RICE PRODUCTION WITH CENTER PIVOT IRRIGATION

E. D. Vories, W. E. Stevens, P. L. Tacker, T. W. Griffin, P. A. Counce

ABSTRACT. *While continuous-flood irrigation, the most common method for U.S. rice production, can have a fairly high irrigation application efficiency, factors such as soil variability and the size of most Mid-South farming operations often combine to reduce the efficiency. Center pivot irrigation is a way to reduce irrigation water use in some cases and allow rice in the crop rotation in other situations when flooding is not practical. Rice was produced at the University of Missouri Fisher Delta Research Center Marsh Farm at Portageville in 2009 and 2010 and irrigated every other day with a 150-m-long center pivot irrigation system. An experimental crop coefficient function was developed and included in a beta version of the Arkansas Irrigation Scheduler (AIS). It was used with daily short grass reference evapotranspiration (ET_o) calculated from weather data collected on site to estimate the daily soil water deficit (SWD). Weather conditions were warmer and much drier in 2010 and ET_o was higher each month. In 2009, there were totals of 34 days with irrigation and 414 mm of water applied. In 2010, there were totals of 45 days with irrigation and 503 mm of irrigation water applied. In 2009, the cultivar Templeton had the highest observed grain yield (8.31 Mg ha^{-1}) and irrigation water use efficiency (IWUE; 2.0 kg m^{-3}). In 2010, the cultivar Francis had the highest observed grain yield (8.2 Mg ha^{-1}) and IWUE (1.6 kg m^{-3}). In addition to the higher temperatures in 2010, yields were probably impacted by the fact that rice was produced in the field the two previous years. Future research will use the beta version of the AIS to schedule irrigations, which should indicate whether the crop coefficient is adequate and allow producers a system for scheduling center pivot irrigation on rice.*

Keywords. *Irrigation, Rice, Center pivot irrigation, Rice irrigation, Water management.*

The Lower Mississippi Water Resource Area (WRA 08, also called the Mid-South) contains 4.6 million ha of farmland in portions of the U.S. states of Missouri, Kentucky, Arkansas, Tennessee, Mississippi, and Louisiana (USDA-NASS, 2010a). Mid-South farmers grew over 0.7 million ha of rice in 2008, 68% of the total U.S. rice crop (USDA-NASS, 2010a). In parts of the world, a portion of the rice is produced in an upland, rainfed culture. U.S.-produced rice is grown almost exclusively in a flooded culture, although a small amount is produced with furrow irrigation. In the dry-seeding system commonly used in the Mid-South, the crop is flooded at approximately the V-4 growth stage (Counce et al., 2000) and a continuous flood is maintained until after heading. Failure to maintain an adequate flood depth results in dry portions of the field, leading to increased weed and fertilizer problems and low yields. Excessive irrigation wastes water and energy and increases pressure on levees; furthermore, soil, fertilizers, and pesticides may be carried in runoff from over-watered agricultural fields.

Irrigation application efficiency is generally defined as the ratio of the volume of irrigation water stored in the root zone and available for evapotranspiration (ET) to the volume delivered from the irrigation system (Smajstrla et al., 2002). For continuous flood irrigation, the volume delivered must not only be adequate to provide for ET, but also to maintain the desired flood depth. Burt et al. (2000) reported the potential application efficiency for continuous flood irrigation, the method used for most Mid-South rice, is 80% under practical conditions, which is within the range they reported for center pivot systems (75%-90%).

A portion of many crops in the U.S. Mid-South is still produced without irrigation. Therefore, another useful value for evaluating irrigated crop production in the region is irrigation water use efficiency (IWUE). Although not all authors use the same definition, in this report IWUE was defined as the ratio of the increase in grain yield above rainfed production to the volume of water applied by irrigation, or the additional yield produced per unit of irrigation water applied.

In practice, much water is lost from fields using surface irrigation, including continuous flood. Water is lost from many Mid-South rice fields through runoff from the field, seepage through outside levees, and deep percolation

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The authors are **Earl D. Vories, ASABE Member,** Agricultural Engineer, USDA-ARS, Fisher Delta Research Center, Portageville, Missouri; **William E. (Gene) Stevens,** Professor, Plant Scientist, University of Missouri Fisher Delta Research Center, Portageville, Missouri; **Phil L. Tacker, ASABE Member,** Irrigation Engineer, Delta Plastics, Little Rock, Arkansas; **Terry W. Griffin,** formerly Associate Professor, Department of Agricultural Economics and Agribusiness – Extension, Little Rock, Arkansas; and **Paul A. Counce,** Professor, Rice Physiologist, University of Arkansas Rice Research and Extension Center, Stuttgart, Arkansas. **Corresponding author:** Earl D. Vories, USDA-ARS, Fisher Delta Research Center, P.O. Box 160, Portageville, MO 63873; phone: 573-379-5431; e-mail: Earl.Vories@ars.usda.gov.

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below the root zone. The combination of alluvial, eolian, and seismic activity over the years has resulted in highly variable soils in the Mid-South. Counties in northeast Arkansas and southeast Missouri, now part of a major rice producing region of the United States, were greatly impacted by a series of earthquakes in 1811-1812. As a result, farmers must be cautious when selecting fields to produce flooded rice. Freeland et al. (2008) discussed sand blows and fissures created by the quakes and despite land grading efforts by farmers, these features still persist in fields and affect the abilities of soils to hold flood irrigation water for rice production.

Mid-South farming operations are typically spread out over large areas, requiring farmers to simultaneously manage numerous irrigation systems at different locations. One worker is often responsible for managing several fields, requiring him/her to move from field to field to determine when to begin water application and returning to the field to determine if the irrigation is complete and discontinue pumping. The time required to irrigate each field is different and often differences are observed within fields due to factors like highly variable soil texture and topography. Most Mid-South farmers produce multiple crops, so they may be harvesting wheat and planting double-crop soybeans at the same time they are applying the initial flood to rice. Excessive irrigation applications often occur because it is not possible to closely monitor each field.

