5-2020

Simulating Soybean-Rice Crop Rotation and Irrigation Strategies in Arkansas Using APEX

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Biological Engineering Program

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Undergraduate Honors Thesis

Abstract

Rice is one of the most prevalent and relied upon resources around the world. Despite such prominence, cultivation techniques for this crop are not perfect. Precise irrigation amounts and optimal crop rotations are still not completely understood. As the global population continues to grow and resources are depleted, maximizing the efficiency of cropping systems becomes more urgent. The goal of this study was to shed light on these questions using the Agricultural Policy/Environmental eXtender (APEX) model to simulate five fields in soybean-rice rotation in Arkansas. First, the model was calibrated to accurately represent the observed yields in the area. Then, two long-term scenarios were simulated: one in which rice-rice was compared to a soybean-rice rotation in terms of yield, and another in which irrigation amounts were increasingly reduced to see the effects on rice yields. Contrary to expectation, rice-rice showed higher yields in most fields. The results of the reduced irrigation scenario differed by field, but reducing irrigation generally reduced yield in all fields except one with continuous flood irrigation.

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1. Introduction and Literature Review

1.1 Arkansas Crops

The state of Arkansas accounts for 47.9% of rice production in the United States, making it the largest rice producer in the country (Hardke, 2019). The area of rice produced in Arkansas is 467,816 hectares, 49% of the total hectarage used for rice in the U.S. (Hardke, 2019). Of this hectarage, 68.5% is planted in rotation with soybean as of 2018 (Hardke, 2019). Arkansas is also the tenth largest producer of soybean in the country, with an estimated planted area of 1,214,057 hectares ("Ag Facts," 2020; NASS USDA, 2019). According to Watkins et al. (2004), a two-year soybean-rice rotation is a typical rotation used in Arkansas. In areas with limited water or problems caused by red rice, a variety of rice that is colored red by its anthocyanin content and a major yield-reducing weed (Shivrain et al., 2010), a three-year rice-soybean-soybean rotation may be used. Although rice-rice systems have higher gross returns because of the high value of rice, rotations with soybean are generally more profitable due to the low production costs of soybean (Watkins et al., 2004).

Soybean is known to increase available nitrogen in the soil through nitrogen fixation (Scherner et al., 2018). Since much of the nitrogen is removed from the field during harvest, the benefits of nitrogen fixation by soybean may be minimal (Peoples et al., 2009). However, crops in rotation with soybean are still shown to increase in yield, if, perhaps, for a variety of reasons not necessarily related to nitrogen (Peoples et al., 2009) such as weed and pest management (Filizadeh, Rezazadeh, & YOUNESI, 2007; Scherner et al., 2018). It may be useful for future analyses of the profitability of soybean-rice compared to rice-rice to simulate long-term differences in yield and nitrogen stress between the two rotations.

1.2 Irrigation

Water is one of the most important agricultural resources in the world, yet less than 0.01% of earth's water is available for use (Pennington et al., 2020). The alluvial aquifer used for agricultural irrigation in Arkansas is decreasing in connection to rice production (Smith et al., 2007). Of irrigated rice hectarage in Arkansas, 76% uses groundwater, and the rest uses surface water (Hardke, 2019). The implementation of reduced agricultural water usage is becoming increasingly necessary.

Different irrigation methods for rice have been implemented. The most common method is flooding, which generally involves beginning flooding early in the growth of the rice and maintaining a depth of about 51-102 mm (2-4 inches) (Henry, Daniels, Hamilton, & Hardke, 2018). Conventional flooding uses a large amount of water, a significant portion of which may be lost as runoff (Henry et al., 2018). Deeper flood depths (102-152 mm) may also be used to suppress disease (Henry et al., 2018). According to Henry et al. (2016), flood irrigation involves either straight or contour levees, which act as spillways through which water can flow into each paddy following the slope of the field. Generally, in conventional flooding, or cascade, farmers fill the highest paddy and allow water to flow into the lower paddies through the levee gates, but others prefer starting at the bottom and "stair-stepping" the water back up (Henry et al., 2018). Another alternative to filling only the highest paddy and allowing water to flow down is multiple-inlet irrigation (MIRI), which utilizes polypipe laid along the length of the field to fill each paddy at the same time (Henry et al., 2016). This technique can reduce the amount of water pumped, reduce waste due to runoff, and reduce the wear on levee gates due to over-pumping (Henry et al., 2018). Multiple inlet irrigation can be used with both straight and contour levees. The multiple inlet technique represents about 33% of total Arkansas rice hectarage, while conventional flood is used on about 56% (Hardke, 2019). Zero-grading is another practice in flooded fields, which involves precision-leveling the field and flooding from multiple sides to increase the uniformity of the flood

(Henry et al., 2016). Zero-graded fields can be flooded quickly but take longer to drain, so this method is mostly used for continuous rice (Henry et al., 2016).

Furrow irrigation involves pumping water into trenches or furrows dug in between rows of crops and allowing the water to flow down using the slope of the field (USGS). One advantage of furrow irrigation is a reduction of water use because water is only applied to the furrows (Rai, Singh, & Upadhyay, 2017). Interest has risen recently in the use of furrow irrigation for rice, which has increased from 2.7% of total Arkansas rice hectarage in 2016 to 7.7% in 2018 (Hardke, 2019). Furrow irrigation is best suited for fields with steep slopes, such that the number of levees required would take up too much area, or fields that are otherwise difficult to flood (Henry et al., 2018). While furrow irrigation has the capacity to achieve similar yields using less water compared to flood irrigation, doing so can be difficult. Studies in this area are inconclusive, and other factors, such as agronomic management, may be involved (Henry et al., 2018).

