Return on investment in irrigation practices in response to the rate of adoption on an agricultural landscape

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Abstract

Concerns about groundwater depletion from conventional agricultural irrigation in the Mississippi Delta have led to the technological innovation of more-efficient irrigation practices. With Arkansas being the largest producer of rice and the tenth largest producer of soybeans in the United States, the irrigation demand of these crops has put pressure on producers to find ways to irrigate more efficiently. Research into water conserving irrigation techniques has helped preserve water resources, maintain yields, and maximize farm profits. As groundwater levels in the Delta continue to decrease, the price of pumping water increases, making the prospect of investment in new technologies more attractive. The paper will address potential returns on investment in efficient irrigation practices for furrow irrigated soybeans and flood irrigated rice. The depletion of the aquifer and the return on investment from efficient irrigation practices depends on the well-pumping decision of farms across the landscape. More farms adopting the efficiency-enhancing practices will increase the return on investment in those practices because these methods stabilize groundwater levels across the landscape. We explore how the rate of adoption of efficient irrigation practices on the landscape ultimately influence the return on investment.

Keywords: Irrigation, Groundwater conservation, Surface water delivery

JEL Classifications: Q15, Q24, Q25

Introduction

Agriculture in the Mississippi Delta relies heavily on the use of groundwater irrigation. The groundwater made available by the aquifer in this area has led to Arkansas being the number one producer of rice and the tenth largest producer of soybean in the nation. This heavy reliance on groundwater is leading to farmers paying the price of overproduction. As the groundwater level continues to recede each year as the aquifer is perpetually depleted, producers are having to invest more money in groundwater pumping than ever before. Growing concerns for groundwater availability have led to an increase in the use of water conserving irrigation systems. This transition to water conservation systems is due to both the environmental and economic investment of these technologies. Although irrigation reducing techniques may have a positive impact on groundwater availability, these techniques must also be economically beneficial. Producers make decisions mainly on the economic returns that the irrigation systems generate. The rate of adoption of efficient irrigation techniques will have an impact on aquifer depletion into the future. Not only does this rate of adoption reduce water use across the Delta, but it also reduces the cost of water pumping for other farmers in the area, therefore increasing returns on investment.

This model will look to factor in adoption rates across the Mississippi Delta when comparing conventional irrigation systems with two efficient irrigation techniques for two irrigation intensive crops: rice and soybean. The two water-conserving irrigation techniques include a soybean package based on the Mississippi State University RISER program and a rice package that uses a zero-grade irrigation system. Each package is compared to conventional irrigation systems in three different aspects: 1) yield produced, 2) water consumption, and 3) set up costs. The model then maps the change in yield, water use, and aquifer level over 10-year periods for a total of 30 years for each different scenario and each different crop type. The total farm benefit is recorded every 5 years for the 30 year time period. The model will look to encourage the use of the irrigation reduction packages for the conservation of the aquifer and the economic benefit of the producer.

The model will use cells to represent each site across the study area. These cells will be used to estimate both the aquifer depletion and economic returns at each cell based on the irrigation packages that have been selected. By calculating the overall values for each cell in the study area, it is possible to understand the total depletion volume of the aquifer and total economic benefits for producers. The rate which the aquifer depletes supply will have an impact on the groundwater pumping costs. By taking the total yield of each crop and using market prices, it is possible to calculate the revenue for each cell. The revenue minus the costs then gives the total economic benefit for each cell. The model also maps the adoption rate of the efficient irrigation practices to determine the effects on the aquifer volume and groundwater pumping costs over the study area. The greater the adoption, the less the aquifer will deplete; therefore, pumping costs will be reduced, and the economic returns will be increased.

The following section will describe the parameters of the model and the map of the changes in water use, yields, and returns. The rates of diffusion required to map the adoption rates of the irrigation methods will also be described. Following the description of the adoption rates will be details regarding the data used for the model. Then, after the results, discussion of the results and conclusions will conclude.

Methods

The model will use different cells (*m*) to track aquifer volume, groundwater pumping, and yields based on adoption rate of irrigation practices for soybean and rice. The timeframe will be over a 30-year period from 2016 to 2046.

Land Constraint

The cumulative amount of land used (*j*) is tracked for land types (*n*) used for each of the crops in the study, which are soybean and rice, using the different irrigation technologies (k). These technologies include conventional for rice and soybean, RISER program for soybean, and zero-grading for rice, non-irrigated sorghum, and the Conservation Reserve Program (CRP). The tracking of land used, land type, and technologies will be tracked over a given period (*t*) at each site (*i*) using the formula L_{ijk} (*t*). The land constraint formula will only allow for the amount of land used over time to be equal to the original land available for production at that specific site, giving the following (Eq.1):

(1) $$\sum_j \sum_k L_{ijk}(t) = \sum_j \sum_k L_{ijk}(0) .$$

A constraint included in the land balance equation is the historical maximum and minimum crop specific acreage, ($L\min_j \le \sum_i \sum_k L_{ijk}(t) \le L\max_j$). The land constraints include limits on crop rotation, capital availability, the suitability of land, and the knowledge of producers in using different crops. The optimization of economic returns and maximizing aquifer volume are subject to the land balance equation.

