice weed control is not understood.

In the drill seeded, delayed-flood production system, rice is grown upland until the four- to five-leaf stage (Street and Bollich 2003). Traditionally, a flood is then established and maintained until 2 wk prior to harvest. This flood has historically been established for "control of weeds and other pests" (Buehring and Bond 2008; Massey et al. 2014). Alternate wetting and drying irrigation is managed identically to continuous flood up to 21 d after flooding, at which time water level within each paddy is allowed to subside to an established threshold. After reaching the desired AWD threshold, irrigation is applied until paddy water level reaches 10- to 15-cm depth, and this process is repeated until 2 wk prior to harvest. Allowing paddy water level to subside, rather than maintaining a flood allows for capture of rainfall that increases water use efficiency up to 59% (Atwill et al. 2020; Atwill et al. 2021). Additionally, AWD irrigation management maintains rice yield compared with continuously flooded rice.

Similar to other crops, weeds are a major limiting factor in rice production (Northsworthy et al. 2011). Barnyardgrass is the most troublesome grass weed for rice in Mississippi (Norsworthy et al. 2013; Bond and Buehring 2008; Talbert and Burgos 2007). For the midsouthern USA, herbicides offer the most practical, effective, and economical means of reducing weed competition in early rice growth stages prior to flooding (De Datta 1981; Norsworthy et al. 2013; Wilson et al. 2014). The most critical period of barnyardgrass control in rice is during early growth stages (PRE to LPOST). Flooding is an effective means of inhibiting emergence of most terrestrial weeds and controls many emerged annual and perennial weeds common to the midsouthern USA (Norsworthy et al. 2011).

Weed species, population, and emergence are affected by soil moisture content and reduced water depth under AWD management (De Datta 1981; Kent and Johnson 2001). Grassy weeds are controlled with flood depths of 5 to 10 cm (De Datta 1981). Similar control of grasses is achieved using contact and soil-residual herbicides. Considerations for rice weed control are timing of herbicide application, mode of action used, and selectivity of herbicides on weed species present or expected in the field. Proper timing of weed control, not necessarily method, is the single most important factor in obtaining weed-free fields. The lack of a continuous flood under AWD water management warrants effective use of herbicides to maximize weed control and rice grain yield (Tuong and Bhuiyan 1999).

Imazethapyr is an acetolactate synthase (ALS; EC 2.2.1.6) inhibitor that is registered for use in Clearfield® rice technology and controls barnyardgrass in drill seeded, delayed-flood rice production system (Anonymous, 2011; Masson et al. 2001; Pellerin et al. 2004). Norsworthy et al. (2013) reported that ALS herbicides, including imazethapyr, imazamox, and bispyribac-sodium are used as the sole herbicides on 42% of the imidazolinone-resistant rice hectares in Arkansas and Mississippi. Herbicidal activity of the imidazolinones is affected by soil moisture conditions; however, flood depth does not influence imazethapyr efficacy (Malefyt and Quakenbush 1991; Masson et al. 2001). Control of barnyardgrass with imazethapyr is negatively correlated with soil moisture due to dilution effects (Schreiber et al. 2017; Zhang et al. 2006).

Producer adoption of AWD is hindered by limited research on weed management under semi-aerobic environments (Scherder et al. 2003; Massey et al. 2014). This research was conducted to determine whether irrigation and Clearfield herbicide treatments interact to affect barnyardgrass control and rice yield.

Materials and Methods

A study to compare the efficacy of Clearfield rice herbicide treatments for AWD irrigation management compared to a continuous flood was conducted in 2015 (33.40ºN, 90.93ºW), 2016 (33. 40ºN, 90.92ºW), and 2017 (33. 40ºN, 90.93ºW) at the Mississippi State University Delta Research and Extension Center in Stoneville, MS. Soil was a Sharkey clay (very fine, smectitic, thermic Chromic Epiaquert) with a pH ranging from 8.0 to 8.2 and organic matter content ranging from 1.9 to 2.1%. Experimental sites were in a 1:1 soybean to rice rotation. Field preparation each year consisted of disking and field cultivation in the fall, followed by light field cultivation prior to planting. Emerged spring vegetation was controlled using glyphosate (Roundup® Weathermax® 4.5 L, Monsanto Company, 800 N. Lindburgh Blvd., St. Louis, MO 63167) at 1,120 g ae ha^{-1} prior to planting. Barnyardgrass was surface-seeded each year prior to planting to ensure uniform infestation.

The Clearfield long-grain rice cultivar 'CL151' (Horizon Ag, LLC, Memphis, TN) was drill-seeded at 75 kg ha^{-1} (330 seed m^2) at a depth of 2 cm with a small-plot grain drill (Great Plains 1520, Great Plains Mfg., Inc., 1525 East North St., Salina, KS 67401) equipped with double-disk openers and press wheels spaced 25.4 cm apart. Individual sub-plots consisted of six rows measuring 4.6 m in length. Rice plots were managed upland until the one-tiller growth stage, and nitrogen fertilizer was applied as urea (46-0-0) at 165 kg ha^{-1} immediately prior to initial flooding. All plots were managed according to Mississippi State University recommendations to minimize insect and disease pressure (Buehring 2008). Dates of agronomic management practices are reported in Table 2.1 for all years.

Experimental units were arranged in a split-plot within a randomized complete block whole-plot design structure with irrigation (I) as the whole plot and herbicide treatment (H) as the subplot (Figure 1). Within each year, four replicates of the irrigation treatment were tested with three sub-samples of herbicide treatment included within each whole-plot unit. The irrigation treatments were:

1. Continuous flood where rice was grown upland until the one- to two-tiller stage followed by (fb) a 10- to 20-cm flood that was maintained until 2 wk prior to harvest.
2. Alternate wetting and drying, where rice was grown upland until the one- to two-tiller stage fb a 10- to 20-cm flood that was maintained for 21 d. From 21 d after flooding until rice flowering, paddy water level was allowed to subside to 20 cm below the soil surface, at which time irrigation was applied to return paddy water level to a 10-cm flood. During rice flowering, a 10-cm flood was maintained, then allowed to subside to 20-cm below soil surface until 2 wk prior to harvest. Paddy water level was monitored using a perforated PVC tube embedded into the paddy (Lampayan et al. 2014). For this experiment, an AWD threshold of 20 cm below the soil surface was chosen to simulate a water level beyond the recommended threshold of -10 cm to encourage barnyardgrass growth and imitate extreme wetting and drying conditions (Atwill et al. 2020).

The sub-plot factor consisted of seven herbicide mixtures and timings with all imazethapyr applications applied at 105 g ai ha^{-1}, imazamox at 43.8 g ai ha^{-1}, and bispyribac-sodium at 37.5 g ai ha^{-1}. Subplot treatments included: 1) imazethapyr applied at the two- to threeleaf growth stage (EPOST) fb imazethapyr immediately prior to flooding (PRFLD); 2) imazethapyr PRE fb imazethapyr at the four-leaf to one-tiller growth stage (LPOST); 3) imazethapyr EPOST fb imazethapyr PRFLD fb imazamox 7 days after flooding (PTFLD); 4) imazethapyr EPOST fb imazamox PRFLD fb imazamox PTFLD; 5) imazethapyr plus bispyribac-sodium EPOST fb imazethapyr PRFLD; 6) imazethapyr EPOST fb imazethapyr plus bispyribac-sodium PRFLD; 7) imazethapyr plus bispyribac-sodium EPOST fb imazethapyr plus bispyribac-sodium PRFLD; 8) no herbicide as a nontreated control. All treatments (excluding nontreated control) included crop oil concentrate at 1% v/v (Agri-Dex, a 99% crop-oil concentrate, Helena Chemical Co., 5100 Poplar Ave., Memphis, TN 38137). Treatments were applied with a CO_2-pressurized backpack sprayer and hand-held boom equipped with extended range flat-fan spray nozzles (XR11002 TeeJet nozzles, Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60189) set to deliver 140 L ha^{-1} at 172 kPa. Barnyardgrass control and rice injury was visibly estimated at 21 d after treatment final application (DAFA) on a scale of 0 to 100% where 0 = no rice injury or barnyardgrass control and 100 = complete plant death or barnyardgrass control. Rice maturity was calculated as number of days from emergence to 50% heading (50% of rice plants with visible panicles in each plot).

Plots were harvested when the grain moisture reached approximately 18% with a Wintersteiger Delta (Wintersteiger USA, Salt Lake City, UT) small-plot combine equipped with a Harvest Master Grain Gauge (Juniper Systems, Inc. Logan, UT). Final rice grain yields were adjusted to 12% moisture content.

All data were subjected to ANOVA using the Mixed Procedure (Littell et al. 2006) in SAS 9.4 (SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513-2414). Type III statistics were used to test all possible fixed effects or interactions among the fixed effects. Replication of irrigation treatment (nested within year) and herbicide treatment (nested within year and irrigation treatment) were considered random effects. Considering year an environmental or random effect permits inferences about treatments to be made over a range of environments (Blouin et al. 2011; Carmer et al. 1989). Treatment means were averaged for each herbicide treatment within each replication of irrigation treatment for barnyardgrass control and rice yield. When weed control variances were not homogeneous, data were arcsine transformed (Onofri et al. 2009). Delineation of transformed data was similar to nontransformed data; therefore, only nontransformed data are reported (Northsworthy et al. 2011). Least-square means were calculated, and mean separation ($P \leq 0.05$) was produced using PDMIX800 in SAS software, which is a macro for converting mean-separation output letter groupings (Saxton, 1998).