Hogan et al. (2007) estimated that flood irrigation for a rice crop required more than twice as much irrigation water as the methods used with other crops grown in the Mid-South. In Arkansas, the Rice Production Handbook reported typical values for the amount of irrigation water applied to rice on Arkansas soils ranged from 610 to 1220 mm (Tacker et al., 2001). Similarly, Vories et al. (2006) reported a range of 460 to 1435 mm observed for 33 Arkansas rice fields during the 2003 through 2005 growing seasons, and Smith et al. (2006) reported values from 382 to 1034 mm in Mississippi in 2003 and 2004. YMD (undated) reported an 8-year (2002-2009) average irrigation water use of 914 mm in Mississippi, with a range of 579 to 1158 mm for 24 fields in 2009. Even at the low end of the Handbook range (610 mm), rice production in Arkansas over the 10 years from 2000 through 2009, based on harvested cropland hectares from USDA-NASS (2010b), required an average of 3.6 billion m^3 of irrigation water per year.

The large amount of water applied to rice has resulted in two problems: the energy costs associated with pumping make up a substantial portion of the rice production budget and the cost is greatly influenced by fluctuations in energy prices; and water shortages are being observed in some Mid-South rice-producing areas. The U.S. Army Corps of Engineers (2000) reported that by 1915, only about a decade after commercial rice farming began in the region, the alluvial aquifer was already being tapped at a rate that exceeded its ability to recharge in some areas. The aquifer serves as the principal water source for agriculture in eastern Arkansas and surrounding areas, and similar problems have been encountered with some Mid-South surface water sources. Efforts are underway in some areas to supplement groundwater by diverting surface water for irrigation (Tacker et al., 2010). While such transfers are common in much of the United States, with the Colorado River being perhaps the best example, they are much rarer in the Mid-South.

Reducing the irrigation requirement for rice has been a goal of farmers and researchers for many years. Vories et al. (2005) reported on a multiple inlet approach to flooding rice fields, where water is distributed over the whole field simultaneously. They reported an average 24% less irrigation water required than for conventional flooding, where water is applied to the highest-elevation area and distributes over the field by gravity flow, and the method has been widely adopted. Vories et al. (2002) reported consistently lower yields with furrow irrigation of rice than for flooded production. Studies with center pivot systems during the 1980s in Louisiana (Westcott and Vines, 1986) and Texas (McCauley, 1990) reported large yield reductions compared with flooded production. Interest in the center pivot method has increased since the earlier studies were conducted and Stevens et al. (2012) provided an overview of recent research on center pivot irrigation of rice. Center pivot systems typically have high application efficiencies, with published values as high as 90% (Burt et al., 2000), but producers will not readily abandon flooded production for an alternative system that produces lower yields. However, Vories et al. (2010) reported comparable yields between center-pivot irrigated and flooded rice on a producer's field in Arkansas and many producers are looking for additional options in crop choice on fields not well suited to flooded production.

Problems observed when rice was produced with center pivot irrigation in the earlier studies included inadequate weed control, disease outbreaks such as blast (*Pyricularia grisea*), and center-pivot drive towers getting stuck in muddy soil. The problems precluded widespread adoption of the system at that time. Improved genetics, tower and sprinkler arrangements, herbicides, and fungicides, together with improved management system strategies have all led to renewed interest in center pivot rice production, both in the United States and internationally. In response to that interest, Valley (Valmont Irrigation, Valley, Nebr.) began working with the University of Missouri and USDA-ARS to investigate center pivot irrigation of rice in Portageville in 2008 (Stevens et al., 2009). The project was in conjunction with international and U.S. on-farm work that Valley was conducting and with research the University of Missouri and USDA-ARS were conducting with the Missouri Department of Natural Resources.

Even though annual rainfall in the U.S. Mid-South is generally sufficient for limited production of crops other than rice, periods of drought during the growing season make irrigation essential for optimum yields of all widely produced summer crops. Furthermore, climate change is expected to increase the frequency and severity of drought in the region. Irrigation scheduling, the correct timing of irrigation during the growing season, is complicated in sub-humid regions like the Mid-South by factors such as cloudy weather, rainfall, high relative humidity, and temperature swings caused by the movement of weather fronts. Weather conditions in sub-humid regions vary greatly from year to year and even within a year and the variability must be accounted for in the scheduling system. Most commonly used methods either measure or estimate soil water content. Many types of instruments have been developed to measure soil water content using many different kinds of technology. Areas with highly variable soils like the U.S. Mid-South require a large number of sensors to adequately describe the soil moisture status of a field. Wiring the sensors together in a network is seldom compatible with field operations, so a great deal of labor is required to visit the sensors and obtain the readings. This has limited the use of soil water measurements for irrigation scheduling in the region. However, as sensor technology continues to improve and wireless networking of sensors becomes less costly and more reliable, direct measurement of soil moisture will become more common.

Most methods that estimate soil water deficit from weather data rely on a crop coefficient to relate crop evapotranspiration (ET_c) to short grass reference evapotranspiration (ET_o) at different growth stages. FAO 56 (Allen et al., 1998) presented crop coefficients for a number of crops and locations and suggested procedures for adapting them to other locations and conditions. In the single crop coefficient approach, the effects of transpiration and evaporation are combined into a single coefficient (K_c). In the dual crop coefficient approach the effects of crop transpiration and soil evaporation are determined separately. Two coefficients are used, with a basal crop coefficient (K_{cb}) describing plant transpiration and a soil water evaporation coefficient (K_e) describing evaporation from the soil surface. Allen et al. (1998) reported that the dual procedure is best for real-time irrigation scheduling for high frequency irrigation with systems such as center pivots.