Currently in use on only 3% of Arkansas rice hectarage is a practice known as intermittent flooding or alternate wetting and drying (AWD). In AWD, a field is flooded and allowed to dry alternately rather than remaining flooded continuously throughout the season. The idea is to reduce water use and greenhouse gas emissions while not reducing yield. According to Carrijo et al. (2017), mild AWD reduced water used by 23.4% without a significant reduction in yield, and even severe AWD only resulted in yield losses of 22.6% when compared to continuous flooding. Studies seem to generally agree that AWD was able to reduce water usage without a “significant loss in yield.” Pandey et al. (2010) found that AWD “reduces field water application by 15–20% without significantly affecting yield and increases the productivity of total water input.” According to Rejesus et al. (2011), who performed a study in the Philippines, the use of what is referred to as “safe AWD” reduces the amount of time irrigation needs to be used “without a statistically significant reduction in yields and profits.” In safe AWD, the water level is allowed to drop to 15-20 cm below the soil surface before irrigation is applied.

Irrigation is applied to about 2-5 cm above the surface (as opposed to traditional continuous flooding at about 5-10 cm), and during flowering, the field is kept flooded (Rejesus et al., 2011). Nalley et al. (2015) compared three different regimes called AWD/40, AWD/60, and AWD/40-Flood in Arkansas. In the AWD/40 regime, irrigation was applied when the saturated soil water holding capacity was under 40% at a depth of 10 cm. The AWD/60 regime is the same thing but at a water holding capacity of 60%. The AWD/40-Flood regime maintains the AWD/40 regime after the initial flooding until the R0-R1 growth stage (meaning the panicle has started to form) (Nalley et al., 2015). Compared to continuous flooding, AWD/40 Flood resulted in yield loss of 0.88% and water reduction of 18%, AWD/60 resulted in yield loss of 5% and water reduction of 31%, and AWD/40 resulted in yield loss of 12.6% and water reduction of 44% (Nalley et al., 2015). Before the development of "safe AWD," application of AWD irrigation could be complicated and very site-specific, and recommendations on the severity of the dry periods were varied (Lampayan, Bouman, Palis, & Flor, 2016). More studies should be implemented to find the optimum irrigation amounts and how much yield would be sacrificed if irrigation needs to be reduced. A model of increasingly severe irrigation regimes could be useful for finding the limits of AWD irrigation.

1.3 Nutrients

Fertilizer efficiency is also tied to irrigation management. Nitrogen is the most critical and most costly nutrient to rice producers because of the abundance in which it is required (Roberts, Slaton, Wilson, & Norman, 2016). Roberts et al. (2016) found that early nitrogen application should be carried out immediately before flooding to incorporate the nitrogen into the soil and to avoid nitrogen loss due to volatilization and denitrification. With proper management, nitrogen fertilizer applied after the pre-flood application is generally incorporated with 65-80% efficiency (Roberts et al., 2016). The effects of furrow irrigation on nutrient efficiency are still under evaluation (Henry et al., 2018). Furrow irrigation likely leads to higher nitrogen losses through volatilization and denitrification compared to flood irrigation (Hefner & Tracy, 1991). For furrow irrigated fields with shallow slopes, Henry et al. (2018)

recommend applying the recommended amount of nitrogen fertilizer before flooding and another 45 kg (100 pounds) of urea two weeks later. Fields with steep slopes that do not hold water as well require smaller, more frequent applications (Henry et al., 2018). It is a recommended practice to block the ends of the furrows; holding water on the field and reducing runoff will increase nutrient efficiency (Henry et al., 2018). Multiple inlet irrigation may increase nutrient efficiency, while AWD should cause no change in management (Henry et al., 2018). Dong et al. (2012) reported that AWD caused an increase in nitrogen loss to nitrification-denitrification compared to continuous flood, although even in AWD, these losses were not agronomically significant. Tillage practices also affect fertilizer efficiency, and fields with reduced tillage or no tillage may need extra nitrogen applied to account for volatilization and the decomposing of plant residue if large amounts of this residue are left on the field (Roberts et al., 2016).

1.4 The Agricultural Policy/Environmental eXtender (APEX) model

Crop models are useful tools in evaluating the environmental and agricultural effects of various management techniques and environmental factors. In this study, we were interested in the crop yield and how it was affected by different irrigation management, crop rotation, tillage, and fertilization for rice and soybean at the farm scale. We selected the Agricultural Policy/Environmental eXtender (APEX) model, which is a model for small-medium watersheds and heterogeneous farms (Gassman et al., 2010).

The APEX model was developed as an improvement on the Environmental Policy Integrated Climate (EPIC) model, a model originally developed to analyze the relationship between erosion and productivity of soil (Flowers, Williams, & Hauck, 1996; Williams, Izaurralde, & Steglich, 2008; Williams, Jones, Kiniry, & Spanel, 1989). The EPIC model has a wide array of components and simulation capabilities and is able to compare various management systems. It is limited, however, in that the area considered for drainage is taken to be a homogeneous area of up to around 100 ha (Williams et al., 2008). The APEX model is able to use EPIC's capabilities on a heterogeneous watershed divided into homogeneous sub-areas, with water routing capacity from one sub-area to another, making the model able to simulate the entire watershed (Williams et al., 2008).

The APEX model has been used in more than 270 journal articles since 2010 (Elliott & Elliott, 2017). APEX has successfully modeled irrigation and nitrogen management (Cavero et al., 2012), as well as a variety of best management practices (Zhang et al., 2016). APEX has also been used to model the effects of soil, tillage, irrigation, and cropping systems on productivity (Zhang et al., 2016). The Blackland Research & Extension Center at Texas A&M currently develops APEX more than EPIC, making APEX more useful for studies going into the future. APEX was chosen for this study to simulate rice-soybean rotations for a combination of future utility, ease-of-use, and comprehensiveness in terms of crop and rotation simulating abilities (Cavero et al., 2012; Le, 2011).

The scope of this work involves calibration and validation of the APEX model to represent the yield at the research sites accurately, evaluation of the effects on yield, water stress and nitrogen stress of an annual soybean-rice rotation as compared to a rice-rice rotation, and similar evaluation of the effects of increasingly water-stressed scenarios on rice. The goals were to: (1) determine whether including soybean in the rotation had a significant effect on rice yield or nitrogen stress and (2) find the point of maximum water stress before rice yields were significantly affected.