Results and Discussion

The central hypothesis of this research was that AWD irrigation will decrease total water applied and have no adverse effect on barnyardgrass control or rice yield. Barnyardgrass control was not different between irrigation level and averaged 95% (Table 2.2). No rice injury was observed for any treatment at 21 DAFA, and heading ranged from 90 to 93 d after emergence (data not shown). With exception of 80% barnyardgrass control with imazethapyr PRE fb LPOST, control of barnyardgrass was ≥ 95% for all herbicide rate and timing combinations ($P=0.0009$, Table 2.3). Herbicide treatment had no effect on rice yield while rice yields were reduced 11% with AWD compared with CONV ($P \leq 0.0001$, Table 2.2). Relative to the regional standard, i.e. continuous 10- to 15-cm flood, an AWD threshold of 20-cm below the soil surface decreased water use 53% (Table 2.2). These data demonstrate that AWD will reduce consumptive water use without influencing barnyardgrass control.

Barnyardgrass control with residual herbicides in both aerobic and saturated environments is maintained relative to conventional rice production systems. Application of imazethapyr at the same rate, timing, and soil moisture conditions of this study resulted in 95% barnyardgrass control 9 weeks after treatment (WAT, Norsworthy et al. 2008). Barnyardgrass control was 98% with clomazone and quinclorac PRE and was not different between a constant 10- to 15-cm flood and five AWD thresholds (48, 41, 34, 27, and 21% volumetric water content) (Scherder et al. 2003). These data indicate that midsouthern USA rice producers can utilize existing barnyardgrass management in AWD production.

Control of barnyardgrass was more dependent on herbicide than irrigation treatment. In both the CONV and AWD drill-seeded, delayed-flood production systems, rice is managed identically until 21 d after flooding (i.e. 50 to 60 d after emergence), which is well beyond the critical weed control period for rice (Levy et al 2006; Scott et al. 2018). Consequently, weed management prior to initiation of AWD is not different than CONV. When timely applications are utilized, imazethapyr applied PRE fb LPOST controlled barnyardgrass up to 96% (Ottis et al 2003). Conversely, our work demonstrated a reduction in barnyardgrass control for imazethapyr PRE fb LPOST and was attributed to lack of control for emerged barnyardgrass (Table 2.4). Similarly, Northsworthy et al. (2008) reported a LPOST application of imazethapyr resulted in incomplete control of escaped barnyardgrass. Loss of weed control at LPOST termination timing was attributed to large plant size and ineffectiveness of treatments to provide acceptable early-season control (Avila et al. 2005; Norsworthy et al. 2008; Scott et al. 2018). These data suggest that adoption of AWD will have no adverse effect on control of barnyardgrass as compared to CONV; rather, timely application of effective imazethapyr in both AWD and CONV irrigation is the primary driver of barnyardgrass control.

The absence of an interaction between herbicide and irrigation treatments indicates that concerns over rice yield loss from reduced weed control in AWD systems is not warranted. As expected, we observed 12% reduction in rice yield under the extreme AWD environment (Table 2.3). However, reduction in rice yield attributed to inadequate barnyardgrass control was not evident. When an AWD threshold of 10-cm below soil surface (BSS) is utilized, barnyardgrass control and rice yield should be similar to that of CONV.

Optimizing the timing of irrigation for rice and other crops in the midsouthern USA with established thresholds may reduce withdrawal from the Mississippi Valley River Alluvial Aquifer (MVRAA) up to 39.5% relative to producer standards (Atwill et al. 2020; Wood et al. 2020). At the field scale, optimizing rice irrigation timing and scheduling based on a threshold of 10-cm BSS decreased total water applied up to 39% relative to the regional standard. (Atwill et al. 2021; Massey et al. 2014). Similarly, at the plot scale, irrigating rice at a threshold of 10-cm below the soil surface decreased the amount of water applied 44% (Atwill et al. 2021; Lampayan et al. 2015; Belder et al. 2004). However, rice producers are reluctant to adopt best management practices if they perceive the new technology will have an adverse effect on weed control (Norsworthy et al. 2011; Lampayan et al. 2014; Massey et al. 2014).

The objective of this research was to determine whether irrigation and Clearfield herbicide treatments interact to affect barnyardgrass control and rice yield. Irrigation treatment had no effect on barnyardgrass control. With exception of 80% barnyardgrass control with imazethapyr PRE fb LPOST, control of barnyardgrass was > 95% for all other herbicide rate and timing combinations. Herbicide treatment had no effect on rice yield, while rice yield was lower with AWD relative to CONV. These data indicate that midsouthern USA rice producers can capture the water-saving benefits of AWD with no adverse effect on the control of barnyardgrass in the Clearfield rice production system.

Tables and Figures

Table 2.1 Dates of agronomic management practices and herbicide application dates in an experiment to evaluate barnyardgrass control of conventional rice during 2015, 2016, and 2017 in Stoneville, MS.[a]

Management	2015	2016	2017
Planted	14 May	12 May	11 May
PRE[a] Application	15 May	14 May	12 May
DPRE[a] Application	20 May	17 May	17 May
Fertilized	24 June	11 June	13 June
PRFLD[a]	21 June	11 June	12 June
Flood Establishment	25 June	12 June	14 June
PFLD[a]	1 July	20 June	21 June
Flowering	6 Aug.	5 Aug.	29 July
Harvest	12 Sept.	22 Sept.	10 Sept.

[a] Abbreviations: PRE, preemergence; DPRE, delayed preemergence; PRFLD, preflood; PFLD, postflood

Table 2.2 Significance of the main effects of irrigation and herbicide treatment and interaction among the main effects for barnyardgrass control at 21 d after final application (DAFA) and rice grain yield, and effect of irrigation treatment on water applied in an experiment evaluating Clearfield herbicide treatments at Stoneville, MS, in 2015, 2016, and 2017[a].

Effect	Barnyardgrass Control	Grain Yield	Water Applied
		P-value	
Irrigation	0.9864	<0.0001	<0.0001
Herbicide	0.0009	0.7672	NA[b]
Irrigation x Herbicide	0.9567	0.5948	NA[b]

[a] The Mixed Procedure was used with year as a random-effect parameter
[b] NA, not applicable: Water applied to the whole plot ‘irrigation’ was independent of herbicide treatment within the irrigation treatment

Table 2.3 Effects continuous flood and alternate wetting and drying on barnyardgrass control 21 d after final application (DAFA), rice grain yield and water applied in an experiment evaluating Clearfield herbicide treatments at Stoneville, MS, in 2015, 2016, and 2017.

Irrigation treatment	Irrigation threshold[a]	Barnyardgrass Control	Rice yield	Applied Irrigation
	cm	%	kg ha^{-1}	ha-mm
Continuous Flood	+10	94	7890a	1060a
AWD	-20	94	7010b	522b
LSD		3.0	283.6	34

[a] Irrigation threshold is reported as distance (cm) relative to the soil surface

Table 2.4 Effects of imazethapyr plus bispyribac-sodium followed by imazethapyr, imazamox, or bispyribac-sodium on barnyardgrass control 21 d after final application (DAFA) and rice grain yield in an experiment evaluating Clearfield herbicide treatments at Stoneville, MS, in 2015, 2016, and 2017.

Herbicide treatment[b]	Rate	Timing	Barnyardgrass Control	Rice yield
	g ai ha^{-1}		%	kg ha^{-1}
Imazethapyr fb[c]	105	EPOST	95a	7640
Imazethapyr	105	PRFLD		
Imazethapyr fb	105	PRE	80b	7310
Imazethapyr	105	LPOST		
Imazethapyr fb	105	EPOST	96a	7490
Imazethapyr fb	105	PRFLD		
Imazamox	44	PTFLD		
Imazethapyr fb	105	EPOST	95a	7470
Imazamox fb	44	PRFLD		
Imazamox	44	PTFLD		
Imazethapyr + Bispyribac-sodium fb	105	EPOST	96a	7510
Imazethapyr	105	PRFLD		
Imazethapyr fb	105	EPOST	96a	7380
Imazethapyr + Bispyribac-sodium	105	PRFLD		
Imazethapyr + Bispyribac-sodium fb	105	EPOST	97a	7330
Imazethapyr + Bispyribac-sodium	105	PRFLD		
LSD			10.6	394.9

[a] Means within a column followed by the same letter were not statistically different according to the difference of least-square
means at P = 0.05.

[b] A crop-oil concentrate (COC) was added at a rate of 1% v/v.

[c] Abbreviations: fb, followed by

References

Anonymous (2011) Newpath® Herbicide Product Label. EPA Reg No. 241-412. Research Triangle Park, NC: BASF

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CHAPTER III

ALTERNATE WETTING AND DRYING RICE IRRIGATION EFFECTS ON BARNYARDGRASS CONTROL FOR CONVENTIONAL RICE

Abstract

Rice (*Oryza sativa* L.) is traditionally flooded to suppress weed germination and growth. This study was conducted to determine whether the efficacy of conventional herbicides is affected by alternate wetting and drying (AWD) irrigation management. The effects of irrigation management and herbicide program on water applied, barnyardgrass (*Echinochloa crus-galli* L.) control, and grain yield were investigated at the Delta Research and Extension Center in Stoneville, MS on a Sharkey clay (very fine, smectitic, thermic Chromic Epiaquert). Water applied was 53% less for AWD than the standard irrigation system, that is, maintaining a continuous 10- to 15-cm flood. Alternate wetting and drying either had no effect or improved herbicidal efficacy and rice grain yield up to 9% relative to the standard irrigation system. These data indicate that midsouthern USA rice producers can capture the water-saving benefits of AWD with no adverse effect on the control of barnyardgrass using conventional rice herbicides.