Using estimated soil water deficit to schedule irrigation can be greatly simplified with publicly available computer programs such as the Arkansas Irrigation Scheduler (AIS; Cahoon et al, 1990). The AIS uses a dual crop coefficient approach to calculate a water balance to use in scheduling irrigation, similar to managing a checkbook. The system balance represents the soil water deficit (SWD), the difference between the soil's existing moisture content, summed over the rooting depth, and the moisture content of the soil at its well-drained upper limit (~24 h after surface water was removed). Rooting depth is not used explicitly in the program, but is implicit in the choice of a maximum allowable SWD or management allowed depletion (MAD). Cahoon et al. (1990) provided a detailed description of the program and Vories et al. (2009) provided information about changes to the program after the earlier publication.

Because almost all U.S. rice is produced with flood irrigation, the AIS program does not address irrigation scheduling for rice. Similarly, most other irrigation scheduling programs were developed for regions where rice is not produced and do not include recommendations for rice. Successful production of rice without a continuous flood will require timely irrigation and thus accurate estimates of SWD for irrigation scheduling. The overall objective of this research was to develop guidelines for producing sprinkler irrigated rice. Specific objectives of this study were: 1) to produce commonly grown Mid-South rice cultivars on coarse-textured soil using center pivot irrigation with grain yields comparable to flooded production; and 2) to adapt the AIS to calculate estimated SWD for non-flooded rice and observe the estimated SWD throughout the growing season.

MATERIAL AND METHODS

A field study was conducted at the University of Missouri Fisher Delta Research Center Marsh Farm at Portageville (36° 25'N, 89° 42'W), approximately 14 km west of the current channel of the Mississippi River and within the New Madrid Seismic Zone. Soil mapping units within the 10-ha field included Tiptonville silt loam (fine-silty, mixed, superactive, thermic Oxyaquic Argiudolls), Dundee sandy loam and silt loam (fine-silty, mixed, active, thermic Typic Endoaqualfs), and Reelfoot loam and sandy loam (fine-silty, mixed, superactive, thermic Aquic Argiudolls) (USDA-SCS, 1971) (fig. 1). Soil cores collected from five locations in the field showed average sand contents in the upper 0.76 m of the soil profile ranged from 59% to 82% and rice is not typically produced on such a sandy field in the Mid-South. However, the soil variability made it a good site to observe the potential of sprinkler irrigated rice and examine how an irrigation scheduling method for rice would perform under different conditions.

In addition to several small-plot studies included under the center pivot system to investigate cultivar performance and herbicide and fertility management (Rhine et al., 2011), a large-plot cultivar study was drill seeded in 6-m wide by approximately 120-m long plots with a 190-mm drill spacing on 19 May 2009 and 7 May 2010. Six commonly grown Mid-South cultivars ('Francis,' 'Templeton,' 'Taggart,' 'Cocodrie,' 'Wells,' and 'Catahoula') were planted in a randomized complete block arrangement with three replications. Dry urea (46% N) was broadcast at 38 kg N ha^{-1} at the V4 growth stage (Counce et al., 2000) and an Inject-O-Meter (Clovis, N. Mex.) injection pump was used to apply five weekly urea ammonium nitrate (UAN, 32% N) applications at 23 kg N ha^{-1} each by fertigation for a total of 151 kg N ha^{-1}. The field was irrigated with a 150-m-long Valley center pivot irrigation system. Because the cultivars ranged from susceptible (Francis) to resistant (Templeton) to blast (Lee, 2009), all plots received two azoxystobin fungicide applications applied by chemigation each year. However, to look for the presence of blast and investigate the effectiveness of the chemigation, additional 76-m long by 6-m wide strips of each cultivar did not receive fungicide. The smaller areas were not replicated and therefore were not included in the data analyses.

Because of the variable soils in the field, the high sand contents, and the uncertainty concerning the rooting depth of the rice plants, it was decided to make frequent, relatively low-volume irrigation applications. A target

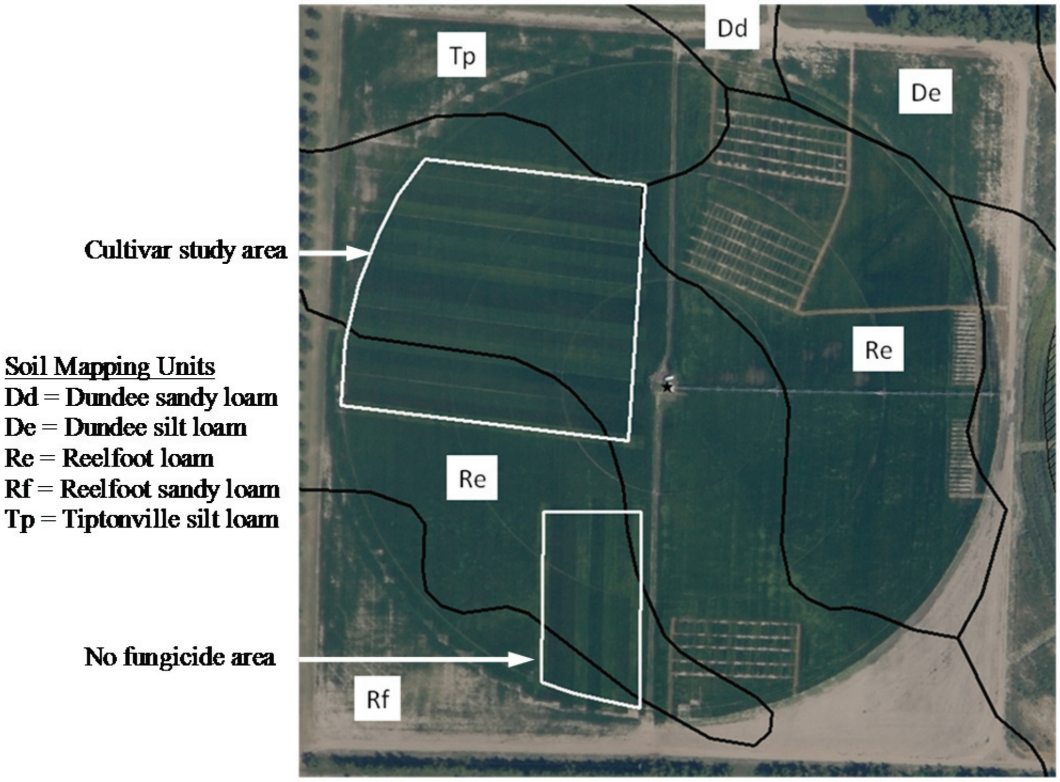

Figure 1. Study area at University of Missouri Fisher Delta Research Center Marsh Farm showing soil mapping units (USDA-SCS, 1971). Background image was taken on 7 August 2010.