2. Methodology

2.1 Site Description

The experimental fields in this study consist of five fields in an annual rice-soybean rotation coded as R2, R3, R5, R7, and R8. These fields are located in Faulkner (R7), Lonoke (R2, R5, R8), and Prairie (R3) counties in central Arkansas (Figure 1). The soil in R7 is Perry clay, in hydrologic soil group D, while the rest of the fields are Stuttgart (R2, R5), Dewitt (R3), and Calhoun (R8) silt loam in hydrologic soil group C/D. The R7 field is located about 80km from the others, which are within 13km of each other. Table 1 summarizes the general characteristics of these fields.

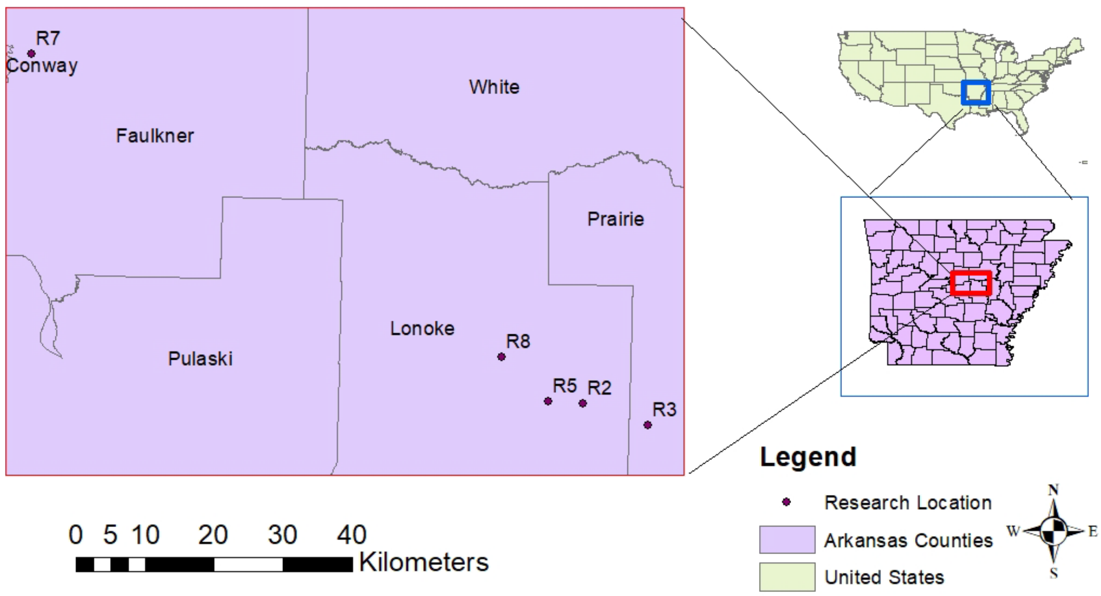

Figure 1: The five experimental fields labeled with dots in counties in Arkansas, United States.

Table 1: Soil characteristics of the experimental fields, including soil series, soil texture, hydrologic soil group (HSG), area, and slope. Soil information was found from Web Soil Survey (NRCS USDA, 2019). Areas and slopes were given by farmers or found using Google Earth (Google, 2020).

Field	Soil series	Soil Texture	HSG	Area (ha)	Slope (%)
R2	Stuttgart	Silt Loam	C/D	40.46	0.28
R3	Dewitt	Silt Loam	C/D	52.61	0.16
R5	Stuttgart	Silt Loam	C/D	23.47	0.51
R7	Perry	Clay	D	49.94	0.21
R8	Calhoun	Silt Loam	C/D	27.52	0.10

2.2 Management

Historically, most of these fields have been planted in rice-soybean rotation for anywhere from 10 to more than 60 years (Moreno-Garcia, 2019). Rice management information to input into the APEX model was collected from the farmers, including cultivar, field operations, seeding rate, planting date, fertilizer, herbicide/pesticide applications, irrigation start and end date, irrigation amount, irrigation type, and harvest date (Table 2). When irrigation amounts were not available from farmers, literature values were used (Moreno-Garcia, 2019). The rice seeding rates were converted from kg/ha to plants/ha using bulk seed densities from Hardke et al. (2017). The cultivar was never specified in the model, but different bulk seed densities were used according to the cultivar. For soybean, a seeding rate of 345,947 seeds/ha was given by one of the farmers. Assuming an 85% germination rate, this would result in 296,526 plants/ha, which is reasonable considering seeding rates given by Ashlock et al. (2014). Thus, a value of 296,526 plants/ha was used for all fields R5 and R8, while R2, R3, and R7 had a similar seeding rate of 296,400 plants/ha

Soybean was generally planted in late May and harvested around the second week of October. No nitrogen fertilizer was applied to soybean, per the Arkansas Soybean Production Handbook (Slaton, Roberts, & Ross, 2013). Each soybean field received 92 kg/ha of potassium and 24 kg/ha of phosphorus, except for R7, which received no fertilizer.

Table 2: Field management for rice, including tillage, irrigation, planting rates, planting and harvest dates, and fertilizers (elemental Phosphorus – P and Potassium – K).

Field	Tillage	Cultivar	Irrigation			Planting		Harvest Date	Fertilizers		
			Inlet	Type	Amount (mm)	Rate (plants/ha)	Date		N (kg/ha)	P (kg/ha)	K (kg/ha)
R2	Reduced	XP753	MIRI	AWD	751	851805	1-May	4-Sep	176	9	77
R3	Reduced	XP753	CVF	AWD	610	813087	6-May	7-Nov	174	15	56
R5	Reduced	G214	Furrow	Furrow	635	735650	12-Apr	15-Sep	202	19	56
R7	No till	G214	CVF	CF	1649	942286	11-May	7-Oct	176	20	N/A
R8	Reduced	G214	CVF	AWD	737	963226	6-May	20-Sep	169	14	50

*Note: R7 – an additional 11.2 kg/ha elemental nitrogen was added. AWD – Alternate Wetting and Drying, CF – Continuous Flood MIRI – Multiple Inlet Irrigation, CVF – Conventional flooding, G214 – Gemini 214.