Introduction

Rice is traditionally flooded to suppress weed germination and growth, but this approach is negatively affecting the sustainability of irrigated agriculture in the midsouthern USA. In the drill seeded, delayed-flood production system, rice is grown upland until the four- to five-leaf stage (Street and Bollich 2003). Traditionally, a flood is then established and maintained until 2 wk prior to harvest. Prior to the introduction of selective herbicides, flooding was the primary means for weed control in rice (Buehring and Bond 2008; Chhokar et al. 2014; Massey et al. 2014). The cultural practice of applying a flood for weed control has persisted; consequently, irrigation applied per hectare for rice production is greater than all other crops grown in the midsouthern USA (Massey et al. 2017). Alternate wetting and drying (AWD) water management is effective at reducing irrigation amounts in the midsouthern USA; however, the implications of AWD on conventional rice weed control is not understood.

Alternate wetting and drying irrigation is managed identically to continuous flood up to 21 d after flooding, at which time water level within each paddy is allowed to subside to an established threshold. After reaching the desired AWD threshold, irrigation is applied until paddy water level reaches 10- to 15-cm depth, and this process is repeated until 2 wk prior to harvest. Allowing paddy water level to subside, rather than maintaining a flood allows for capture of rainfall that increases water use efficiency up to 59% (Atwill et al. 2020; Atwill et al. 2021). The adoption of alternative rice irrigation strategies has been low as producers fear an adverse effect on weed control.

Weeds are a major limiting factor in rice production (Northsworthy et al. 2011). Barnyardgrass is the most troublesome grass weed for rice in Mississippi (Norsworthy et al. 2013; Bond and Buehring 2008; Talbert and Burgos 2007). For the midsouthern USA, herbicides offer the most practical, effective, and economical means of reducing weed competition in early rice growth stages prior to flooding (De Datta 1981; Norsworthy et al. 2013; Wilson et al. 2014). The most critical period of barnyardgrass control in rice is during early growth stages (PRE to LPOST). Flooding is an effective means of inhibiting emergence of most terrestrial weeds and controls many emerged annual and perennial weeds common to the midsouthern USA (Norsworthy et al. 2011). Herbicides allow for selective and effective control of grass weeds in rice production (Tuong and Bhuiyan 1999). Scherder et al (2002) reported that control of barnyardgrass under intermittent flood conditions can be achieved with pre-emergence, early post emergence conventional herbicide programs commonly used in midsouthern USA rice production. For midsouthern USA rice production, herbicides offer the most practical, effective, and economical means of reducing weed competition in early growth stages prior to flood establishment (DeDatta 1981).

Weed species, population, and emergence are affected by soil moisture content and reduced water depth under AWD management (De Datta 1981; Kent and Johnson 2001). Grassy weeds are controlled with flood depths of 5 to 10 cm (De Datta 1981). Similar control of grasses is achieved using contact and soil-residual herbicides. Considerations for rice weed control are timing of herbicide application, mode of action used, and selectivity of herbicides on weed species present or expected in the field. Proper timing of weed control, not necessarily method, is the single most important factor in obtaining weed-free fields. The lack of a continuous flood under AWD water management warrants effective use of herbicides to maximize weed control and rice grain yield (Tuong and Bhuiyan 1999).

Clomazone and quinclorac provide effective control of barnyardgrass when applied preemergence (PRE) and are the top two herbicides recommended for PRE residual application in rice (Norsworthy et al. 2007). Clomazone was labeled for use in rice production in 2000, and is currently the standard herbicide for control of annual grasses in rice including barnyardgrass (Osterholt et al. 2019; Talbert and Burgos 2007). Degradation of clomazone is faster under flooded conditions than aerobic conditions, and is suitable for weed control in alternate irrigation regimes for rice (Schreiber et al. 2017; Senseman 2007). Quinclorac was first introduced for rice in 1992 and has since been an integral part of rice weed control in the mid-south, however, applications of quinclorac alone are not common due to increased prevalence of resistant biotypes of barnyardgrass (Norsworthy et al. 2013).

Pendimethalin and thiobencarb are useful soil residual herbicides for rice production and can be applied delayed preemergence (DPRE) after rice has imbibed water for germination but before rice and weeds emerge (Jordan et al. 1998). Pendimethalin undergoes rapid degradation under anaerobic conditions (Senseman 2007), and early season application at DPRE will undergo the same soil moisture conditions prior to initiation of water cycling in AWD compared to CF. Thus, control of weeds is expected to be similar among irrigation regime for pendimethalin until 21 days after flood establishment. Conversely, thiobencarb is rapidly and strongly adsorbed to soil and is persistence under anaerobic conditions is 3 to 4 times greater than under aerobic conditions (Senseman 2007) but is susceptible to attack from aqueous oxides present in sunlit water of flooded rice fields. Additionally, thiobencarb is known to exhibit phytoxoic properties in soils that develop anaerobic conditions after planting which may lead to increased efficacy on rice and grass weeds (Anonymous 2015; Groth et al. 1997)

Rice weeds that are not completely controlled prior to flooding must be addressed with application of herbicide 2-3 days prior to or after flood establishment. Control of barnyardgrass is more effective when applied immediately prior to flood establishment (PRFLD), however postflood (PTFLD) applications can be made to control escaped weeds (Barber et al. 2019). Fenoxaprop, cyhalofop, and bispyribac-sodium are common herbicides used to control barnyardgrass for PRFLD and PTFLD application timing (Norsworthy et al. 2013). Efficacy of these selective postemergent herbicides increases with soil moisture at the time of application. Specific water management practices in regards to efficacy are addressed on the herbicide labels and should be taken into account when building a herbicide program for alternate rice irrigation regimes. For example, fenoxaprop requires a minimum of 2 to 3 days after application until a permanent flood is established.

Pre- and Post-emergent herbicide applications for grass control in rice are critical for maximizing yield in the mid-south, and efficacy of these herbicides under AWD water management should be investigated. Producer adoption of AWD is hindered by limited research on herbicide efficacy and grass control under semi-aerobic environments (Scherder et al. 2003; Massey et al. 2014). This study was conducted to determine whether the efficacy of conventional herbicides is affected AWD irrigation management.

Materials and Methods

A study to compare the efficacy of soil and foliar applied rice herbicide treatments for AWD irrigation management compared to a continuous flood was conducted in 2015 (33.40ºN, 90.93ºW), 2016 (33. 40ºN, 90.92ºW), and 2017 (33. 40ºN, 90.93ºW) at the Mississippi State University Delta Research and Extension Center in Stoneville, MS. Soil was a Sharkey clay (very fine, smectitic, thermic Chromic Epiaquert) with a pH ranging from 8.0 to 8.2 and organic matter content ranging from 1.9 to 2.1%. Experimental sites were in a 1:1 soybean to rice rotation. Field preparation each year consisted of disking and field cultivation in the fall, followed by light field cultivation prior to planting. Emerged spring vegetation was controlled using glyphosate (Roundup® Weathermax® 4.5 L, Monsanto Company, 800 N. Lindburgh Blvd., St. Louis, MO 63167) at 1,120 g ae ha^{-1} prior to planting. Barnyardgrass was surface-seeded each year prior to planting to ensure uniform infestation.

The Clearfield long-grain rice cultivar 'CL151' (Horizon Ag, LLC, Memphis, TN) was drill-seeded at 75 kg ha^{-1} (330 seed m^2) at a depth of 2 cm with a small-plot grain drill (Great Plains 1520, Great Plains Mfg., Inc., 1525 East North St., Salina, KS 67401) equipped with double-disk openers and press wheels spaced 25.4 cm apart. Individual sub-plots consisted of six rows measuring 4.6 m in length. Rice plots were managed upland until the one-tiller growth stage, and nitrogen fertilizer was applied as urea (46-0-0) at 165 kg ha^{-1} immediately prior to initial flooding. All plots were managed according to Mississippi State University recommendations to minimize insect and disease pressure (Buehring 2008). Dates of agronomic management practices are reported in Table 3.1 for all years.

Experimental units were arranged in a split-plot within a randomized complete block whole-plot design structure with irrigation (I) as the whole plot and herbicide treatment (H) as the subplot (Figure 1). Within each year, four replicates of the irrigation treatment were tested with three sub-samples of herbicide treatment included within each whole-plot unit. The irrigation treatments were:

3. Continuous flood where rice was grown upland until the one- to two-tiller stage followed by (fb) a 10- to 20-cm flood that was maintained until 2 wk prior to harvest.
4. Alternate wetting and drying, where rice was grown upland until the one- to two-tiller stage fb a 10- to 20-cm flood that was maintained for 21 d. From 21 d after flooding until rice flowering, paddy water level was allowed to subside to 20 cm below the soil surface, at which time irrigation was applied to return paddy water level to a 10-cm

flood. During rice flowering, a 10-cm flood was maintained, then allowed to subside to 20-cm below soil surface until 2 wk prior to harvest. Paddy water level was monitored using a perforated PVC tube embedded into the paddy (Lampayan et al. 2014). For this experiment, an AWD threshold of 20 cm below the soil surface was chosen to simulate a water level beyond the recommended threshold of -10 cm to encourage barnyardgrass growth and imitate extreme wetting and drying conditions (Atwill et al. 2020).