Water Constraint

The different use of crops and irrigation technology (*k*) changes the irrigation demanded, wd_{jk}. The irrigation demanded is the total need for irrigation after natural rainfall. The amount of groundwater available in acre-feet stored in the aquifer below site (*i*) at the end of the time period (*t*) is the variable $AQ_i\ (t)$. The amount of water pumped from the ground for irrigation use is $GW_i\ (t)$ during period *t*. Precipitation, underlying aquifers, and streams all contribute to the natural recharge of groundwater at each site (*i*) over a given period, annotated as nr_i.

To get a true representation of the volume of water in the aquifer, the model must account for water that flows underground from site (*i*) into the aquifer in site (*k*). To account for the groundwater that is then pumped from site k, a negative quadratic function of hydraulic diffusivity and distance between the sites (*i*) and k is annotated as p_{ik}. The total water that runs out from site (*i*) is $\sum_{k=1}^{m} p_{ik} GW_k(t)$.

The total cost to pump an acre-foot of groundwater from site (*i*) in time period (t) is $GC_i\ (t)$. Total pumping costs are dependent on three different aspects: 1) the cost of using a pump to lift one acre foot of water, c^p, 2) the depth of the aquifer to reach the groundwater, dp_i, and 3) the capital costs of constructing and maintaining a well per acre-foot of water, c^c. As the groundwater availability declines due to the aquifer depletion rate, the cost to pump water from the well increases due to an increase capital costs to extract the water.

During each period for each crop grown at the site, the total amount of water used for irrigating the crops must be less than the total amount of groundwater that is pumped (Eq. 2). The aggregate volume of water present in the aquifer is dependent on the volume of water in the aquifer from the previous period plus the amount of water that is acquired from natural recharge minus the volume of water pumped by neighboring sites (Eq. 3). The cost of pumping groundwater for irrigation is calculated by taking the cost of pumping one acre-foot of water, c^p, multiplied by the depth to reach the groundwater, which is subject to depleted distance of the aquifer below the site (i), plus the capital costs of constructing and maintaining the well, c^c (Eq. 4).

(2) $$\sum_j \sum_k wd_{jk} L_{ijk}(t) \leq GW_i(t) ,$$

(3) $$AQ_i(t) = AQ_i(t-1) - \sum_{k-1}^{m} P_{ik} GW_k(t) + nr_i ,$$

(4) $$GC_i(t) = c^c + c^p \left[dp_i \frac{(AQ_i(0) - AQ_i(t))}{\sum_j \sum_k L_{ijk}(0)} \right] .$$

Economic Returns Objective

Predicting relative price changes can be difficult; furthermore, the influence price changes have on water and crop decisions are irrelevant to aquifer depletion. Thus, the price per unit of crop is held constant in real terms over time, pr_j. When considering the cost to produce one acre of each crop, the water use costs are excluded. The water use costs are dependent on the type of crop (*j*) and the irrigation technology used (*k*), which are both constant in real terms to give the annotation ca_{jk}. The irrigation technology (*k*) to yield crop (*j*) per acre at site (*i*) is y_{ijk} and is held constant. To find the net value per crop (j) then $pr_j y_{ijk}$ - ca_{jk}, where the costs for water pumping is excluded. A discount factor is also used to maintain consistent values over time, δ_t .

The equation for maximizing net returns of farm production is

(5) $$\max_{L_{ijk},GW_i(t)} : \sum_{t=1}^{T} \delta_t \left[\sum_{i=1}^{m} \sum_{j=1}^{n} (y_{ijk} - ca_{jk}) L_{ijk}(t) - GC_i(t) GW_i(t) \right].$$

Technology adoption constraint

The adoption of the new irrigation technology packages will be constrained at site level and landscape level. At the site constrained scenario the total acreage of conventionally irrigated rice *ri* and acreage of conservation irrigated rice *rp* at each site *i* at time period *t*, plus the total acreage of conventionally irrigated soybean *so* and acreage of conservation irrigated soybean *sp* at each site *i* at time period *t*, is less than or equal to the total initial land acreage multiplied by the cumulative adoption proportion *Ad* at time *t* (Eq. 6).

(6) $$L_{i,ri,rp}(t) + L_{i,so,sp}(t) \leq L_{i,ri}(0) Ad(t)$$

At the landscape constrained rate of adoption the total change of conventionally irrigated rice *ri* and conservation irrigated rice *sp* at all sites *i* at time period *t*, plus the total change in conventionally irrigated soybean *so* and conservation irrigated soybean *sp* across all sites *i* at time period *t*, will be less than or equal to the total initial land acreage across all sites *i* multiplied by the cumulative adoption proportion at time *t* (Eq. 7).