2.2.1 Tillage

Most fields received some sort of reduced tillage, with the exception of R7, which was a no-till field (Table 2). Reduced tillage is defined as limiting soil disturbance in order to control plant residue (USDA, 2016b). Reduced tillage is basically the same as conventional tillage but involves fewer field passes (Moreno-Garcia, 2019). No-till is defined as no disturbance to the soil in order to control plant residue (USDA, 2016a). For the farmers in this study, no-till involves performing no tillage or land labor (Moreno-Garcia, 2019).

2.2.2 Irrigation

Three types of irrigation: conventional flooding, MIRI, and furrow were used in this study. The only field in furrow irrigation was R5. The fields R3, R7, and R8 were conventionally flooded fields, and R2 used MIRI (Moreno-Garcia, 2019). The R2, R3, and R8 fields were considered AWD, meaning the fields were allowed to dry between irrigations rather than staying flooded the whole time (Moreno-Garcia, 2019). The R7 field was flooded continuously (Moreno-Garcia, 2019). For the rice model, we used the total irrigation amount given by the farmers and evenly distributed it, irrigating once per week. Using this method, the drying periods of AWD were not well represented in the model. There was also no difference between conventional flooding and MIRI in the model. Total irrigation amounts are shown in Table 2.

For soybean, the general start and end times of irrigation were given by farmers, but the amount of water applied was not. Based on information by Tacker and Vories (2014) in the Arkansas Soybean Handbook, a value of 254 mm (10 inches) per season was used. For the soybean model, irrigation was applied about twice per month, with 51 mm of water per application.

2.3 WinAPEX

WinAPEX is the interface to the APEX model developed by Blackland Research and Extension Center (Magre et al., 2006). Through it, one can access the control files, watersheds, subareas, and weather station files. The control file (Appendix 1) controls how the simulation runs, including start year, duration, and weather input code. Input weather data (Appendix 2) downloaded from PRISM (Daly & Bryant) includes daily maximum and minimum temperatures and precipitation from 1981 until 2018. The watershed variables (Appendix 3) include latitude and longitude, weather station, nutrient uptake rates, and others. Within the watershed, there is a subarea editor (Appendix 4) with options for editing county, soil, operation schedule, and slope, among others.

Input for the management as discussed in section 2.2 includes field operations, seeding rate, planting date, fertilizer, irrigation start and end date, irrigation amount, and harvest date. Each rice and soybean was created as a single annual crop in the WinAPEX interface management editor (Appendix 5) and then combined into a soybean-rice rotation in a Microsoft access file. This access file also contains other model input information including management data, weather data, and various model parameters.

2.4 Calibration/Validation

Calibration of an APEX model can be carried out at the scale of a single subarea (field), a landscape, or an entire watershed (Wang, R. Williams, et al., 2012). In this study, each field is a standalone subarea; thus, there is no water routing between fields. The values for slope and soil series were adjusted for each subarea. The slope and soil series are shown in Table 1, along with the other field characteristics.

Calibration of the model was performed using the observed yields from the year 2018 for rice and 2017 for soybean. Validation was performed with soybean yields from the available data in 2019. The R7 field was fallow for both 2017 and 2019, so observed soybean yields were not available. When we ran the model before calibration, the yields were very low, so adjustments were made to the crop parameters for rice and soybean. The parameters were first adjusted one at a time to determine the effects they would have on yield and stress. According to the APEX user manual, the crop parameters to be revised, if necessary, are harvest index (HI) and biomass-energy ratio (WA) (Steglich & Williams, 2008). The WA had the greatest effect on yield, which became the driving variable in the calibration. According to Cabelguenne et al. (1999), radiation use efficiency (RUE, RUE=WA * 10), and HI are representative of the genetic progress of the plant, so fitting the values for WA and HI within a certain range was deemed less important than calibrating the model to reflect observed crop yields.

2.5 Scenarios

The baseline scenario of this study was the management input from the information obtained from sections 2.1 and 2.2. All the crop parameters remained the same as in the calibration process for rice and soybean, regardless of varying irrigation managements or site characteristics The single or double crop management for rice-rice or soybean-rice was used to simulate a 20 year period, from 2018-2038. The APEX model generates monthly weather data based on the historical data (1981- 2018), which in turn is used to generate APEX weather input data for the future simulation (Steglich & Williams, 2008). Two scenarios were performed as part of this study focusing on (1) crop rotation and (2) irrigation reduction in rice.

In the crop rotation scenario, the purpose was to compare rice yield and nitrogen stress between soybean-rice and rice-rice rotations. Other than the rotation, the management systems for rice were identical. The expectation for this scenario was that the nitrogen fixation associated with soybean would increase the rice yield in the long run. We wanted to examine the effects in the long-term future and decided to compare the results of the simulation over 20 years, from 2018-2038.

In the irrigation reduction scenario, rice irrigation amounts were reduced in increments of 10% of the baseline irrigation (which varied for each field), up to 60% reduced irrigation (RI) for each field in soybean-rice rotation. The goal of this scenario was to find the point at which water stress has a significant impact on rice yield. The same time period, 2018-2038, was chosen for consistency.

2.6 Statistical Methods

Several statistical analyses were performed to determine whether the model was well-calibrated to the observed crop yields. One method used was percent bias (PBIAS), which is good for continuous, long term simulations (Moriasi, Gitau, Pai, & Daggupati, 2015). However, if bias is equal in both directions, it will appear as though the PBIAS is low, which may be deceptive. Moriasi et al. (2015), therefore, recommends using PBIAS along with other statistical methods. The PBIAS for crop yield and biomass is considered acceptable at 25% (Wang, R. Williams, et al., 2012). Percent difference analyses and t-tests were also performed to determine if there was a significant difference between simulated and observed yields. Since the standard deviation of the observed data was more than twice that of the predicted, a t-test assuming unequal variances was used. These analyses were performed separately for rice and soybean.