The subplot factor herbicide treatment consisted of seven herbicide mixtures and timings, and included: 1) clomazone applied at planting (PRE) at 892 g ai ha^{-1}; 2) quinclorac applied at planting (PRE) at 564 g ai ha^{-1}; 3) pendimethalin applied delayed-preemergence (DPRE) at 1 kg ai ha^{-1}; 4) thiobencarb applied DPRE at 4.4 kg ai ha^{-1}; 5) fenoxaprop applied at preflood, or 1 to 2 tiller growth stage (PREFL) at 122 g ai ha^{-1}; 6) cyhalofop applied PRFLD 313 g ai ha^{-1}; 7) bispyribac-sodium applied post-flood (PTFLD) at 38 g ai ha^{-1}; 8) no herbicide as a nontreated control (Table 3.2). All treatments (excluding nontreated control) included crop oil concentrate at 1% v/v (Agri-Dex, a 99% crop-oil concentrate, Helena Chemical Co., 5100 Poplar Ave., Memphis, TN 38137). Treatments were applied with a CO_2-pressurized backpack sprayer and hand-held boom equipped with extended range flat-fan spray nozzles (XR11002 TeeJet nozzles, Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60189) set to deliver 140 L ha^{-1} at 172 kPa. Dates of application events are reported in Table 3.1. Barnyardgrass control and rice injury was visibly estimated at 21 d after treatment final application (DAFA) on a scale of 0 to 100% where 0 = no rice injury or barnyardgrass control and 100 = complete plant death or barnyardgrass control. Rice maturity was calculated as number of days from emergence to 50% heading (50% of rice plants with visible panicles in each plot).

Plots were harvested when the grain moisture reached approximately 18% with a Wintersteiger Delta (Wintersteiger USA, Salt Lake City, UT) small-plot combine equipped with a Harvest Master Grain Gauge (Juniper Systems, Inc. Logan, UT). Final rice grain yields were adjusted to 12% moisture content.

All data were subjected to ANOVA using the Mixed Procedure (Littell et al. 2006) in SAS 9.4 (SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513-2414). Type III statistics were used to test all possible fixed effects or interactions among the fixed effects. Replication of irrigation treatment (nested within year) and herbicide treatment (nested within year and irrigation treatment) were considered random effects. Considering year an environmental or random effect permits inferences about treatments to be made over a range of environments (Blouin et al. 2011; Carmer et al. 1989). Treatment means were averaged for each herbicide treatment within each replication of irrigation treatment for barnyardgrass control and rice yield. When weed control variances were not homogeneous, data were arcsine transformed (Onofri et al. 2009). Delineation of transformed data was similar to nontransformed data; therefore, only nontransformed data are reported (Northsworthy et al. 2011). Least-square means were calculated, and mean separation ($P \leq 0.05$) was produced using PDMIX800 in SAS software, which is a macro for converting mean-separation output letter groupings (Saxton, 1998).

Results and Discussion

The central hypothesis of this research was that AWD irrigation management will decrease water applied while having no adverse effect on barnyardgrass control or rice yield. As postulated, AWD reduced water applied 53% and either had no effect or improved herbicidal efficacy and rice grain yield up to 9% relative to the standard irrigation system (Table 3.4). These data indicate that midsouthern USA rice producers can capture the water-saving benefits of AWD with no adverse effect on the control of barnyardgrass with conventional rice herbicides.

Optimizing the timing of irrigation for rice and other crops in the midsouthern USA with established thresholds may reduce withdrawal from the Mississippi Valley River Alluvial Aquifer (MVRAA) up to 39.5% relative to producer standards (Atwill et al. 2020; Massey et al. 2014; Wood et al. 2020). In this study, irrigating rice at a threshold of 20-cm below the soil surface decreased the amount of water applied 50% (Atwill et al. 2021; Lampayan et al. 2014; Belder et al. 2004). However, rice producers are reluctant to adopt best management practices if they perceive the new technology will have an adverse effect on weed control (Norsworthy et al. 2011; Lampayan et al. 2015; Massey et al. 2014).

The adoption of AWD in the midsouthern USA could reduce total withdrawal from the MRVAA. Similar to this study, small-plot research indicated that an irrigation threshold of 20 cm below the soil surface reduced applied irrigation in AWD 32% relative to CF (Atwill et al. 2020). At the farm scale, AWD reduces water use from 18 to 44% in the midsouthern USA (Nalley et al. 2015; Massey et al. 2014; Atwill et al. 2020). The reduction in water use under AWD irrigation management is largely due to improved rainfall capture (Chalapecka et al 2021; Massey et al. 2014). Conventional rice flood management constitutes constructing outlets, i.e., levee gates, in each levee to impound water to a depth of 10 cm at the bottom of the paddy. The flood is maintained at 10 cm above the soil surface; therefore, rainfall that increases the water level above 10 cm is lost as surface runoff. Drying events in AWD produce a freeboard to capture rainfall, thereby increasing the flood depth without irrigation.

Control of barnyardgrass with PRE applied herbicides clomazone and quinclorac were not different under AWD compared to CF, however control of barnyardgrass with clomazone was 6 to 10% greater than quinclorac applied PRE (Table 3.5). Regardless of irrigation treatment, clomazone applied PRE, cyhalofop applied PREFL and bispyribac-sodium applied PTFLD controlled barnyardgrass 93 to 97%. Fenoxaprop provided the least amount of control compared to all other herbicide treatments with 59 and 64% control for AWD and CF, respectively. Similar control has been observed when fenoxaprop is applied PREFL and is attributed to a second flush of weeds during the period from application to establishment of permanent flood (Anonymous 2014; Talbert and Burgos 2007; Zhang et al. 2005). No grass control was employed from planting to the PREFL application of fenoxaprop, and emerged barnyardgrass was suppressed rather than controlled for this treatment (Anonymous 2014).

For DPRE treatments, thiobencarb provided up to 24% more control than pendimethalin, however control of barnyardgrass with thiobencarb under CF was 8% less than AWD irrigation. Greater control of barnyardgrass with thiobencarb over pendimethalin at DPRE timing has been reported (Talbert and Burgos 2007). Loss of thiobencarb efficacy in CF may be attributed to increased degradation in anaerobic versus aerobic soil moisture conditions, degradation via aqueous oxidants in sunlit water, or Delayed Phytoxicity Syndrome (DPS) commonly associated with the herbicide (Braverman et al. 1990; Chen 2002; Groth et al. 1999). Additionally, Doran et al. (2006) noted a lag period of 20 days in the degradation of thiobencarb under aerobic versus anaerobic soil conditions.

Barnyardgrass control in rice with conventional residual herbicides is maintained or improved using AWD irrigation compared to a continuous flood. Complete control of barnyardgrass with application of clomazone PRE, quinclorac PRE, pendimethalin DPRE, and thiobencarb DPRE under similar rice irrigation regimes (Scherder and Vories 2002). In this study, reduced control of quinclorac PRE and pendimethalin DPRE compared to other herbicide treatments was evident, yet were similar among irrigation treatments. While this study was conducted using single applications of single chemistry groups to control barnyardgrass, this is not recommended in commercial production. Rather, growers should employ resistance management techniques that rotate herbicides having different modes of action, use tank mixtures having different modes of action, and avoid sequential applications of the same herbicide or herbicides having the same mode of action (Talbert and Burgos 2007). These practices remain true regardless of irrigation management, and data from this study indicates that chemical weed control for barnyardgrass can be managed identically for AWD and CF irrigation management.

This research suggests that AWD irrigation management does not negatively affect yield due to either water stress or lack of grassy weed control compared to a CF. Similar to this research, AWD at the small plot and field scale maintained or improved rice grain yield in the midsouthern USA up to 11% relative to CF (Atwill 2020; Massey et al. 2014; Nalley et al. 2015). Maintaining yield with a corresponding decrease in water application improves irrigation water use efficiency.

This study was conducted to determine whether the efficacy of conventional herbicides is affected by alternate wetting and drying (AWD) irrigation management. Alternate wetting and drying reduced water applied by more than 50% and had no adverse effect on the control of barnyardgrass or rice grain yield. Midsouthern USA rice producers may be able to capture the water-saving benefits of AWD while having no adverse effect on conventional rice herbicide programs or rice productivity.

Tables and Figures

Table 3.1 Dates of agronomic management practices and herbicide application dates in an experiment to evaluate barnyardgrass control of conventional rice during 2015, 2016, and 2017 in Stoneville, MS.[a]

Management	2015	2016	2017
Planted	14 May	12 May	11 May
PRE[a] Application	15 May	14 May	12 May
DPRE[a] Application	20 May	17 May	17 May
Fertilized	24 June	11 June	13 June
PRFLD[a]	21 June	11 June	12 June
Flood Establishment	25 June	12 June	14 June
PFLD[a]	1 July	20 June	21 June
Flowering	6 Aug.	5 Aug.	29 July
Harvest	12 Sept.	22 Sept.	10 Sept.