application of 13 mm on every other day in the absence of rain was chosen. The application amount exceeded typical observations of ET_o at the location and since rice is commonly produced in a flood it was felt that excess water was preferable to inadequate water until a better understanding of the production system was obtained. Additional irrigations were applied to activate herbicides and fertigate or chemigate as needed. Irrigation applications were terminated when the grain color began to change to gold or straw suggesting crop maturity (Moldenhauer and Slaton, 2001). Although the goal of this research is to enable irrigation scheduling for rice with the AIS, the intent for this preliminary study was to insure adequate soil moisture and observe the estimated SWD throughout the season.

To adapt the AIS for non-flooded rice, an experimental short grass reference crop coefficient function was developed, included in a beta version of the AIS, and used to estimate the daily SWD. The addition of the rice crop coefficient was the only change to the AIS in the beta version. A daily ET_o was calculated using the standardized Penman-Monteith equation (ASCE-EWRI, 2004) from weather data collected at the University of Missouri Fisher Delta Research Center Marsh Farm and placed on the Agricultural Electronic Bulletin Board (AgEBB; http://agebb.missouri.edu/). In addition, Watermark sensors (Irrometer Co., Riverside, Calif.) were placed approximately 150 and 300 mm below the soil surface in four locations, avoiding the sandiest areas. Sensors were connected to a central datalogger (Campbell Scientific, Logan, Utah) and the data were automatically stored on a web page updated every five minutes on AgEBB to be available when deciding whether to irrigate following rainfall.

The plan of work included harvesting the large-plot cultivar study with a field-scale combine equipped with a yield monitor to allow study of the yield distribution in the field. However, equipment failure in 2009 made it necessary to harvest with smaller equipment. A 1.5-m-wide area was harvested from the center of each of the large strips on 20 October with a Massey Ferguson 8XP combine with an onboard system for harvest weight and moisture determination (Kincaid Equipment Manufacturing, Haven, Kan.). The harvest areas were either 90- or 120-m long, depending on the position within the pivot. Grain yields were adjusted to 0.12 g/g d.b. moisture content. Yield data were analyzed using the Statistical Analysis System (SAS 9.2 for Windows; SAS Institute Inc., Cary, N.C.) PROC GLM. Tests were considered significant at the 0.05 level of probability and Fisher's protected least significant difference (LSD) was used to compare treatment means for significant ($p \leq 0.05$) effects.

In 2010, the center 3.6 m of each strip was harvested with a Gleaner R-52 combine (AGCO, Duluth, Ga.) with an Ag Leader Insight (Ag Leader Technology, Ames, Iowa) yield monitor system on 16 October. The yield monitor was calibrated by harvesting several samples of varying size at different ground speeds and therefore different feed rates and weighing the grain on commercial scales. Grain moisture readings were calibrated at the same time by comparing the yield monitor data to the average of three readings from each calibration load determined with a

Moisture Chek PLUS (Deere and Company, Moline, Ill.) portable grain moisture tester.

Because the high-density datasets collected with yield monitors and other instruments tend to violate some of the assumptions inherent in traditional statistical methods such as analysis of variance (ANOVA), different types of analyses are required. The Moran's I test statistic of the aspatial ordinary least squares (OLS) regression residuals is a measure of spatial autocorrelation and can be interpreted as a spatial correlation coefficient (Anselin, 1988). The Moran's I test statistic for a random variable, **x**, is given by:

$$I = \frac{n}{S_o} \frac{\mathbf{x}'\mathbf{W}\mathbf{x}}{\mathbf{x}'\mathbf{x}} \tag{1}$$

where **x** is a *n x 1* vector of observations as deviations from the mean, **W** is an $n \times n$ spatial weights matrix, and S_o is the sum of elements of **W** (Cliff and Ord, 1981; Anselin, 1988). Values range from -1 to 1, with high positive values of Moran's I interpreted as high (low) values having neighbors of high (low) values. A negative Moran's I signifies high and low value observations occur as neighbors. Site-specific yield data tends to be strongly positively spatially autocorrelated at the density with which yield monitor data are collected due to omitted spatial variables (Griffin et al., 2007). The spatial error process model has spatially autocorrelated residuals and is similar to the traditional aspatial model with the exception that the error term ε is spatially autocorrelated. The spatial error model is given as:

$$y = X\beta + \varepsilon, \;\; \varepsilon = \lambda W \varepsilon + \mu \tag{2}$$

or in reduced form as:

$$y = X\beta + (I - \lambda W)^{-1}\mu \tag{3}$$

where y is an $n \times 1$ vector of dependent variables, X is an $n \times k$ matrix of explanatory variables, β is a $k \times 1$ vector of regression coefficients, ε is an $n \times 1$ vector of residuals, λ is a spatial autoregressive parameter, **W** is an $n \times n$ spatial weights matrix, and μ is a well-behaved, non-heteroskedastic uncorrelated error term (Anselin, 1988).

Yield data were "cleaned" with the Yield Editor program (v. 1.02; Sudduth and Drummond, 2007) to remove erroneous data points. The Geographic Information System (GIS) program ArcMap 9.3 (ESRI, Redlands, Calif.), together with Excel 2007 (Microsoft, Redmond, Wash.) was used for managing and manipulating the extensive yield datasets collected. Spatial error process models were estimated using maximum likelihood with OpenGeoDa 0.9 spatial analysis software (GeoDa Center for Geospatial Analysis and Computation, Tempe, Ariz.) for the large, spatially referenced datasets. Yield data from the cultivar experiment were analyzed with the most appropriate methods: ANOVA for the aspatial data collected in 2009 and spatial econometric techniques for the georeferenced data in 2010.