3. Results

3.1 Calibration and Validation

In the end, rice crop parameter values were manually adjusted for biomass-energy ratio (WA), harvest index (HI), fraction of growing season when leaf area declines (DLAI), plant population for crops & grass – 1st point on curve (PPLP1), and plant population for crops & grass – 2nd point on curve (PPLP2) to the values shown in Table 3. The curve referred to is the plant population curve (plants/m^2 versus percent of maximum leaf area index). The crop parameter values are in agreement with Tatum (2019), and PPLP1 and PPLP2 are the same as Le et al. (2018). An adjustment of soybean HI was made from 0.3 to 0.38. The HI was the only parameter changed for soybean. A typical HI for soybean is around 0.3-0.4 (Le et al., 2018). Table 4 shows the calibration results of rice yield. As can be seen in the table, there is a PBIAS between the simulated and observed yields of -13.05%, and the percent difference between the mean simulated and mean observed yields was -12.25%. The model consistently over-predicted the yield, possibly indicating that the WA or HI was too high; however, the PBIAS with these parameter values was the lowest of all the iterations performed during calibration, and well within the acceptable 25% limit (Moriasi et al., 2015). Table 5 shows the calibration and validation results of soybean yield. The calibration results (2017) gave a PBIAS of 0.94% and a percent difference of .095%. The validation results (2019) gave a PBIAS of 6.09% and a percent difference of 6.28%. The 2017 and 2019 data sets together gave a PBIAS of 3.49% and a percent difference of 3.55%.

Table 3: Rice crop parameters calibrated for all fields. Same as Tatum (2019). PPLP1 and PPLP2 are the same as Le et al. (2018).

Variable	Description	Default Value	Calibrated Value
WA	Biomass-energy ratio	25	35
HI	Harvest index	0.5	0.56
DLAI	Fraction of growing season when leaf area declines	0.8	0.9
PPLP1	Plant population for crops and grass - 1st point on curve	125.6	20.5
PPLP2	Plant population for crops and grass - 2nd point on curve	250.95	100.9

Table 4: Calibration results of observed and simulated rice yields in tons per hectare in the year 2018.

Field	OBS (t/ha)	SIM (t/ha)	PBIAS	% Difference
R2	9.35	9.76		
R3	9	9.66		
R5	7.02	9.87	-13.05	-12.25
R7	9.05	10.3		
R8	9.25	9.78		
ALL	8.73	9.78		
Std Dev	0.97	0.25		

*Note: OBS – Observed yield, SIM – Simulated yield, Std Dev – Standard Deviation, PBIAS – Percent Bias.

Table 5: Calibration and validation results of observed (OBS) and simulated (SIM) soybean yields in tons per hectare.

Field	Calibration				Validation				Average	
	OBS 2017 (t/ha)	SIM 2017 (t/ha)	PBIAS 2017 (%)	% Difference 2017	OBS 2019 (t/ha)	SIM 2019 (t/ha)	PBIAS 2019	% Difference 2019	PBIAS total	percent difference total (%)
R2	2.93	3.36			3.45	3.17				
R3	3.22	3.39			3.21	3.14				
R5	4.1	3.36	0.94	0.95	4	3.18	6.09	6.28	3.49	3.55
R7	N/A	N/A			N/A	N/A				
R8	3.51	3.52			2.81	3.16				
Std Dev	0.50	0.08			0.50	0.02				

*Note: OBS – observed yield, SIM – simulated yield, Std Dev – Standard Deviation, PBIAS – percent bias. Percent difference is calculated (OBS - SIM)/average*100%.

3.2 Crop Rotation Scenarios

The expectation for the rice-rice scenario was that removing soybean from the rotation would be detrimental to the rice yield since soybean is known to increase soil nitrogen (Scherner et al., 2018). As can be seen in Table 6, in all fields except R8, the opposite was true. Based on the paired t-tests, the only statistically different result was that in R5. No significant differences were seen in the water stress on the crops. Rice-rice also showed significantly fewer nitrogen stress days in R2, R5, and R8.

Table 6: Long-term simulation from 2018-2038.

	Average Yield (t/ha)			Average Nitrogen Stress Days		
Field Code	Soybean-Rice Rotation	Rice-Rice	Percent Difference	Soybean-Rice Rotation	Rice-Rice	Percent Difference
R2	9.61^{a}	9.65^{a}	-0.40	20.00^{a}	16.83^{b}	17.18
R3	8.81^{a}	9.32^{a}	-5.66	30.24^{a}	22.69^{a}	28.52
R5	9.75^{a}	9.85^{b}	-1.01	3.02^{a}	1.57^{b}	63.30
R7	9.36^{a}	9.70^{a}	-3.57	9.25^{a}	7.04^{a}	27.04
R8	9.56^{a}	9.31^{a}	2.63	26.49^{a}	18.35^{b}	36.32

*Note: Superscripts of different letters across the same row denote a significant difference at alpha=0.05 using the paired t-test. The analysis is separated between yield, water stress, and nitrogen stress. The percent difference is calculated (Soybean-Rice – Rice-Rice)/average*100%.

3.3 Limiting Irrigation Scenario

The goal of simulating increasingly limited irrigation scenarios was to find the point at which the effect of water stress on yield became significant and determine if water was being wasted in the current management. As can be seen in Table 7, the results varied for each field. Generally, average yields decreased with irrigation reduction, except in the continuously flooded field, R7, which showed a consistent increase in yield until RI 60% which dropped below baseline yield. The AWD fields, R2, R3, and R8, had similar patterns of consistent decrease in yield when decreasing the amount of water. The furrow irrigated field, R5, also had consistently decreasing yield. The most consistent effect seemed to be had on R5, possibly because R5 had the steepest slope, making it more difficult to hold water in the field. The largest overall effect was in R8, possibly because of the high plant density (Table 2), increasing competition for resources between the plants. The overall effect of reduced irrigation, as can be seen in Figure 2, was a reduction in yield.