(7) $$\sum_i L_{i,ri,rp}(t) + L_{i,so,sp}(t) \leq \sum_i L_{i,ri}(0) Ad(t)$$

Policies

A variety of policy options are considered for groundwater conservation. They include cost share options for the rice and soybean irrigation technology packages by modifying ca_{jk}, limiting groundwater use, taxing groundwater pumping *GC*, and a subsidizing CRP. The cost share for the rice package (zero-grade leveling) and soybean package (soil moisture sensors, surge valves, and poly-pipe planner) is set at 60% based on the rates from the Natural Resource Conservation Service's (NRCS) Agricultural Water Enhancement Program (NRCS 2014). The limit on groundwater use at each site (*i*) is to be no greater than the current groundwater use at each site (*i*) for all periods (*t*). A tax on groundwater pumping costs of 1% will be used to achieve groundwater conservation similar to the limits on groundwater use. A subsidy on CRP will be set at 1% to achieve groundwater conservation that is similar to liming groundwater use.

Data

The study area is made up of 2,724 sites across 11 counties in Arkansas. These sites are within three eight-digit hydrological unit code (HUC) watersheds (Figure 1). The Arkansas Delta has been selected due to the unsustainable groundwater pumping that has been occurring in the area. The various sites allow for a better understanding of farmer decisions on crop allocation and water use over a spatially differentiated landscape. The initial crop acreage over each cell comes from the Crop Land Data Layer from 2013 (Johnson and Mueller, 2010). More detail regarding that crop acreage can be seen in supporting information (Table S1). For crop yields, a proxy of the average county crop yields is used for each of the crops. Costs associated with the production of crops and the maintenance and ownership of irrigation technologies and wells are held at a constant rate in inflation-adjusted terms. A real discount rate of 2% is based on a 30-Year Treasury Bond yield over the last decade of 5% (US Department of the Treasury, 2012), minus an expected inflation rate of 3%.

Groundwater use and recharge

The depth to the water table and the initial saturated thickness of the aquifer is taken from the Arkansas Natural Resources Commission (ANRC 2012). This information can be found in supporting information Table S1. A depletion of the aquifer occurs as the saturated thickness of the aquifer begins to reduce. The initial size of the aquifer is the product of the saturated thickness of the aquifer multiplied by acreage. A calibrated model of recharge from 1994 to 1998 from natural precipitation and surface streams is used to determine the natural recharge (nr_i) of the Alluvial aquifer (Reed, 2003). As groundwater is pumped from surrounding areas, the size of the aquifer at that specific cell is reduced. With groundwater flowing from surrounding aquifers into the depleted cells, the volume of water is dependent upon diffusivity of the aquifer and the distance from the pump. By taking the hydraulic diffusivity and dividing it by the square of the shortest distance between the pumped well and the nearby aquifer, this defines how much pumping from a nearby well depletes the aquifer. Hydraulic diffusivity can be defined as the ratio of the transmissivity and the specific yield of the unconfined alluvial aquifer (Barlow and Leake 2012). Transmissivity is the product of hydraulic conductivity and saturated thickness, while the hydraulic conductivity is the rate of groundwater flow per unit area under a hydraulic gradient. Specific yield is a dimensionless ratio of water drainable by saturated aquifer material to the total volume of that material. The hydraulic conductivity comes from spatially coarse pilot points digitized by Clark, Westerman and Fugitt (2013). The closer the distance to a pumped well and the larger the hydraulic diffusivity is, the greater the aquifer depletion is beneath the specific cell.

Farm Production

Table S2 includes the cost to produce each crop, which is derived from the 2012 Crop Cost of Production estimates (Division of Agriculture, 2012). These costs do not include the cost of irrigation. The costs of irrigation include the fuel, lube and oil, irrigation labor, and poly pipe for border irrigation plus the levee gates for the flood irrigation of rice, which are all dependent on the amount of water pumped (Hogan et al., 2007). Capital costs of irrigation, which are not dependent on the amount of water pumped, include wells, pumps, gearheads, and power units, which are charged on a per acre-foot basis.

During the growing season, the average irrigation required for soybeans is an acre foot full, excluding natural rainfall. For rice, the irrigation required is greater than three acre-feet (Powers, 2007). Crop prices are determined by using the five-year average of December futures prices for harvest time contracts for all crops (GPTC, 2012). The parameters, detailed in Table S2, are held constant over time, as it is difficult to understand the tradeoff between groundwater scarcity and economic returns when prices, yields, and production change over time.