RESULTS AND DISCUSSION

IRRIGATION SCHEDULING

FAO 56 (Allen et al., 1998) suggested general values for the lengths of the growth stages and associated K_{cb}, pointing out that regional differences affect the values. Figure 2 shows the suggested values for rice. Although the initial stage reported in FAO 56 begins at planting, many factors can impact the time from planting to emergence. Therefore, AIS and many other scheduling programs begin at emergence and the data in figure 2 were based on an assumed 5 d from planting to emergence. The FAO 56 crop coefficient varied from 0.45 to 1.15 based on days after planting; however, because dry seeding (i.e., seeds sown into dry soil similar to the procedure with other agronomic crops) is practiced for the majority of U.S. rice, as opposed to water seeding (i.e., seeds broadcast onto a flooded field) or transplanting, the initial K_{cb} would probably be considerably less than the value suggested for rice (1.0).

Several changes were made for the basal crop coefficient included in the AIS beta version (fig. 2). An initial development stage of 25 d was used, which is similar to FAO 56. However, rather than a constant K_{cb} during the initial stage, the value increased from a minimum of 0.2 (the minimum value used in the AIS) to 0.51. This change was made to partially compensate for the small root system associated with the developing seedlings since the AIS does not directly consider rooting depth. Although the maximum allowable SWD could be changed during the season as the root zone changes, the method of compensating for root zone changes presented here was believed to be easier for the end user (i.e., rice producer). During "typical" Mid-South weather conditions, irrigation during the initial growth stage is often applied to activate herbicides and fertilizers rather than required to alleviate drought stress. However, with the variable Mid-South weather and soils and the sensitivity of rice plants to drought stress, irrigation needs during this portion of the growing season cannot be ignored.

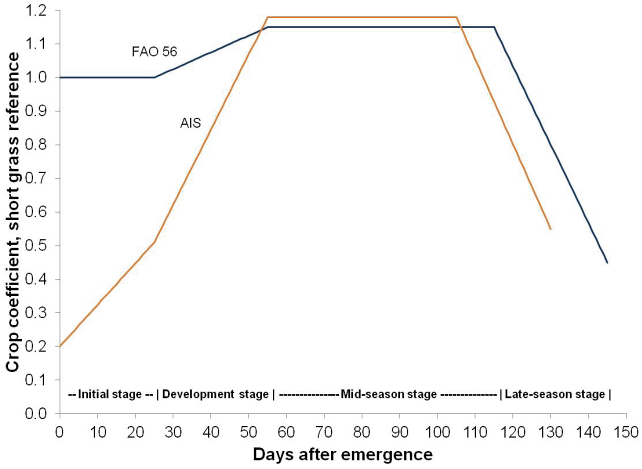

Figure 2. Basal crop coefficient, short grass reference, for rice from suggested values in FAO 56 (Allen et al., 1998) assuming 5 days from planting to emergence and the values in the Arkansas Irrigation Scheduler beta version.

A development stage length of 30 d was used, the same as in FAO 56. However, the peak K_{cb} value for the Mid-South is 1.18 based on the adjustment procedures presented in FAO 56 (Henggeler, J.C., University of Mo., personal communication). A mid-season growth stage of 50 d was used, approximately the R0 through R7 growth stages (Counce et al., 2000). The late-season stage will be variety and season specific and will end with harvest at approximately 120 d after emergence in most cases.

Weather conditions varied considerably between the two growing seasons, with 2010 being warmer and much drier (table 1). August was the driest month in both years, but June, July, and August, the principal months for irrigation, were each much drier in 2010. Similarly, ET_o was higher each month in 2010, with an average for the 6-month growing season of 15% higher.

In 2009, the first irrigation was applied on 19 June and the final on 11 September (fig. 3) for a total of 34 days with irrigation and 414 mm of water applied. Measurable rainfall (≥0.25 mm) was recorded on 31 days during the irrigation period for a total of 296 mm; however, much of the rainfall probably ran off the field without soaking into the root zone. The AIS assumes that rainfall or irrigation will recharge the root zone until SWD = 0 and any additional rainfall or irrigation will be lost as runoff (Vories et al., 2009). Since irrigation resulted in SWD = 0 on many days (fig. 3), even relatively small rainfall amounts would be expected to result in runoff. Data from the Watermark sensors were logged starting on 22 July through the remainder of the irrigation period (fig. 4). While soil moisture tension measured by the shallower (150 mm) sensors ranged from approximately 10 to 70 kPa, the deeper (300 mm) sensors provided more stable measurements, usually between 30 and 50 kPa. As commonly observed in the region, the individual sensor readings were quite variable and attempting to infer information about specific water contents would not be appropriate. Therefore, it was not possible to use the sensor data to calculate water use to compare with the estimates from the AIS.

In 2010, the first irrigation was applied on 24 May and the final on 1 September (fig. 5) for a total of 45 days with irrigation and 503 mm of irrigation water applied. Measurable rainfall was recorded on 27 days during the irrigation period for a total of 219 mm; however, as before, much of the rainfall probably ran off the field without soaking into the root zone. Data from the Watermark sensors were logged starting on 21 July through the remainder of the irrigation period (fig. 6). While the shallower (150 mm) sensors appeared to stay wetter than the previous year with the additional irrigation applications, the deeper (300 mm) sensors were again usually between 30 and 50 kPa.