[a] Abbreviations: PRE, preemergence; DPRE, delayed preemergence; PRFLD, preflood; PFLD, postflood

Table 3.2 Sources of materials for all products used in an experiment to evaluate barnyardgrass control of conventional rice during 2015, 2016, and 2017 in Stoneville, MS.[a]

Herbicide/Product	Trade name	g L^{-1}	Manufacturer
Clomazone	Command 3ME	360	FMC Corporation, Philadelphia, PA www.fmccrop.com
Quinclorac	Facet L	180	BASF Corporation, Research Triangle Park, NC www.agriculture.basf.com
Pendimethalin	Prowl 3.3EC	313	BASF Corporation, Research Triangle Park, NC www.agriculture.basf.com
Thiobencarb	Bolero	958	Valent U.S.A. Corporation, Walnut Creek, CA www.valent.com
Fenoxaprop-p-etyhl	Ricestar HT	70	Bayer CropScience LP, Research Triangle Park, NC www.cropscience.bayer.us
Cyhalofop-butyl	Clincher SF	285	Dow AgroSciences LLC, Indianapolis, IN www.corteva.com
Crop oil concentrate	Agri-Dex	---[a]	Helena Agri-Enterprises, Collierville, TN www.helenaagri.com
Bispyribac-sodium	Regiment	---[b]	Valent U.S.A. Corporation, Walnut Creek, CA www.valent.com
Surfactant	Phase II	---[c]	Loveland Products Inc., Greeley, CO www.lovelandproducts.com

[a] The crop oil concentrate is formulated at 17% nonionic surfactant and 83% unsulfonated oil residue

[b] The formulation of bispyribac-sodium is a water-dispersible powder that contains 80% ai by weight [c] The surfactant is formulated as 80carbamides, alcohol ethoxylates, methylated esters of fatty acids, polyether modified polysiloxane and 20% inactive ingredients

Table 3.3 Significance of the main effects of irrigation and herbicide treatment and interaction among the main effects for barnyardgrass control at 21 d after final application (DAFA) and rice grain yield in an experiment evaluating residual and foliar herbicide treatments at Stoneville, MS, in 2015, 2016, and 2017. [a]

Effect	Barnyardgrass Control	Rice Grain Yield	Water Applied
	--------------------- P value --------------------		
Irrigation	0.3923	0.2338	<0.0001
Herbicide	<0.0001	0.0110	na
Irrigation x Herbicide	0.0202	0.3646	na

[a] The Mixed Procedure was used with year as a random-effect parameter

Table 3.4 Significance of the main effects of irrigation and herbicide treatment and interaction among the main effects for barnyardgrass control at 21 d after final application (DAFA) and rice grain yield in an experiment evaluating residual and foliar herbicide treatments at Stoneville, MS, in 2015, 2016, and 2017.

Irrigation treatment	Irrigation threshold[a]	Barnyardgrass Control[a]	Rice yield	Water Applied[b]
	cm	%	kg ha^{-1}	mm
Continuous Flood	+10	94	7660	1060a
AWD[c]	-20	94	7480	522b
LSD		NS	NS	34

[a] Data are expressed as percentage of control. Means within a column followed by the same letter for each parameter are not significantly different at $P \leq 0.05$.

[b]Data are expressed as a mm of water. Means within a column followed by the same letter for each parameter are not significantly different at $P \leq 0.05$.

[c]Abbreviation: AWD, alternate wetting and drying

Table 3.5 Effects of seven herbicides for continuously flooded (CF) and alternate wetting and drying (AWD) rice irrigation on barnyardgrass control 21 d after application during 2015, 2016, and 2017 in and experiment conducted in Stoneville, MS.

Herbicide treatment	Rate	Timing[a]	Barnyardgrass Control[b]		Rice Grain Yield
			CF	AWD	CF + AWD[c]
	kg ai ha^{-1}		% of control		kg ha^{-1}
Clomazone	0.892	PRE	94a	94a	7680a
Quinclorac	0.564	PRE	88bc	84c	7690a
Pendimethalin	1	DPRE	75d	71d	7600a
Thiobencarb	4.4	DPRE	87bc	95a	7620a
Fenoxaprop-p-etyhl	0.078	PREFL	64e	59e	7270b
Cyhalofop-butyl[c]	0.313	PREFL	97a	95a	7760a
Bispyribac-sodium[d]	0.038	PTFLD	93ab	95a	7700a
LSD			5		497

[a] Timing abbreviations: PRE, preemergence; DPRE, delayed preemergence; PREFL, preflood; PTFLD, postflood

[b] Data are expressed as a percentage of the control. Means within a column followed by the same letter for each parameter are not significantly different at $P \leq 0.05$.

[c] No interaction of irrigation x herbicide treatment was detected, therefore data are pooled over irrigation treatment. Means within a column followed by the same letter for each parameter are not significantly different at $P \leq 0.05$.

[d] Methylated seed oil (MSO) added at a rate of 1% v/v.

[e] Phase II adjuvant added at a rate of 1% v/v.

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CHAPTER IV

ALTERNATE WETTING AND DRYING REDUCES AQUIFER WITHDRAWAL IN MISSISSIPPI RICE PRODUCTION SYSTEMS

Abstract

Water level declines in the Mississippi River Valley Alluvial Aquifer (MRVAA) are attributed largely to withdrawals for rice (*Oryza sativa* L.) irrigation. This study was performed to determine if alternative irrigation strategies for rice could reduce withdrawal from the MRVAA without having an adverse effect on yield and profitability. Research was conducted at 19 on-farm locations across the Delta region of Mississippi from 2014 through 2016 to determine the effects of irrigation water management practice, i.e., conventional flood via cascade (CONV), multiple side inlet (MSI), and MSI coupled with alternate wetting and drying (AWD), on aquifer withdrawal, rough rice grain yield, irrigation water use efficiency (IWUE), and net returns above irrigation costs. Compared to CONV and MSI, up to 39% less water was applied to AWD ($P < 0.0001$). Rice grain yield for AWD was not different from either CONV or MSI ($P = 0.1343$), despite substantial reductions in water use. Relative to standard irrigation strategies, AWD maintained or increased net returns up to \$238 ha^{-1} for pumping depths from 5.5 m to 122 m and diesel prices from \$0.42 L^{-1} to \$0.98 L^{-1} ($P \leq 0.0003$). Irrigation water use efficiency was up to 59% greater for AWD relative to conventional systems due to the positive effects of the former on water use while maintaining yield ($P = 0.0034$). These data demonstrate that AWD

can reduce withdrawal from the MRVAA while maintaining or improving yield and net returns relative to irrigation strategies currently employed across the midsouthern USA rice belt.

Introduction

The Mississippi River Valley Alluvial Aquifer is the primary source of water for the irrigation of crops in the midsouthern USA (Massey et al., 2017). For over 50 years, agricultural withdrawal from the MRVAA has exceeded long-term recharge rates, causing a decline in water levels of 0.15 to 0.45 m yr^{-1} (Wax, Pote, & Merrell, 2008; Massey et al., 2017; Arkansas Natural Resources Commission, 2019). Continued reliance on the MRVAA raises concerns regarding the long-term sustainability of irrigated, row-crop agriculture in the midsouthern USA (Wax et al., 2008).

Rice irrigation accounts for almost half of the agricultural withdrawal from the MRVAA. Irrigated hectarage for major row crops in the Lower Mississippi River Valley includes 590,000 ha rice, 1.6 million ha soybean, 508,000 ha corn, and 342,000 ha cotton (USDA-NASS, 2018). Per hectare, irrigation applied to rice, soybean, corn, and cotton was determined to be 9200, 2800, 3100, and 1800 m^3 ha^{-1} yr^{-1}, respectively, over a 12-year period in the Delta region of Mississippi (Massey et al., 2017). Irrigation practices are similar across the midsouthern USA; therefore, Massey et al.'s (2017) irrigation rates are an acceptable estimate for the entire region (Massey, Smith, Adviento-Borbe, Reba, & Avila, 2019). Assuming 90% of row crop irrigation in the Lower Mississippi River Valley is supplied from the MRVAA, estimated withdrawal is approximately 4.9×10^9 m^3 yr^{-1} for rice, 1.4×10^9 m^3 yr^{-1} for corn, 4.0×10^9 m^3 yr^{-1} for soybean, and 0.6×10^9 m^3 yr^{-1} for cotton (Massey et al., 2017; Massey et al., 2019; USDA-NASS, 2018a). Development and implementation of rice production systems that maintain productivity with less applied water per hectare will improve sustainability of the MRVAA.

In the midsouthern USA, rice is grown in a drill seeded, delayed-flood production system on contour-levee and/or precision-leveled straight-levee fields. In contour-levee fields, levees are constructed perpendicular to the native slope (Smith et al., 2007; Street & Bollich, 2002). In straight-levee fields, levees are constructed 50- to 70-m apart perpendicular to a consistent slope of 0.1 – 0.2%, while zero grade rice is grown on level basin fields (Mississippi State University, 2008; Smith et al., 2007). On both contour-levee and precision-leveled fields, upland conditions are preserved until approximately 40-45 days after emergence, at which point a 5- to 10-cm flood is established and maintained until two weeks prior to harvest. Water is either cascaded across the field from a single irrigation point source or to multiple paddies simultaneously via disposable lay-flat polyethylene tubing, i.e., multiple side-inlet irrigation (Massey et al., 2017).

The water required to produce rice in the drill seeded, delayed-flood production system is a function of field preparation and irrigation delivery technique. Contour-levee, cascade flood and straight-levee, cascade flood require similar water inputs of 10,371 m^3 ha^{-1} (1,037 mm) and 9,806 m^3 ha^{-1} (981 mm), respectively, but are greater than the 7,950 m^3 ha^{-1} (795 mm) for straight-levee, MSI (Massey et al., 2017). Zero-grade requires 5,738 m^3 ha^{-1} (574 mm), which is less than the previously mentioned field preparation and irrigation delivery techniques (Massey et al., 2017).The majority of rice hectarage in the midsouthern USA is cascade flooded and requires 76% more water than zero-grade systems, which account for only 10% of rice production. Irrigation strategies that reduce the amount of water applied to rice are needed to improve sustainability of the MRVAA.