The capital costs associated with irrigation are assumed to be paid off over time; these costs are then divided by the acre-feet of water that is pumped from the well to give a value for capital costs per acre foot applied. The cost of fuel per acre foot of water from the aquifer is dependent on amount of fuel that is needed to pump the water. The cost of fuel per acre foot of water from the aquifer is subject to the depth of the water table. Diesel use ranges from 13 gallons of diesel per acre foot for a 100 foot well to 26 gallons of diesel per acre foot for a 200 foot well (Hogan et al., 2007). The diesel needed per acre-foot for pumping water to and from the reservoir is 6 gallons (Hogan et al., 2007). We use $3.77 per gallon of diesel fuel (EIA, 2012) and add 10% to fuel cost to account for oil and lube for irrigation equipment (Hogan et al., 2007).

Irrigation Technologies

The conventional irrigation technique for soybeans in the Arkansas Delta is the use of furrow irrigation by passing water through poly-pipes. In this model, the alternative irrigation method for soybean will be the Row-crop Irrigation Science and Extension Research (RISER) program that has been created by researchers as Mississippi State University. This combination of irrigation technology will be known as the Soybean Package. The program looks to irrigate row-crops more efficiently and economically by maximizing profits and minimizing water usage (Mississippi State University Extension, 2013)**.** The program uses a combination of tools, which include the Mississippi Irrigation Scheduling Tool (MIST) and soil sensors. To optimize water efficiency, the Pipe Hole and Universal Crown Evaluation Tool (PHAUCET), which is a computerized program that determines the appropriate hole size for poly-pipes to irrigate crops, is used.

In the Arkansas Delta, the conventional rice irrigation system is flood irrigation. The alternative method used in this model will be zero-grade irrigation. This irrigation technique looks to use precision leveling combined with drainage ditches to increase irrigation efficiency and improve water management (Hignight, Bradley, & Anders, 2009). This alternative irrigation technique will be known at the Rice Package.

Both the Soybean Package and the Rice Package result in alterations in yield, water use, and technology cost compared to conventional irrigation techniques. These changes are quantified as a percentage compared to conventional methods; these parameters can be seen in the supporting information Tables S3, S4, and S5. Literature to quantify the changes in yield, water use, and technology cost can also be found within these tables; the information provided is the best possible representation of how the alternative irrigation method differs from the conventional techniques. Although alternative technologies are used in the study area, the model assumes that the conventional irrigation method is used initially to get the best understanding of trade-offs between farm profits and aquifer conservation when adopting the alternative irrigation techniques.

Rate of adoption

The rate of adoption of the irrigation conserving technologies is calculated for both a minimum adoption rate scenario and a maximum adoption rate. The calculation for each uses an origin acceptance level of 0.1. This figure represents a minimum adoption rate of 10%, which is the point at which adoption is carried out after an experimental stage (Griliches, 1957). This origin acceptance level value is used for both minimum and maximum scenarios. The rate of adoption also accounts for rate of acceptance. This is the rate at which people will adopt the technology, the figure for this in the minimum adoption scenario is 0.32**.** The rate of acceptance for the maximum adoption scenario is 0.5. A ceiling figure is also used for the rate of adoption, which is the maximum point at which the technology will be adopted. In this model, the ceiling figure for the minimum adoption scenario will be 0.55. For the maximum adoption rate scenario, the ceiling figure is 0.85. These values are taken from (Griliches, 1957). This paper reports a logistic trend function by state for technological adoption. The origin acceptance level, rate of acceptance, and ceiling figure are then used to calculate both the marginal proportion and the cumulative proportion over the time period of 30 years, where marginal proportion is Mp, cumulative proportion is Cp, origin acceptance level is O, rate of acceptance is Ra, and the ceiling figure is C. At time 0, the Cp is equal to O. For years 2 to 30, the marginal proportion can be calculated using the cumulative proportion from the previous year, Cp_p, which can be seen in (Eq. 8). The cumulative proportion for years 2 to 30 also uses the cumulative proportion from the previous year, which is added to the marginal proportion for the current year, Mp_c. This equation can be seen in (Eq. 9).

$$Mp = O \times Cp_{t-1} \times \left(\frac{1 - Cp_{t-1}}{C} \right), \quad (8)$$

$$Cp = Mp_t + Cp_{t-1}. \quad (9)$$

The calculations were carried out for both the minimum and maximum adoption rate scenarios; the cumulative proportions can be seen in Figure 1 for the minimum adoption scenario and Figure 2 for the maximum adoption rate scenario.