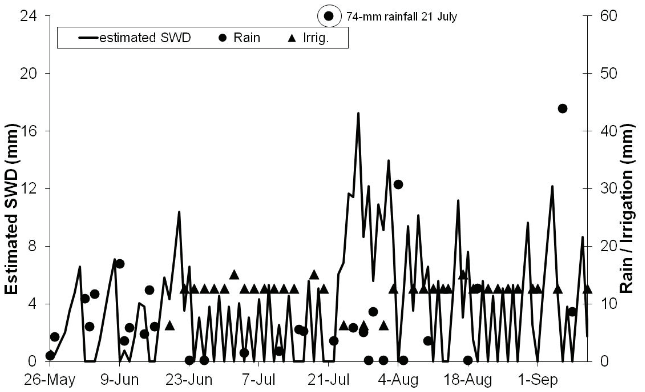

Figure 3. Estimated soil water deficit, rainfall and irrigation applied to study field between emergence and the final irrigation in 2009.

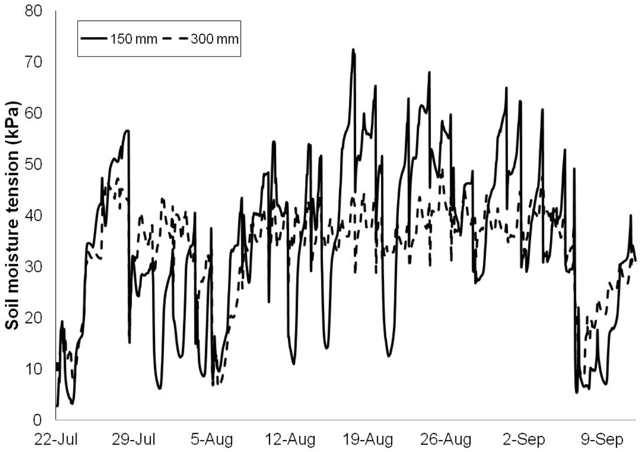

Figure 4. Soil moisture tension from Watermark sensors at two depths in study field between initiation of sensor logging and the final irrigation in 2009. Values shown are average of four locations.

Table 1. Observed weather conditions at University of Missouri Fisher Delta Research Center Marsh Farm during the 2009 and 2010 growing seasons.[a]

	Weather Parameter						
Year	April	May	June	July	August	September	6-month Average
	Average Daily Maximum Air Temperature (°C)						
2009	21	25	32	30	30	27	28
2010	24	28	34	33	34	30	31
	Average Daily Minimum Air Temperature (°C)						
2009	9	16	21	21	19	18	17
2010	12	17	23	23	23	17	19
	Average Daily Short Grass Reference Evapotranspiration[b] (ET_o, mm d^{-1})						
2009	3.3	3.6	5.1	4.2	4.3	3.0	3.9
2010	3.8	4.3	5.4	5.1	4.8	3.6	4.5
	Cumulative Rainfall (mm)						
2009	127	183	79	112	48	155	117
2010	130	178	33	74	10	48	79

[a] From University of Missouri Agricultural Electronic Bulletin Board (AgEBB; available at http://agebb.missouri.edu/).

[b] ET_o reported on AgEBB beginning 22 July 2010; previous values calculated with PMday (Snyder, 2001) using weather data from AgEBB.

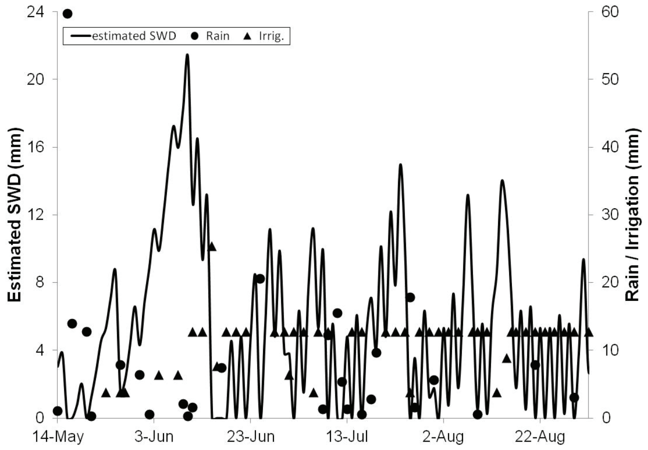

Figure 5. Estimated soil water deficit, rainfall and irrigation applied to study field between emergence and the final irrigation in 2010.

No direct flooded comparison was included in the study due to the high infiltration rates associated with the soils in the study field. However, Runsick et al. (2009) reported on 13 flooded rice fields in Arkansas where total irrigation application was measured. The total irrigation amounts ranged from 356 mm, less than the 414 mm applied to the rice in our study, to 1,168 mm, with 10 of the 13 fields reporting greater total applications than the 414 mm applied to the center pivot rice in 2009. In 2010, they reported on 9 fields with total irrigation amounts ranging from 500 mm, similar to the 503 mm applied to the rice in our study, to 1,880 mm (Runsick et al., 2010), with 8 of the 9 fields reporting greater total applications than the 503 mm applied to the center pivot rice in 2010.

The estimated SWD calculated by the AIS appeared to respond as expected with the frequent irrigation, while casual observations and yields from the different studies in the field suggested that the crop was not drought stressed. In both seasons the estimated SWD never reached 25 mm, but included a short period that was greater than the rest of the season (i.e., late July 2009 and early June 2010). However, in both cases the soil surface was wet from small rains and irrigations and the crop did not appear stressed. The AIS data indicated that the estimated SWD was at 0 on many days (figs. 3 and 5), suggesting that more irrigation water may have been applied than was necessary for optimal crop growth.