An irrigation management practice for rice that may reduce withdrawal from the MRVAA while maintaining profitability is alternate wetting and drying (Carrijo, Lundy, & Linquist, 2017; Lampayan, Rejesus, Singleton, & Bouman, 2015; Massey, Walker, Anders, Smith, & Avila, 2014). In AWD, the flood is allowed to subside after each irrigation resulting in alternating cycles of saturated and unsaturated soil conditions. Reported benefits of AWD include the potential to reduce greenhouse gas emissions, rice grain arsenic concentrations, and water use, although yield response is variable (LaHue, Chaney, Adviento-Borbe, & Linquist, 2016; Linquist et al., 2018; Nalley, Linquist, Kovacs, & Anders, 2015). Small plot data indicate that AWD can reduce water use in rice 2-fold compared to a conventional flood; however, AWD must be validated at the production scale prior to widespread adoption (Gholson, 2020; Massey et al., 2014). The objectives of this research were to determine the effects of AWD on rice water use, grain yield, IWUE, and net returns above irrigation cost compared to MSI and CONV rice irrigation in the Delta region of Mississippi.

Materials and Methods

Study Site and Experimental Design

Research was conducted in the Delta region of Mississippi from 2014 through 2016 on 19 sites, each consisting of three adjacent fields with the same cultivar, soil texture (Soil Survey Staff, NRCS, 2020), planting date, and management practices (Table 4.1; Figure 4.1). Three irrigation treatments, straight-levee, cascade flood (CONV), straight-levee, multiple side-inlet (MSI), and straight-levee, MSI, alternate wetting and drying (AWD), were investigated in this research. Each treatment was randomly assigned to one of the three fields at each location. For the CONV treatment, irrigation was established and maintained via water entering the field in the uppermost paddy and cascaded into subsequent rice paddies by gravity flow through a levee gate set at 10 cm above the soil surface. Under MSI irrigation management, a 10 cm flood was maintained by delivering water simultaneously to each paddy via polyethylene tubing placed perpendicular to the levees through the center or along the perimeter of the field. The rate of water distribution to an individual paddy was calculated as described by Thomas, Street, and Tacker (2004):

$$Paddy\ Flow\ (L\ min^{-1}) = \frac{Paddy\ Area\ (ha)\ \ x\ Well\ Output\ (L\ min^{-1})}{Field\ Size\ (ha)}$$

Alternate wetting and drying utilized the MSI delivery technique; however, from three weeks after initial flood establishment to rice flowering, and from the end of rice flowering until two weeks prior to harvest, the flood subsided to 10 cm below the soil surface after each irrigation before the 10-cm flood was reestablished. On average, approximately three drying events per season initiated flood reestablishment, with a range of two to six per season. Throughout rice flowering, a 5- to 10-cm flood was maintained. Paddy water level in fields managed under AWD were monitored with one perforated PVC tube installed in the middle of the rice paddy that was located approximately 1/3 from the top of the field (Lampayan, Samoy-Pascual et al., 2015). Seepage through levees separating the paddies resulted in field conditions up slope and down slope of the perforated PVC tube to be slightly drier and wetter, respectively, than at the location where water level was monitored. The placement of the water level monitoring tube was selected to reduce the area in which flood abatement exceeded 10 cm below the soil surface, while concurrently allowing the flood to subside in lower paddies.

Prior to flood establishment, a McCrometer flow tube with attached Mc®Propeller bolt-on saddle flowmeter (McCrometer, Hemet, CA) was placed at the inlet of each field to monitor irrigation water applied. Cooperating producers mechanically harvested fields, reported rice grain yield using calibrated onboard yield monitors, and verified the accuracy of reported yields with scale tickets. Rice grain yields were adjusted to 12% moisture content. Irrigation water use efficiency was calculated as described by Vories, Tacker, and Hogan (2005):

$$IWUE = \frac{Y}{IWA}$$

where IWUE is irrigation water use efficiency (kg ha-mm^{-1}), Y is rice grain yield (kg ha^{-1}), and IWA is irrigation water applied (mm).

Economic Analysis

The irrigation costs used in this research incorporated irrigation enterprise budgets developed by utilizing the Mississippi State University Budget Generator. Net returns were calculated as rice grain yield multiplied by rice price, less total specified costs. The rice price was held constant at \$0.27 kg^{-1}, the average price reported by USDA at Greenville, MS for the August, September, and October harvest periods for the 2014, 2015, and 2016 crop years (see Mississippi portal for rice at https://www.ers.usda.gov/data-products/commodity-costs-and-returns/commodity-costs-and-returns/#Recent Costs and Returns: Rice). Total specified costs varied according to irrigation treatment, diesel price, and well depth.

Total specified costs vary by irrigation treatment because of differences in irrigation delivery technique and water management. For each treatment, irrigation costs are divided into diesel, other direct, and total fixed costs (Table 4.2, Supplemental Tables S1 and S2). Diesel costs vary among irrigation treatments as a function of fuel costs for pumping. Other direct costs and fixed costs for each irrigation treatment are associated with irrigation set up and application costs (Mississippi State University 2013, 2014, and 2015). For all treatments, the irrigation set up costs included costs for labor, fuel, repair and maintenance of equipment, supplies and interest associated with surveying and marking levees, building levees, installing gates, removing gates, removing levees, and capital recovery costs associated with land forming, well, pump and engine. Irrigation setup for MSI and AWD also included costs for polyethylene tubing, labor to install and remove the polyethylene tubing, and repair and maintenance costs on machinery associated with installing and removing the polyethylene tubing. Irrigation application costs included irrigation labor to apply water.

Diesel price is a major variable cost associated with pumping, therefore a sensitivity analysis was conducted to evaluate a baseline, high, and low diesel price. The baseline diesel price was \$0.70 L^{-1}, which was the average diesel price used in MSU budgets for 2014, 2015, and 2016 crop years (Mississippi State University 2013, 2014, 2015). Diesel prices for the high- and low-price scenarios were taken from the USDA Prices Paid Survey for the 2007-2016 timeframe for the Delta States region (USDA-NASS, 2018b). The maximum annual average reported diesel price for the 2007- 2016 timeframe of \$0.98 L^{-1} was used in the high-price scenario, and the lowest price of \$0.42 L^{-1} was used in the low-price scenario. Diesel prices effect the unit price of diesel, while well depth effects the quantity of diesel used in pumping.

Both total direct and total fixed costs vary according to well depth. Deeper well depths require greater diesel consumption per unit volume of water lifted than shallower well depths, which increases total direct costs for deeper well depths. To evaluate the effect of well depth on net returns, four different depths were considered: Relift of 5.5 m, standard well depth of 42.6 m, deep well depth of 61 m, and SPARTA depth of 122 m. Irrigation was assumed to be supplied at 590 m^3 hr^{-1} for the Relift alternatives, 454 m^3 hr^{-1} for the 42.6-m Standard Depth well alternatives, 409 m^3 hr^{-1} for the Deep Depth 61-m well alternatives, and 284 m^3 hr^{-1} for the Sparta Depth 122-m well alternatives. Total fixed costs vary among water-lifting depths according to pump, well depth, and power unit (Table 4.2; Bryant et al., 2017). The values for purchase price and fuel consumption are based on personal communications with Mississippi Delta-region irrigation equipment input and service providers. The Relift alternatives utilize a

75-hp tractor as a power unit, with all other alternatives using a 100-hp stationary diesel engine for power.

Statistical Analysis

All data were subjected to ANOVA using the GLIMMIX procedure of SAS (Statistical Analytical System Release 9.4; SAS Institute Inc., Cary, NC). For water use, yield, and IWUE analyses, irrigation treatment was considered a fixed effect with year, farm nested within year, and year*irrigation as random effects. For the analysis of net returns, irrigation treatment and well depth were fixed effects while year, farm, and their interactions with irrigation treatment and well depth were considered random effects. Degrees of freedom were estimated using the Kenward-Roger method (Kenward & Roger, 1997). Least-square means were calculated for all data and differences were considered significant at $\alpha = 0.05$.

Results and Discussion

General Site Statistics

During the three-year study (2014-2016), data for comparisons were collected from 19 sets of fields ranging from 5.5 to 42.0 ha (Table 4.1). Farms in this study were dispersed throughout the Delta region of Mississippi, USA. The soil textures of the experimental units at each location included silt loam, silty clay, silty clay loam, and clay, which represented 5%, 16%, 21%, and 58% of the sites, respectively.

Environmental, Agronomic, and Economic Implications for AWD

A central hypothesis of this research was that managing rice under AWD would decrease total water applied while having no adverse effect on yield, IWUE, or net returns relative to CONV and MSI. Managing the flood via AWD in a straight-levee system reduced the amount of water applied 39 and 23% relative to CONV and MSI, respectively ($P < 0.0001$; Table 4.3). Relative to a continuous flood, AWD had no adverse effect on rice grain yield ($P = 0.1343$; Table 4.3), but increased IWUE up to 58% ($P < 0.0001$). Alternate wetting and drying management of the flood either maintained or improved net returns relative to standard regional flood management strategies. In comparison to CONV, AWD had greater net returns at all diesel prices and well depths. Net returns for AWD were similar to MSI except at a baseline diesel price of \$0.70 L^{-1} and well depth of 122 m and a high diesel price of \$0.98 L^{-1} and well depth ≥ 61 m ($P \leq 0.0003$; Table 4.4). Results from this on-farm research affirm that AWD can reduce the amount of water applied without having an adverse effect on yield, net returns, and IWUE.