Results

Table 6 shows the results of the model for changes in land use, water use and economic conditions over the 30-year time frame. The results use baseline data to compare changes with a minimum and maximum adoption rate scenario. The results show that the baseline land use for conventionally irrigated rice is 210,000 acres, conventionally irrigated soybean is 343,000 acres, dry land sorghum is 45,000 acres, and CRP is 92,000 acres. There is no conservation irrigation acreage for the baseline data. For low site constrained rate of adoption, the land use figures change when there are 97,000 acres of conventionally irrigated rice and 362,000 acres of conventionally irrigated soybean. There are 121,000 acres of conservation irrigated rice and no acreage for conservation soybean. Dryland sorghum drops to 44,000 acres, and CRP also drops to 65,000 acres. For high site constrained rate of adoption the land use for conventionally irrigated rice drops further to 33,000 acres, with conventionally irrigated soybean increasing to 374,000 acres. The conservation irrigated rice increases to 188,000 acres, and conservation irrigated soybean remains at 0 acres. Dryland sorghum remains at 44,000 acres, and CRP reduces further to 51,000 acres. For low landscape constrained rate of adoption, the land use for conventionally irrigated rice was 97,000 acres and conventionally irrigated soybean was 372,000 acres. The conservation irrigation for rice is 121,000 acres and for conservation irrigation soybean there is 0 acres. Dryland sorghum is 45,000 acres and CRP is 51,000 acres. The high landscape constrained rate of adoption shows conventionally irrigated rice dropping to 32,000 acres and conventionally irrigated soybean increasing to 381,000 acres. For conservation irrigated rice, the land use increases to 188,000 acres; the land use for conservation irrigated soybean remains at 0 acres. Dryland soybean drops to 44,000 acres, and CRP falls to 45,000 acres.

The baseline groundwater use over the 30-year period is 5.2 thousand acre feet. In the low site constrained rate of adoption, this figure drops to 4.8 thousand acre feet, and high site constrained rate of adoption groundwater use reduces further to 4.4 thousand acre feet. The low landscape constrained rate of adoption figure is 4.8 thousand acre feet of groundwater use, while the high landscape constrained rate of adoption has a figure of 4.6 thousand acre feet. The aquifer volume at the baseline scenario over the 30-year period with no conservation is 28 thousand acre feet. For low site constrained rate of adoption, the aquifer volume increases to 30 thousand acre feet; the high site constrained rate of adoption increases to a greater rate of 32 thousand acre feet. The low landscape constrained rate of adoption has an aquifer volume of 30 thousand acre feet, and the high landscape constrained rate of adoption is 31 thousand acre feet. In the baseline scenario, the present value of economic returns is $2,082 million. For low site constrained rate of adoption, the present value of economic returns is $2,246 million, and the high site constrained rate of adoption the value is $2,341 million. For low landscape constrained rate of adoption, the present value of economic returns is $2,275 million, and the high landscape rate of adoption value is $2,363 million. The return on investment in the baseline scenario for every dollar spent is $0.416. In the site constrained low adoption scenario, the return on investment is $0.425, and the high adoption rate scenario return on investment is $0.429. For landscape constrained low rate of adoption, the return on investment is $0.426, and the high rate of adoption return on investment is $0.429.

Table 7 shows the results for various policy options at both site and landscape level on the land, water, and economic outcomes. For the low scenario of site constrained rates of adoption, the acreage of rice is 219,000 acres, this acreage remains the same for all polices at site constrained scenarios. The acreage for soybeans is 362,000 acres which is remains the same for both cost share scenarios. The acreage of non-irrigated land at site constrained rate of adoption is 109,000 acres, this remains the same for cost-share policy options. The aquifer volume in 2046 is 30,120 thousand feet, and farm net returns are $2,246 million. There is no government revenue and no groundwater conservation cost. The policy option of subsidizing the rice package technology at site constrained rate of adoption has an aquifer volume of 30,120 thousand acre-feet, this remains constant for cost share of the soybean package. Farm net returns of $2,261 million which is higher than the baseline scenario. The government revenue is -$21.48 million, and the cost of groundwater conservation is -$15 per acre foot. By subsidizing the soybean package at site constrained rate of adoption farm net returns are the same as the baseline scenario. The government revenue is -$0.88 million and there is no conservation cost. By limiting groundwater use at site constrained rate of adoption the acreage of soybean falls to 360,000 acres and the non-irrigated land increases to 111,000 acres. These acrages remain constant for taxing groundwater used and subsidizing CRP. The aquifer volume is increased to 30,180 thousand acre feet and farm net returns are lower at $2,244 million. There is no government revenue and the cost of groundwater conservation is $2 per acre foot. A tax on groundwater use at site constrained rate of adoption results in the aquifer volume increases to 30,230 thousand acre feet and farm net returns decrease to $2,237 million. The government revenue is $12.3 million, and the groundwater conservation cost is $9 per acre foot. Subsidizing CRP at site constrained rate of adoption resulted in the aquifer volume increasing to 30,210 thousand acre feet and the farm net returns increasing to $2,276 million. The government revenue was -$0.5 million, and the cost of groundwater conservation is -$30 per acre foot.