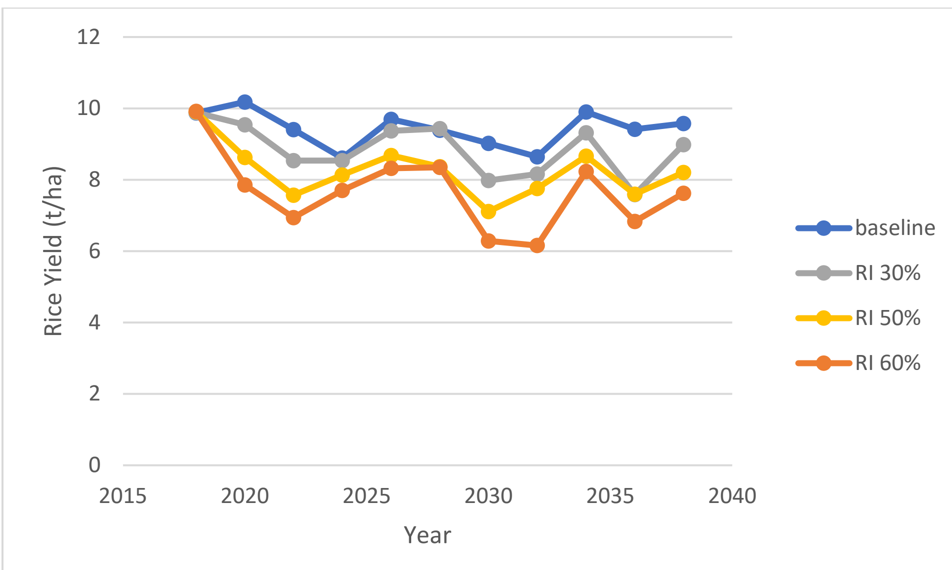

Figure 2: Average simulated rice yield of ALL fields from years 2018-2038 under baseline irrigation and reduced irrigation (RI) percentage: RI 30%, RI 50%, and RI 60%.

Both R3 and R8 had statistically significant differences in yield starting at 20% reduced irrigation. The R2 field had a significant difference at 10% reduced irrigation. The furrow irrigated field, R5, had a significant difference in yield for each reduction of irrigation. The increased yield in R7 became significant at 30% reduced irrigation and continued to increase until it dropped again at 60% reduced irrigation.

Table 7: Average rice yields for baseline (normal) and reduced irrigation (RI) scenarios for the years 2018-2038.

Field	Baseline	RI 10%	RI 20%	RI 30%	RI 40%	RI 50%	RI 60%
R2-AWD	9.79^{a}	9.76^{b}	9.72^{b}	9.64^{bc}	9.38^{cd}	9.25^{d}	8.91^{e}
R3-AWD	8.70^{a}	8.60^{ab}	8.33^{b}	8.41^{b}	8.38^{bc}	7.90^{c}	7.20^{d}
R5-Fu	9.83^{a}	9.70^{b}	9.52^{c}	9.33^{d}	9.10^{e}	8.88^{f}	8.60^{g}
R7-CF	9.20^{a}	9.28^{a}	9.31^{ab}	9.44^{bc}	9.50^{c}	9.65^{c}	8.80^{a}
R8-AWD	9.64^{a}	9.48^{a}	8.86^{a}	7.44^{b}	6.83^{b}	5.52^{c}	4.77^{d}
All	9.43^{a}	9.36^{a}	9.15^{a}	8.85^{a}	8.64^{a}	8.24^{a}	7.66^{b}

*Note: Superscripts of the same letter across the same row denote no statistically significant difference at alpha=0.05 using the paired t-test. RI – Reduced Irrigation, AWD – alternate wetting and drying, CF – continuous flood, Fu - furrow. The 10, 20, 30, 40, 50, and 60% are the amounts by which irrigation was reduced.

4. Discussion

4.1 Calibration and Validation

Upon running a t-test assuming unequal variances, both rice and soybean observed yields were not significantly different from the simulated yields at alpha 0.05. The model consistently overpredicted the rice yield and usually overpredicted the soybean yield; however, the PBIAS was well within the 25% limit deemed satisfactory by Wang et al. (2012). The percent difference between the mean of simulated and observed rice yields was -12.25%, and that of soybean yields was 3.55%. For reference, the yields simulated by Williams et al. (1989) using EPIC were all within 7% of observed yields. It is important to note that the calibration was based solely on the yield from each field, of which only three total years of data were available, one for rice and two for soybean. Including other measurable variables like maybe leaf area index would have made for a more robust calibration.

4.2 Crop Rotation Scenarios

Given that the rice-rice yields were higher in three of the five fields simulated, the results of this study indicate that rice-rice leads to higher yields compared to the soybean-rice rotation. According to the paired t-tests, the only significant difference between rice-rice and soybean-rice yields was in R5, which had a 0.65% difference. Significant differences were seen in nitrogen stress days in both R5 and R2, the soybean-rice rotation having more nitrogen stress days. Peoples et al. (2009) report that the benefits of nitrogen fixation by soybean may be minimal because most of the absorbed nitrogen is removed at harvest. One explanation for the decrease in yield and increase in nitrogen stress with the soybean-rice rotation is that no nitrogen is applied on soybean years, and the nitrogen fixation simulated by the model is not enough to make up for this deficit. This result does seem to be in disagreement with other studies, however, which say that including soybean in the rotation decreases the need for nitrogen fertilizer, if only marginally (Chapman & Myers, 1987). Weed and pest management should also be considered. Filizadeh et al. (2007) and Scherner et al. (2018) both attest to the benefits of soybean-rice rotation with regard to limiting weeds growth. Pesticide application and effects rotation may have on pests, however were not taken into account in this study.