The adoption of AWD in the midsouthern USA could reduce total withdrawal from the MRVAA. Similar to the present study, small-plot research indicated that an irrigation threshold of 10 cm below the soil surface reduced consumptive water use in AWD 32% relative to CONV (Gholson, 2020). A threshold of 60 or 40% of saturated volumetric water at 5 cm below the soil surface decreased water use 18 to 44% in AWD compared to a constant flood (Linquist et al., 2015). Converting from a continuous flood to AWD reduced consumptive water use 24 to 71% in Bangladesh, China, Philippines, and Vietnam (Lampayan, Rejesus et al., 2015; Pan et al., 2017). The reduction in water use under AWD irrigation management is largely due to improved rainfall capture (Massey et al., 2019). Conventional rice flood management constitutes constructing outlets, i.e., levee gates, in each levee to impound water to a depth of 10 cm at the bottom of the paddy. The flood is maintained at 10 cm above the soil surface; therefore, rainfall that increases the water level above 10 cm is lost as surface runoff. Drying events in AWD produce a freeboard to capture rainfall, thereby increasing the flood depth without irrigation.

Increased rainfall capture in rice fields managed under AWD in the midsouthern USA should moderate withdrawal on the MRVAA and increase compliance with state-mandated withdrawal limits. Pooled over land formation practice and irrigation delivery technique, 5.4×10^9 m^3 yr^{-1} is applied to rice in the midsouthern USA with approximately 4.9×10^9 m^3 yr^{-1} originating from the MRVAA (Massey et al., 2019). Data from the present study indicate that adoption of AWD on the landscape would reduce withdrawal from the MRVAA 1.1 to 1.9×10^9 m^3 yr^{-1}, contingent on the current proportion of CONV and MSI hectarage.. In Mississippi, the permitted well withdrawal limit for rice is 914.4 mm yr^{-1}. Rice managed under AWD never exceeded permitted withdrawal throughout the duration of the study. Conversely, rice irrigation managed under MSI and CONV exceeded 914.4 mm yr^{-1} 31% and 53% of the time, respectively. Alternate wetting and drying in rice production can improve the sustainability of the MRVAA and increase compliance with state laws. However, producers will not adopt AWD if the best management practice adversely effects productivity (Asci, Borisova, & VanSickle, 2015).

This study suggests that converting from CONV or MSI to AWD will maintain rice grain yield in the midsouthern USA. Similar to this research, intermittent flooding at the small plot and field scale maintained or improved rice grain yield in the midsouthern USA up to 11% relative to CONV (Gholson, 2020; Massey et al., 2014). Moreover, across a range of environments, that is, temperature, humidity, precipitation, soil texture, and farming practices, converting from continuous flooding to AWD maintained or improved yield up to 15% in Bangladesh, Vietnam, and the Philippines (Lampayan, Rejesus et al., 2015). In Arkansas, an AWD threshold of 40% saturated volumetric water at a depth of 5 cm plus a continuous flood from reproductive growth stages through the remainder of the season maintained yield (Linquist et al., 2015). Similar or increased grain yield for rice in AWD systems may be attributed to the compounding effects of reduced “cold water effects” (Mississippi State University, 2008), lower flood depths (Zeng, Lesch, & Grieve, 2003), increased N mineralization (Reddy & Patrick, 1975), and enhanced N uptake relative to CONV (Dillon et al., 2011). Maintaining yield with a corresponding decrease in water application improves efficiency of water use.

Increased IWUE under AWD relative to continuous flood in this study are in accord with research from major rice-growing countries across the world. In China, IWUE was increased up to 81.9% relative to continuous flooding (Ye et al., 2013; Xue et al., 2013). A meta-analysis determined that total water use efficiency, defined as rice grain yield divided by total irrigation and precipitation input, was increased 24.2% in AWD relative to continuous flooding (Carrijo et al., 2017). These data affirm that amount of rice grain yield per unit of water applied is improved under AWD compared to maintaining a flood.

Alternate wetting and drying management of rice irrigation either maintains or improves net returns relative to standard regional flood management strategies. For pumping depths ranging from 5.5 m to 122 m and diesel prices ranging from \$0.42 L^{-1} to \$0.98 L^{-1}, managing rice under AWD increased net returns \$119 ha^{-1} to \$238 ha^{-1} relative to CONV. Net returns under AWD were not different than MSI except at a baseline diesel price of \$0.70 L^{-1} and well depth of 122 m and a high diesel price of \$0.98 L^{-1} and well depth $\geq$ 61 m. Thus, the advantage of AWD increased as the variable costs of pumping increased. The full results are presented in Table 4.4. These findings are consistent with research in Vietnam, the Philippines, and Bangladesh, which report increases in farm-level income up to 17, 32, and 38%, respectively, for AWD-managed rice compared to conventional water management (Lampayan, Rejesus et al., 2015). Small-plot research in the midsouthern USA also demonstrated that profitability is either maintained or improved by converting from a constant-flood rice production system to AWD (Gholson, 2020; Nalley et al., 2015).

The decrease in diesel, repair and maintenance, and labor costs were the major contributing factors to greater net returns under AWD. Total water applied was 23 and 39% less in AWD than MSI and CONV, respectively, which directly influences the cost of diesel associated with pumping that water. At the baseline diesel price of \$0.70 L^{-1} and well depths from 5.5 m to 122 m, diesel costs for AWD were \$59.11 ha^{-1} to \$116.14 ha^{-1} less than CONV and \$28.65 ha^{-1} to \$54.48 ha^{-1} less than MSI (Table 4.2). As depth to water and diesel price increase, the economic advantage of pumping less water is magnified. Relatedly, less water translates to lower repair and maintenance costs on water-lifting equipment. Although both AWD and MSI have greater fixed expenses associated with laying and removing polyethylene tubing, labor requirements are less for these two systems compared to CONV. Decreased pumping and labor costs of AWD compared to CONV offset the greater fixed costs. These decreased costs and the maintenance of yield result in greater net returns under AWD than CONV for all scenarios examined. The pumping cost savings under AWD resulted in greater net returns than MSI when diesel price and well depth were high. Because AWD does not have an adverse effect on yield or profitability, midsouthern USA producers are more likely to adopt this technology (Asci et al., 2015).

Conclusions

This research was conducted to determine if AWD irrigation in rice can reduce withdrawal from the MRVAA without having an adverse effect on yield or profitability at the field-scale. Intermittent flooding decreased total water use while maintaining or improving rice grain yield and profitability relative to a traditional, continuous flood. Alternate wetting and drying is one of the most promising, current water-saving practices in midsouthern USA rice production. Potential barriers to adoption include a perceived negative effect of AWD on yield, profitability, nitrogen use efficiency, and weed control; however, this research demonstrates that properly managed AWD can improve the sustainability of the MRVAA while preserving or enhancing on-farm profitability.

Tables and Figures

Table 4.1 Year, county, and soil texture for fields where rice irrigation strategies of straight-levee, cascade flood (CONV), straight-levee, multiple side-inlet (MSI), and straight-levee, multiple side-inlet with alternate wetting and drying (AWD) were compared in the Delta region of Mississippi during the 2014 through 2016 growing seasons.

		Figure 1			Field Size (ha)		
Year	**Farm**	**Site No.**	**County**	**Soil Texture**	**CONV**	**MSI**	**AWD**
2014	1	1	Bolivar	Silty Clay Loam	8.9	14.0	24.1
	2	2	Bolivar	Silty Clay	14.0	14.5	14.6
	3	3	Humphrey	Clay	16.7	15.0	18.9
2015	1	1	Bolivar	Silty Clay Loam	10.0	9.6	9.7
	2	4	Bolivar	Silty Clay	6.4	8.8	15.8
	3	5	Bolivar	Clay	14.0	18.5	14.2
	4	5	Bolivar	Clay	17.8	15.3	15.0
	5	6	Sunflower	Silty Clay	7.2	6.3	7.5
	6	7	Sunflower	Silt Loam	16.4	17.9	19.0
	7	8	Tunica	Clay	10.3	8.7	9.3
	8	9	Tunica	Clay	20.0	31.2	33.5
2016	1	4	Bolivar	Clay	29.7	26.5	30.0
	2	5	Bolivar	Clay	42.0	15.8	13.2
	3	5	Bolivar	Clay	20.2	21.6	20.1
	4	1	Bolivar	Silty Clay Loam	23.8	14.5	15.2
	5	2	Bolivar	Silty Clay	11.2	10.0	5.5
	6	10	Leflore	Clay	7.5	14.0	14.4
	7	11	Tallahatchie	Clay	17.0	17.0	17.2
	8	12	Tunica	Clay	30.6	27.4	31.8

Place all detailed caption, notes, reference, legend information, etc here

Table 4.2 Estimated irrigation costs per hectare at estimated least square means of water pumped and low, baseline, and high diesel prices for an experiment where rice irrigation strategies of straight-levee, cascade flood (CONV), straight-levee, multiple side-inlet (MSI), and straight-levee, multiple side-inlet with alternate wetting and drying (AWD) were compared in the Delta region of Mississippi during the 2014 through 2016 growing seasons.