For the low landscape constrained rate of adoption the acreage for rice was 219,000 acres for all policy options, with the exception of taxing groundwater use where the value reduced to 218,000 acres. The acreage for soybean was 372,000 acres and for non-irrigated land the acreage was 98,000. The aquifer volume is 29,980 thousand acre-feet and farm net returns are $2.27 million. For the cost share scenario the acreage of soybean falls to 364,000 acres and non-irrigated land increases to 106,000 acres. The aquifer volume decreases to 29,960 thousand acre-feet and farm net returns increase to $2,286 million. The government revenue is -$21.46 million, and the cost of groundwater conservation is -$12 million per acre-foot. A cost share scenario for the soybean package on a landscape constrained rate of adoption results in soybean and non-irrigated land acreage staying the same as the low adoption rate scenario. The aquifer volume and farm net returns also the same as the low adoption rate scenario. Government revenue is -$0.826 million, and there is no groundwater conservation cost. Limiting groundwater use at landscape constrained rate of adoption results in soybean acreage falling to 370,000 acres and non-irrigated land increasing to 100,000 acres. The aquifer volume increases to 30,040 thousand acre-feet and farm net revenues decrease to $2,273 million. There is no government revenue and the cost of groundwater conservation is $2 per acre-foot. By taxing groundwater use at landscape constrained rate of adoption the acreage for rice falls to 218,000 acres, soybean acres also fall to 362,000 acres and non-irrigated land increases to 109,000 acres. The aquifer volume is increased to 30,130 thousand acre-feet and farm net revenues are reduced to $2,245 million. Government revenue is $1.24 million and groundwater conservation cost is $23 per acre foot. Subsidizing CRP at landscape constrained rate of adoption results in soybean acreage falling to 370,000 acres and non-irrigated land increasing to 100,000 acres. The aquifer volume increases to 30,040 thousand acre-feet, farm net returns increase to $2,276 million, government revenues are -$0.538 million, and the groundwater conservation cost is -$1 per acre-foot.

Discussion

At both site and landscape constrained scenarios, the yields in conventionally irrigated rice are reduced and the yields in rice grown with conservation irrigation technology increases. This result is due to the irrigation rice package reducing irrigation by 40% compared to the conventional irrigation technique. The yield and technology cost parameters are the same for conventional and conservation irrigation technology. For soybean production there is an increase in conventionally irrigated yields and no yields for conservation irrigation technology for both site and landscape constrained scenarios. These dynamics can be explained by the parameters for the conservation technology: although water use reduction of 28.8% is expressed, the technology cost increase of 1% and yield levels remain the same. This means that the cost increase, which will impact economic returns, has a greater impact than the reduction of groundwater pumping cost. Overall, the groundwater use is reduced over the site and landscape constrained scenario with the higher the adoption rate, as groundwater use is reduced, the less groundwater is used. This is explained by the increase in conservation irrigated rice over the sites and landscape. Despite an increase in conventionally irrigated soybean and no conservation irrigated soybean, the reduction in water use for rice offsets the soybean yields, and the irrigation for rice production is much more intensive than soybean production. The acreage of land in dryland sorghum remains consistent at high and low adoption rates in both site and landscape constrained scenarios. Although only rice production takes advantage of these methods, water use is reduced from both irrigation technologies, explaining why no change in the acreage of dryland crop in the study area occurs. Since rice is a much more profitable crop to produce, the majority of the land is switching to the conservation irrigation method for rice production, as there is a greater reduction of water use at no extra cost. The overall groundwater use is reduced, resulting in the aquifer volume increasing at both site and landscape constrained scenario. The aquifer volume shows greater increase with a higher adoption rate with both scenarios. The greater the adoption rate of the irrigation conserving technology, the more groundwater is conserved, which leads to a greater aquifer volume. The reduction in groundwater use also results in greater economic benefits in both site and landscape constrained scenarios. As there has only been a switch to the rice package, the cost of water use has not changed from the conventional method. The reduction in groundwater usage means there are lower groundwater pumping costs; therefore, greater economic returns and a greater return on investment are experienced. A higher adoption rate at both site and landscape constrained scenario results in a greater return on investment. This relationship is due to an increase in the aquifer volume and the groundwater level. All producers will benefit regardless of adopting the technology, as producers who do not adopt the technology are benefiting from the reduced pumping costs associated with a high adoption rate.

At site constrained rate of adoption, introducing a cost share policy on the rice package would result in greater farm net returns due to the cost of groundwater conservation being reduced. This policy would have no impact on the aquifer level or acreage and would cost the government