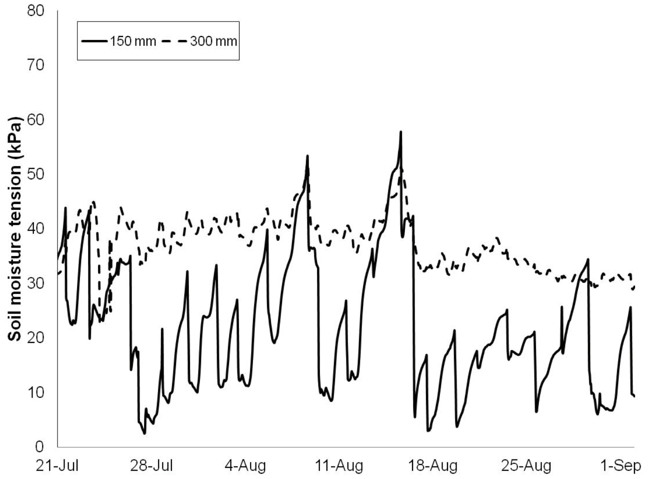

Figure 6. Soil moisture tension from Watermark sensors at two depths in study field between initiation of sensor logging and the final irrigation in 2010. Values shown are average of four locations.

GRAIN YIELD

In 2009, the cultivar Templeton had the highest observed grain yield in the fungicide-treated plots (8.31 Mg ha^{-1}; table 2), although not significantly greater than Cocodrie (7.98) and Taggart (7.86). Catahoula had significantly lower yields than the other cultivars (5.97). The cultivars' yields were comparable to the 7.5 Mg ha^{-1} state-average rice yield for Missouri in 2009 (USDA-NASS, 2010b). Yields for the 13 Arkansas fields ranged from 7.3 to 10.8 Mg ha^{-1} (Runsick et al., 2009).

The IWUE ranged from 2.0 to 1.4 kg m^{-3} for Templeton and Catahoula, respectively. Since the field was irrigated uniformly, the IWUE results mirrored those of yield. Yields for IWUE calculations are generally reduced by the yield of the crop without irrigation. However, in this study the rainfed yields were assumed to be 0. Observations of plants growing outside the irrigated portion of the field confirmed the assumption. Vories et al. (2010) reported hybrid rice IWUEs of 1.7 and 2.1 kg m^{-3} for flood and pivot irrigated fields, respectively, from an Arkansas farm. All of the IWUE values observed in this study were higher than values reported for conventional (0.9 kg m^{-3}) and multiple inlet (1.2 kg m^{-3}) rice from producers' fields reported by Vories et al. (2005). Values for the 13 Arkansas fields ranged from 0.9 to 2.6 kg m^{-3} (Runsick et al., 2009).

The fungicide chemigation appeared effective at controlling blast (data not included). Although no statistical comparisons could be made, blast was observed in the area that received no fungicide and the two cultivars known to be susceptible, Francis and Wells, were severely impacted. Templeton is rated resistant to common blast races (Lee, 2009) and did not appear to have been seriously affected in this study. Taggart is rated moderately susceptible to susceptible for common blast races (Lee, 2009) and may have been impacted, but it did not appear to have been affected as severely as Francis or Wells. However, blast was also observed in many commercial flooded fields in 2009. Additional research is needed to provide a better understanding of the relationship between sprinkler irrigation for rice and the occurrence and control of blast.

Table 2. Grain yield from fungicide-treated plots in large-plot cultivar study in 2009 at University of Missouri Fisher Delta Research Center Marsh Farm.

Cultivar	Grain Yield (Mg/ha @ 12 g/g d.b.)[a]	IWUE (kg m^{-3})[b]
Catahoula	5.97 c	1.44 c
Cocodrie	7.98 ab	1.93 ab
Francis	7.33 b	1.77 b
Taggart	7.86 ab	1.90 ab
Templeton	8.31 a	2.01 a
Wells	7.20 b	1.74 b

[a] Means in a column followed by the same letter are not significantly different at the 5% level of significance.

[b] IWUE = irrigation water use efficiency, calculated as grain yield / irrigation water applied; rainfed yields assumed 0.

After the cleaned yield data (Sudduth and Drummond, 2007) from 2010 were assembled into a database, the data were analyzed with spatial regression techniques in OpenGeoDa software to investigate the relationship for grain yield among the cultivars by explicitly modeling the spatial effects (table 3). Spatial diagnostics were performed using an exogenously chosen Boolean spatial weights matrix specified with a cutoff distance equal to 5.1 m, the minimum distance such that each observation had at least one neighbor. The Moran's I test statistic of the OLS regression residuals indicated spatial autocorrelation was present in the data (Anselin, 1988), thus the null hypothesis of no spatial autocorrelation was rejected (0.55, p<0.001). Lagrange Multiplier tests of OLS residuals did not indicate that spatial autocorrelation was stronger in either the residuals (error) or the dependent variable (lag; data not included); therefore, without an empirical indication of the necessity for a spatial lag model, a spatial error regression analysis was chosen to explicitly model the spatial autocorrelation based on the theoretical notion that models of yield monitor data are spatially autocorrelated due to omitted spatial variables (Griffin et al., 2007). Differences in crop yield response by cultivar were assessed by a significance test on the coefficients of binary dummy variables. Binary variables in the contrast matrix were restricted to sum to zero, i.e. $\Sigma d_i = 0$, so that the coefficients including intercept are interpreted as the difference from overall mean field response rather than difference from an arbitrarily dropped variable.

The spatial autoregressive coefficient, λ, was estimated as 0.67 ($p < 0.001$) for the spatial error model. Furthermore, the likelihood ratio test was highly significant ($p < 0.001$) and the Akaike information criterion was lower for the spatial error model than the OLS model, indicating the spatial error model was an improvement over the OLS. However, the yield estimates and probability levels did not vary greatly between the spatial and aspatial models (table 3). Yield estimates from the spatial analysis ranged from 8.2 to 6.8 Mg ha^{-1} for Francis and Catahoula, respectively. No blast infestation was observed in 2010 and there were no catastrophic yield effects observed in the plots without fungicide treatment similar to Francis and Wells in 2009. However, yields did appear to be reduced, indicating the importance of fungicide treatment or the selection of resistant cultivars or hybrids (data not included). Although Templeton, Taggart, and Cocodrie were the highest yielding cultivars in 2009 (table 2), each yielded less than Francis in 2010. Catahoula was again the lowest yielding cultivar. The cultivars' yields were comparable to the 7.3 Mg ha^{-1} state-average rice yield for Missouri in 2010 (USDA-NASS, 2010b). Yields for the nine Arkansas fields ranged from 7.3 to 10.8 Mg ha^{-1} (Runsick et al., 2010).