4.3 Limiting Irrigation Scenarios

The results showed a decrease in yield with reduced irrigation in all fields except R7. One notable aspect of R7 is that the baseline irrigation amount is almost twice that of the next highest field, so R7 may just be over-irrigated. R7 is also the only field considered to be in continuous flood rather than AWD. Although the drying periods of AWD are not well represented in the model, the difference can be seen indirectly in the discrepancy between irrigation amounts. Exact irrigation amounts are shown in Table 2.

Another interesting aspect of this scenario is that nitrogen stress consistently decreased in all fields with irrigation reduction. This effect on nitrogen by irrigation could be an explanation for the steady increase in yield with reduced irrigation in R7. In R7, average nitrogen stress days went from 9 days at baseline irrigation, to 3 days at RI 50%, and back to 9 days at RI 60% (Table 8). These results could indicate that AWD irrigation not only saves water but may increase yield as well. Yao et al. (2012) and Rejesus et al. (2011) found that, using AWD, irrigation could be reduced by 38% without a significant effect on yield compared to continuous flood. Yang et al. (2017), however, found that severe AWD led to irrigation reduction of 38 to 50%, but also a yield reduction of 19 to 35%. The response of rice yield to irrigation reduction is also dependent on environmental factors, such as precipitation, temperature, and soil; so results vary, and making direct comparisons may be misleading.

Table 8: Average nitrogen stress days for baseline (normal) and reduced irrigation (RI) scenarios for years 2018-2038.

Field	**Baseline**	**RI 10%**	**RI 20%**	**RI 30%**	**RI 40%**	**RI 50%**	**RI 60%**
R2-AWD	18	18	18	17	18	17	17
R3-AWD	30	31	30	27	24	22	21
R5-Fu	1	1	1	0	1	1	1
R7-CF	9	8	8	6	6	3	9
R8-AWD	24	20	16	24	18	21	14
All	16	16	15	15	13	13	12

*Note: RI – Reduced Irrigation, AWD – alternate wetting and drying, CF – continuous flood, Fu - furrow. The 10, 20, 30, 40, 50, and 60% are the amounts by which irrigation was reduced

The results of R5, the only furrow irrigated field, were also unique in that they were the only ones with a statistically significant difference for each iteration. The R5 results could indicate that furrow irrigation is more sensitive to irrigation reduction compared to flood. Indeed, according to Henry et al. (2018), maintaining yield can be difficult with furrow irrigated rice. Furrow irrigated rice also had lower yields compared to flooded rice in studies done in Arkansas (Vories, Counce, & Keisling, 2002) and Australia (Beecher et al., 2006). On the other hand, He (2010) report that furrow irrigation can lead to water use reduction of 41 to 48% and even increase yield by 12 to 14%. Again, environmental factors are likely involved. It is also interesting that the furrow irrigated field had so much less nitrogen stress than the flooded fields. This is likely because of less runoff in the furrow fields, but it is important to note that furrow fields may tend to lose more nitrogen to ammonia volatilization and denitrification than flooded fields, which incorporate nitrogen into the soil during flooding (Roberts et al., 2016). Hefner et al. (1991) also report that furrow irrigation could lead to increased nitrogen loss through denitrification.

5. Conclusions and future studies

Although we were not able to perform a validation for the rice model due to limitations in observed data, APEX was able to accurately model rice yields based on the calibration results. One of the scenarios simulated in this study was a rice-rice versus soybean-rice rotation scenario, which indicated that rice-rice is usually the more productive cropping system in terms of yield and use of nitrogen, likely because nitrogen fertilizer was applied to rice and not to soybean. The results could have long-term implications concerning profits to the farmers, but detailed economic analysis would be needed to determine if long-term rice-rice poses any economic benefits. More studies could be performed in the future comparing the long-term economics of the two rotations.

Another conclusion was from a reduced irrigation scenario, which showed a decrease in yield with decreased irrigation, except in one field (R7) which was likely over-irrigated. These results raise questions about the detriments of over-irrigation which could be examined more closely in future studies. The results in R8 also raise questions about the effect of plant density on yield, which could also be examined more closely in future studies. Furthermore, more detailed studies could be done in the future on the effects of different irrigation methods on crop nitrogen stress and how these differences can be represented in models.

6. Acknowledgments

I want to thank Dr. Kieu Le for the many hours of work she puts into helping me in the modeling and writing process. Her work ethic and dedication are appreciated. I also want to thank Dr. Beatriz Moreno-Garcia for her help in understanding the management operations and serving as an invaluable point of contact to the farmers involved in this study. I would like to thank Dr. Benjamin Runkle for support and encouragement, as well as feedback on the project and insight into the world of rice research. I would like to thank Dr. Luca Doro for help in understanding the nitrogen balance aspect of the model, and I would like to thank Dr. Larry Purcell for taking time to be on my committee and provide feedback. I also want to thank the University of Arkansas Honors College for financial support through an Honors College fellowship.

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8. Appendices

Appendix 1: Control file as used for scenario simulations.

Select by Record Number: 4 | Select by Control Record Name: Rice2018

Edit Record

	EPIC	Varable	Default	Current	New
1	NBYR	Years of simulation duration	40	39	
2	IYR0	Beginning year	1960	2001	
3	IMO	Beginning month	1	1	
4	IDA	Beginning day	1	1	
5	IPD	Print code	2	2	
6	NGN	Weather input code	2345	2345	
7	IGN	Number of random number cycles	0	0	
8	LPYR	Leap year considered	0	0	
9	IET	Potential ET equation	4	1	
10	ISCN	Stochastic CN estimator code	1	1	
11	ITYP	Peak rate estimate code	1	1	
12	ISTA	Soil profile code	0	0	
13	IHUS	Automatic Heat Unit scheduling	0	0	
14	NVCN0	Variable daily CN or non-varying CN	0	0	
15	INFL0	Runoff Q estimation methodology	0	0	
16	MSNP	Nutrient/Pesticide output file	0	0	
17	IERT	Enrichment Ratio method for EPIC or GLEAMS	0	0	
18	LBP	Soluble Phosphorus runoff estimate	0	0	
19	NUPC	N and P plant uptake concentraion code	1	1	