$21.48 million. This policy option would be attractive to farm owners are they would see increased revenues, but the policy would not be attractive from a government point of view as it would increase costs with no impact on the aquifer. The cost share of the soybean package is less effective as there is no change in acreage, aquifer volume or farm net returns and there would be no conservation cost. This would cost the government $0.88 million with no benefits for the farmer or environment making the policy a non-feasible option. Limiting groundwater use would influence the landscape by decreasing in soybean acreage and increasing non-irrigated land. The aquifer volume would also increase due to the reduction in the irritated soybean acreage. The farm net revenues have decreased because of an increase in groundwater conservation cost of $2 per acre-foot. There would be no government revenue, but it may still be an attractive policy option from a conservation point of view as there is an increase in aquifer volume. It would be less attractive to farmers as there is a decrease in net revenues. The tax on groundwater use increases the aquifer volume to greater levels than the limit on groundwater use and also generates a government revenue of $12.3 million. The tax would result in farm net revenues decreasing at a greater amount than the limits on groundwater use. This is due to the groundwater conservation cost of $9 per acre-foot. This policy would also be beneficial from a conservation point of view and for government revenue. It would be greater opposed by farmers due to the greater reduction in farm revenue. A subsidy on CRP would increase the aquifer volume to a level which is greater than the limits on groundwater use and lower than a groundwater tax. Unlike the other policy scenarios the policy would also increase farm net returns which is positive from both a conservation and farming perspective. The increase in farm revenues comes from a reduction on groundwater conservation costs of $30 per acre-foot. The policy would cost the government $0.5 million which over a 30 year period may be a good investment with positive outcomes for both the environment and farm net revenues.

At a low landscape rate of adoption the cost share in the soybean package has no impact on land use, aquifer volume or farm net returns. There is no groundwater conservation at a cost to the government of $0.825 million. This would not be a feasible policy option as it would cost the government for there to be no positive benefits economically or environmentally. The limit on groundwater use reduces the amount of soybean acreage, this is due to soybean being a less profitable crop compared to rice. The loss in soybean acreage then moved into non-irrigated land which causes the aquifer level to increase. As there is less soybean acreage and more non-irrigated land, farm revenues are decreases and soybean is more profitable than the non-irrigated rice, the limit on groundwater use would also increase the cost of pumping groundwater which negatively impacts farm revenues. When taxing groundwater use at landscape level the rice acreage decreases unlike at site level when yield remain the same. The acreage of soybean is also reduced more than at the site level and non-irrigated land is greater at landscape level. This results in a greater aquifer volume and decreased farm revenues. This is due to the groundwater conservation costs being much higher at landscape level compared to site level. These higher groundwater conservations costs shift the landscape to have more non-irrigated crops and therefore reduce the net farm revenues and increase the aquifer volume. The government revenue at the landscape constrained scenario is a less then the revenue in the site constrained scenario. This would make the trade-off between farm net revenues and aquifer conservation a more contentious issue due to the small government revenues. Subsidizing CRP reduces acreage of soybean and increases the acreage of non-irrigated land compared to the baseline. Like at the site constrained scenario both the aquifer volume and farm net returns are increased, but at a decreased scale. This is due to the groundwater conservation costs being reduced, the subsidy would also cost the government $0.538 million. Like at site level, this would be an attractive policy option due to the economic and environmental benefits at a low cost to the government.

Conclusion

Over the 30-year study period of the model, the results show that there is a change in crop use, groundwater use, aquifer volume, and return on investment with the introduction of irrigation conservation technology. The study has shown that even the slightest increase in the cost of irrigation technology can affect the landscape and aquifer level based on the land coverage of conservation irrigated soybean. We also conclude that a higher adoption rate of the irrigation conserving technology can have a positive impact on both farm returns, aquifer volume and returns on investment at both site and landscape constrained scenarios. The benefits of a higher adoption rate are greater at the landscape constrained scenario compared to a site constrained scenario as the adoption rate benefits the overall landscape more since producers who do not adopt the technology reap the benefits of the increased aquifer volume and farm returns as pumping costs are reduced. Another conclusion is that many of polices create a tradeoff between environmental and economic benefits. The policy that did not have this tradeoff was subsidizing CRP because this increased both aquifer volume and farm net returns at a small cost to the government, making it the most feasible policy option. Limitations of the study include the uncertainty in the parameters used in the model to predict the outcome over a 30 year period. This uncertainty in current parameters can be limited using a sensitivity analysis, however, the uncertainty in future prices for crops and unforeseen natural occurrences such as climate change are not taken into account in the model. The versatility of the model allows these uncertainties to be measured which could be a basis for future studies.

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Table 1. Descriptive statistics of the model data across the sites of the study area

Variable	Definition	Mean	Std. Dev.	Sum (thousands)
$L_{i,rice}$	Initial acres of rice	81	99	220,624
$L_{i,isoy}$	Initial acres of irrigated soybean	165	97	448,469
$L_{i,dsorg}$	Initial acres of dry land sorghum	7	23	20,017
$y_{i,rice}$	Annual rice yield (cwt per acre)	71	3	-
$y_{i,isoy}$	Annual irrigated soybean yield	43	3	
$y_{i,dsorg}$	Annual dry land sorghum yield	74	11.33	
dp_i	Depth to water (feet)	57	32	-
AQ_i	Initial aquifer size (acre-feet)	16,315	9,992	44,443
K	Hydraulic conductivity (feet per day)	226	92	-
nr_i	Annual natural recharge of the aquifer per acre (acre-feet)	0.45	0.19	1,225

Note: Number of sites is 2,724.