IWUE values calculated from the spatial analysis estimates ranged from 1.6 to 1.4 kg m^{-3} for Francis and Catahoula, respectively, (table 3) with the value for each cultivar lower than the previous year when yields were generally greater and less irrigation water was applied (table 2). In addition to the higher temperatures in 2010, yields were probably impacted by the fact that rice was produced in the field the two previous years (Olk et al., 2009). Values for the nine Arkansas fields ranged from 0.4 to 2.0 kg m^{-3} (Runsick et al., 2010).

CONCLUSION

Center pivot irrigated rice was produced at the University of Missouri Fisher Delta Research Center Marsh Farm at Portageville in 2009 and 2010. A field-scale cultivar test was conducted and irrigated with a 150-m-long center pivot irrigation system at a target application of 13 mm on alternate days in the absence of rain. An experimental short grass reference crop coefficient function was developed and included in a beta version of the AIS to estimate the daily SWD. Daily ET$_o$ was calculated from weather data collected on site and Watermark sensors were placed in four locations. Irrigation was ceased when the grain color began to change suggesting maturity.

Table 3. Results from regression analyses (dependent variable = grain yield, Mg ha^{-1} @ 12 g/g d.b.) for fungicide-treated plots in 2010 at the University of Missouri Fisher Delta Research Center.

	Ordinary Least Squares			Spatial Error			
Cultivar	Estimate (Mg ha^{-1})	Standard Error	P[a]	Estimate (Mg ha^{-1})	Standard Error	P[a]	IWUE (kg m^{-3})
Mean field effect	7.38		<0.001	7.34		<0.001	
Catahoula	6.84	0.090	<0.001	6.79	0.194	0.005	1.35
Cocodrie	7.32	0.093	0.528	7.26	0.187	0.659	1.44
Francis	8.21	0.091	<0.001	8.22	0.185	<0.001	1.63
Taggart	7.44	0.088	0.531	7.40	0.191	0.760	1.47
Templeton	7.51	0.087	0.134	7.43	0.180	0.604	1.48
Wells	6.96	0.093	<0.001	6.94	0.189	0.032	1.38
λ				0.67	0.022	<0.001	

Measures of Fit	Ordinary Least Squares	Spatial Error
Mean squared error	1.27	0.912
Akaike information criterion	3,287	2,799
Degrees of freedom	984	984

Diagnostics Tests	Value	p
Moran's I (error)	0.555	<0.001
Likelihood ratio test	488	<0.001

[a] Probability values for testing the null hypothesis H$_o$: value = 0, except cultivar yields H$_o$: value = mean field effect.

Weather conditions varied considerably between the two growing seasons, with 2010 being warmer and much drier. Similarly, ET_o was higher each month in 2010. In 2009, there were totals of 34 days with irrigation and 414 mm of water applied. Measurable rainfall was recorded on 31 days during the irrigation period for a total of 296 mm; however, with the low SWD much of the rainfall ran off the field. As expected, soil moisture tension data from the shallower (150 mm) Watermark sensors varied more than from the deeper (300 mm) sensors. In 2010, there were totals of 45 days with irrigation and 503 mm of irrigation water applied. Measurable rainfall was recorded on 27 days during the irrigation period for a total of 219 mm. Data from the Watermark sensors were similar to the previous year, although the shallower (150 mm) sensors appeared to stay wetter. The AIS appeared to respond as expected with the frequent irrigation and yields from the different studies suggested that the crop was not drought stressed. The AIS data suggested that more irrigation water may have been applied than was necessary for optimal crop growth and future research will address fine-tuning the water requirements.

In 2009, the cultivar Templeton had the highest observed grain yield (8.31 Mg ha^{-1}), although not significantly greater than those of Cocodrie (7.98) and Taggart (7.86); each was comparable to the 7.5 Mg ha^{-1} state-average rice yield for Missouri in 2009. The IWUE ranged from 2.0 to 1.4 kg m^{-3} for Templeton and Catahoula, respectively, similar to values reported for flood and pivot irrigated fields (1.7 and 2.1 kg m^{-3}, respectively) for hybrid rice grown by a producer in Arkansas.

In 2010, spatial diagnostics indicated spatial autocorrelation was present in the yield monitor data and a spatial error model was used to analyze the grain yield. Yields ranged from 8.2 to 6.8 Mg ha^{-1} for Francis and Catahoula, respectively. Each was comparable to the 7.3 Mg ha^{-1} state-average rice yield for Missouri in 2010. Although Templeton, Taggart, and Cocodrie were the highest yielding cultivars in 2009, each yielded less than Francis in 2010. IWUE values ranged from 1.6 to 1.4 kg m^{-3} for Francis and Catahoula, respectively, with the value for each cultivar lower than the previous year when yields were generally greater and less irrigation water was applied. In addition to the higher temperatures in 2010, yields were probably impacted by the fact that rice was produced in the field the two previous years.

This study demonstrated that it was possible to produce commonly grown Mid-South rice cultivars on coarse-textured soil using center pivot irrigation and achieve grain yields comparable to flooded production based on the state-average yields and those observed in the University of Arkansas RRVP. Values from the beta version of the AIS, adapted to calculate estimated SWD for non-flooded rice, indicated that the estimated SWD was at 0 on many days, suggesting that more irrigation water may have been applied than was necessary for optimal crop growth. Future research will use the basal crop coefficient developed for non-flooded rice and the beta version of the AIS to schedule irrigations based on allowable SWD and thereby reduce the excess applications. Soil moisture sensors will be used to indicate how well the AIS described soil moisture and the data should indicate whether the current crop coefficient in the AIS is adequate as well as help to develop irrigation scheduling recommendations for rice producers.

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