Delete Record

Set All to Default

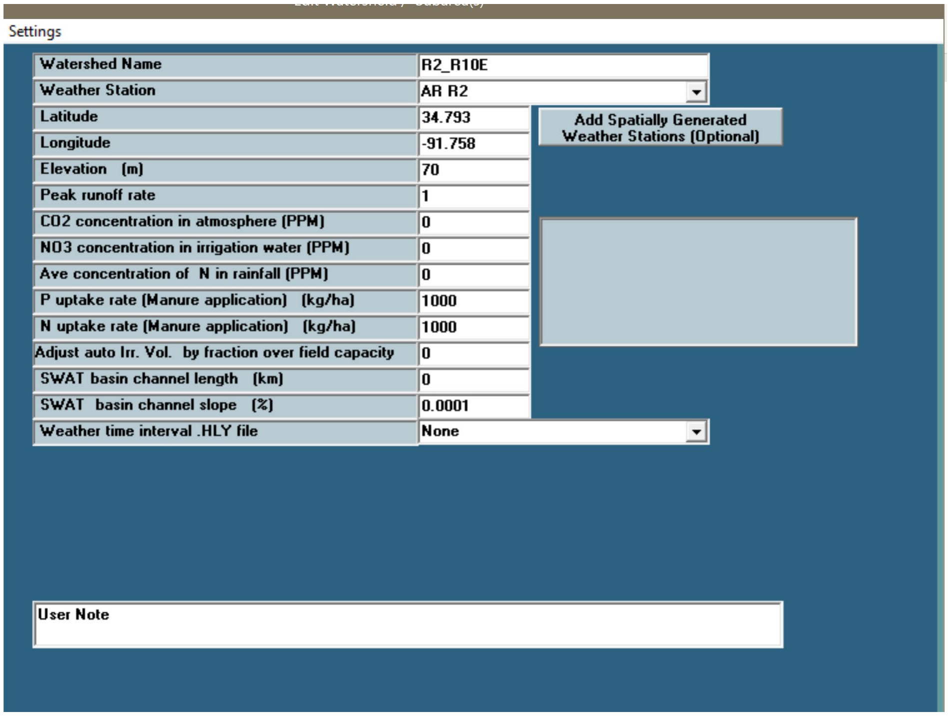
Appendix 2: Weather Station Data for R2.

Choose a Weather Station to edit: AR R2

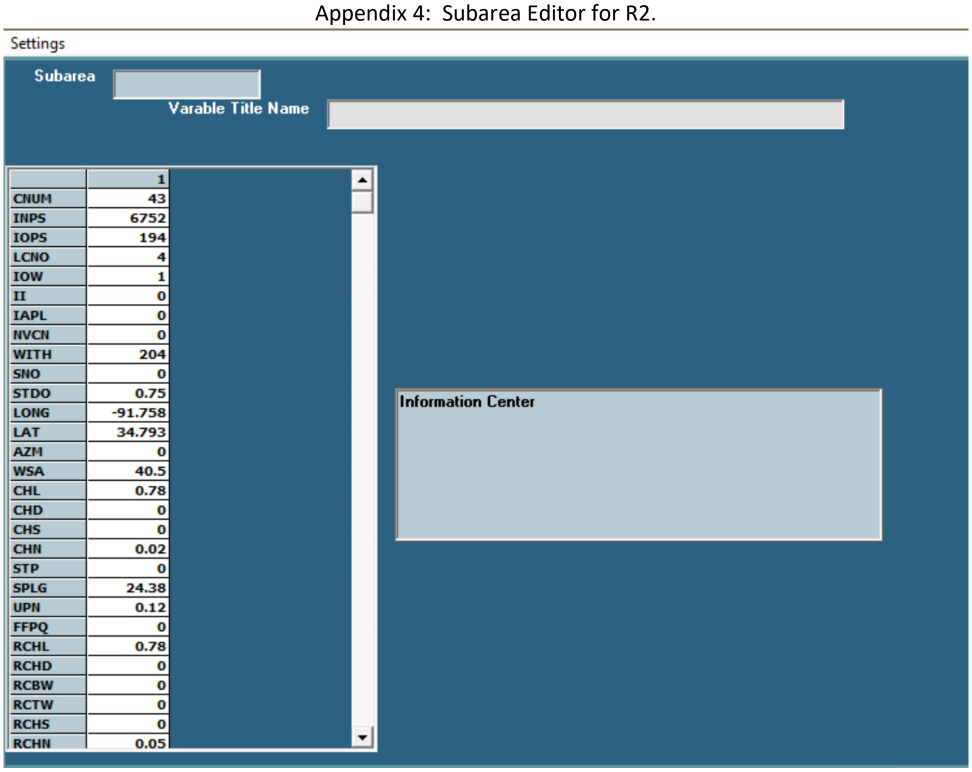
Add A New Weather Station

	Jan. Default	Jan. Current	Jan. New	Feb. Default	Feb. Current	Feb.
Days with rain (days)		7.95			8.24	
Precipitation (mm)		84.57			95.51	
Probability of wet day following dry		0.184			0.218	
Probability of wet day following wet		0.466			0.472	
Solar radiation (MJ/m2)		0			0	
Relative humidity / Dew point		0			0	
Standard deviation - Minimum temp. (C)		5.38			5.32	
Standard deviation - Maximum temp. (C)		6.36			6.88	
Standard deviation - Precipitation (mm)		11.02			11.17	
Skew coefficient - Precipitation		1.886			1.475	
Temp. Minimum (C)		-0.46			1.48	
Temp. Maximum (C)		9.52			12.06	

Appendix 3: Watershed Editor for R2.



Appendix 4: Subarea Editor for R2.



Appendix 5: Management Editor.