Diesel Scenario	**Irrigation Method**	**Cost**	**Water-Lifting Depth**			
			Relift (5.5 m)	**Standard Well (42.6 m)**	**Deep Well (61 m)**	**SPARTA (122 m)**
			$/hectare			
Low Diesel†	CONV‡	Diesel	93.27	113.74	125.62	180.95
		Other Direct	121.94	108.68	110.51	117.23
		Total Fixed	177.00	187.47	192.88	212.77
		Total Specified	392.21	409.90	429.01	510.94
	MSI	Diesel	74.94	90.80	100.21	143.88
		Other Direct	103.07	93.66	95.49	102.21
		Total Fixed	181.55	192.02	197.43	217.31
		Total Specified	359.56	376.48	393.13	463.40
	AWD	Diesel	57.72	70.17	77.43	111.10
		Other Direct	91.54	85.44	87.27	93.98
		Total Fixed	181.55	192.02	197.43	217.31
		Total Specified	330.81	347.63	362.13	422.39
Baseline Diesel	CONV	Diesel	155.07	189.08	208.86	300.85
		Other Direct	121.94	108.68	110.51	117.23
		Total Fixed	177.00	187.47	192.88	212.77
		Total Specified	454.01	485.23	512.25	630.84
	MSI	Diesel	124.61	150.94	166.58	239.19
		Other Direct	103.07	93.66	95.49	102.21
		Total Fixed	181.55	192.02	197.43	217.31
		Total Specified	409.23	436.62	459.49	558.71
	AWD	Diesel	95.96	116.66	128.74	184.71
		Other Direct	91.54	85.44	87.27	93.98
		Total Fixed	181.55	192.02	197.43	217.31
		Total Specified	369.04	394.11	413.43	496.00

Table 4.2 (continued)

Diesel Scenario	Irrigation Method	Cost	Water-Lifting Depth: Relift (5.5 m)	Standard Well (42.6 m)	Deep Well (61 m)	SPARTA (122 m)
			$/hectare			
High Diesel	CONV	Diesel	215.68	263.03	290.52	418.47
		Other Direct	121.94	108.68	110.51	117.23
		Total Fixed	177.00	187.47	192.88	212.77
		Total Specified	514.62	559.18	593.91	748.46
	MSI	Diesel	173.32	209.97	231.74	332.71
		Other Direct	103.07	93.66	95.49	102.21
		Total Fixed	181.55	192.02	197.43	217.31
		Total Specified	457.94	495.65	524.65	652.23
	AWD	Diesel	133.48	162.28	179.10	256.95
		Other Direct	91.54	85.44	87.27	93.98
		Total Fixed	181.55	192.02	197.43	217.31
		Total Specified	406.56	439.73	463.79	568.25

† Low, baseline, and high diesel prices used in the analysis were \$0.42 L^{-1}, \$0.70 L^{-1}, and \$0.98 L^{-1}, respectively.

‡ Estimated least square means for water pumped in CONV, MSI, and AWD were 896, 708, and 546 mm, respectively.

Table 4.3 Estimated least square means for rice grain yield, irrigation water applied, and irrigation water use efficiency (IWUE) for an experiment where rice irrigation strategies of straight-levee, cascade flood (CONV), straight-levee, multiple side-inlet (MSI), and straight-levee, multiple side-inlet with alternate wetting and drying (AWD) were compared in the Delta region of Mississippi during the 2014 through 2016 growing seasons.

Irrigation Strategy	**Yield**	**Irrigation Water Applied**	**Irrigation WUE**
	kg ha^{-1}	mm	kg $ha\text{-}mm^{-1}$
CONV	8295 ± 1017†	896 ± 320a‡	10.5 ± 4.4c
MSI	8482 ± 795	708 ± 233b	13.2 ± 4.7b
AWD	8510 ± 709	546 ± 159c	16.7 ± 4.7a
$P_r > F$	0.1343	< 0.0001	0.0034

† Values shown are the mean ± standard deviation.
‡ Within columns, means followed by the same letter are not significantly different according to LSD (0.05).

Table 4.4 Estimated least square means for net returns for four water-lifting depths at a baseline rice price of $0.27 kg^{-1} and low, baseline, and high diesel prices of $0.42, $0.70, and $0.98 L^{-1}, respectively, for an experiment where rice irrigation strategies of straight-levee, cascade flood (CONV), straight-levee, multiple side-inlet (MSI), and straight-levee, multiple side-inlet with alternate wetting and drying (AWD) were compared in the Delta region of Mississippi during the 2014 through 2016 growing seasons.

		Water-Lifting Depth			
		Relift (5.5 m)	**Standard Well (42.6 m)**	**Deep Well (61 m)**	**SPARTA (122 m)**
Diesel Scenario	**Irrigation Method**	$/hectare			
Low Diesel	CONV	1842 ± 298†b‡	1825 ± 300b	1805 ± 302b	1723 ± 314b
	MSI	1925 ± 215a	1909 ± 215a	1892 ± 216a	1821 ± 219a
	AWD	1961 ± 188a	1945 ± 188a	1930 ± 187a	1870 ± 188a
	P value	0.0003	0.0002	0.0001	< 0.0001
Baseline Diesel	CONV	1780 ± 310b	1748 ± 314b	1722 ± 318b	1603 ± 340c
	MSI	1875 ± 217a	1847 ± 219a	1825 ± 220a	1726 ± 227b
	AWD	1923 ± 187a	1897 ± 187a	1878 ± 188a	1795 ± 189a
	P value	< 0.0001	< 0.0001	< 0.0001	< 0.0001
High Diesel	CONV	1720 ± 322b	1676 ± 330b	1641 ± 337c	1486 ± 369c
	MSI	1827 ± 221a	1790 ± 223a	1760 ± 226b	1633 ± 240b
	AWD	1886 ± 188a	1852 ± 188a	1828 ± 189a	1724 ± 194a
	P value	< 0.0001	< 0.0001	< 0.0001	< 0.0001

† Values shown are the mean ± standard deviation.
‡ Within a diesel scenario and water-lifting depth column, means followed by the same letter are not significantly different according to LSD (0.05).

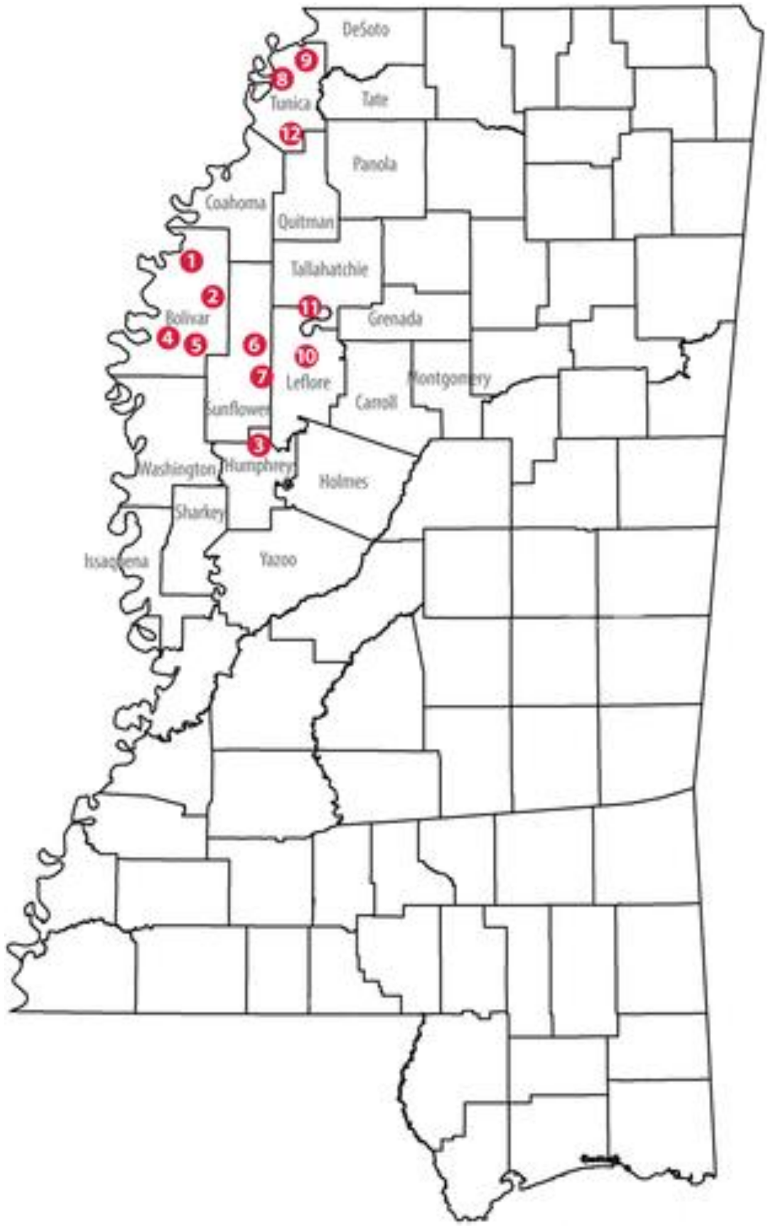

Figure 4.1 On-farm research locations for a study that assessed rice irrigation strategies of straight-levee, cascade flood (CONV), straight-levee, multiple side-inlet (MSI), and straight-levee, multiple side-inlet with alternate wetting and drying (AWD) in the Delta region of Mississippi during the 2014 through 2016 growing seasons.

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