Table 2. Value of model parameters

Parameter	Definition	Value
pr_{rice}	Price of rice ($/cwt)	13.88
pr_{soy}	Price of soybeans ($/bushel)	11.80
pr_{sorg}	Price of sorghum ($/bushel)	4.20
ca_{rice}	Annual production cost of rice ($/acre)	646
ca_{isoy}	Annual production cost of irrigated soybean ($/acre)	349
ca_{dsorg}	Annual production cost of dry land sorghum ($/acre)	270
wd_{rice}	Annual irrigation per acre of rice	2.5
wd_{isoy}	Annual irrigation per acre of soybean	1
c^p	Cost to raise an acre-foot of water by one foot ($/foot)	0.55
δ_t	Discount factor	0.98
O	Origin acceptance level	0.1
Ra_{min}	Minimum rate of acceptance	0.32
C_{min}	Minimum ceiling	0.55
Ra_{max}	Maximum rate of acceptance	0.5
C_{max}	Maximum ceiling	0.85

Table 3 Conservation technologies and adjustment coefficients for yields relative to standard irrigation.

Crop	**Conventional**[1]	**Soybean package***	**Rice package****
Rice	1 .000	--	1.00 [3]
Full season irrigated soybeans	1 .000	1.00 [2]	--

* Soybean package is PHAUCET and Soil Sensors. ** Rice package is zero grade. [1] University of Arkansas 2014; [2] (Mississippi Sate University , 2014); [3] (University of Arkansas, 2016);

Table 4. Conservation technologies and adjustment coefficients for water use relative to standard irrigation.

Crop	**Conventional**[1]	**Soybean package**	**Rice package**
Rice	1 .000	--	0.60 [3]
Full season irrigated soybeans	1 .000	0.712[2]	--

[1]Univeristy of Arkansas 2014; [2] (Mississippi Sate University , 2014); [3] (University of Arkansas, 2016)

Table 5. Conservation technologies and adjustment coefficients for technology cost relative to standard irrigation.

Crop	**Conventional**[1]	**Soybean package**	**Rice package**
Rice	1 .000	--	1.00 [3]
Full season irrigated soybeans	1 .000	1.1076 [2]	--

[1] Univeristy of Arkansas 2014; [2] (Mississippi State University, 2016) [3] (Hignight, Bradley, & Anders, 2009)

Table 6. Land use, water, and economic conditions in 2046 for sensitivities on the rate of conservation technology adoption.

Crop and water conditions	Baseline (No Conservation Practice Adoption)	Site constrained rate of adoption		Landscape constrained rate of adoption	
		Low	High	Low	High
Land use (thousand acres)					
Conventionally irrigated rice	210	97	33	97	32
Conservation irrigated rice	0	121	188	121	188
Conventionally irrigated soybeans	343	362	374	372	381
Conservation irrigated soybeans	0	0	0	0	0
Dryland sorghum	45	44	44	45	44
CRP	92	65	51	54	45
Water conditions (thousand acre-feet)					
Groundwater use	5,200	4,800	4,400	4,800	4,600
Aquifer	28,000	30,000	32,000	30,000	31,000
Economic conditions ($M)					
Present value of economic returns	2,082	2,246	2,341	2,275	2,363
Return on investment	0.416	0.425	0.429	0.426	0.429

Table 7. Policies to encourage groundwater conservation for alternative adoption rates of conservation technologies

Policy	Rice (thousand acres)	Irrigated soybeans (thousand acres)	Non-irrigated land (thousand acres)	Aquifer, 2046 (thousand acre-feet)	Farm net returns, 30yr NPV [a] ($ millions)	Government revenue, 30yr NPV ($ millions)	Groundwater conservation cost [b] ($ per acre-foot)
Low – Site constrained rate of adoption	218	362	109	30,120	2,246	0	0
Cost share on rice package [c]	218	362	109	30,120	2,261	-21.48	No conservation
Cost share of soybean package [c]	218	362	109	30,120	2,246	-0.88	No conservation
Limits on groundwater use	218	360	111	30,180	2,244	0	$2
Tax on groundwater use [d]	218	360	111	30,230	2,237	12.3	$9
Subsidy on CRP	218	360	111	30,210	2,247	-1.1	1.11
Low – Landscape constrained rate of adoption	219	372	98	29,980	2,275	0	0
Cost share on rice package [c]	219	364	106	29,960	2,286	-21.46	No conservation
Cost share of soybean package [c]	219	372	98	29,980	2,275	-0.826	No conservation
Limits on groundwater use	219	370	100	30,040	2,273	0	$2
Tax on groundwater use [d]	218	362	109	30,130	2,245	1.24	$23
Subsidy on CRP	219	370	100	30,040	2,276	-0.538	$0.63

Note: All models use a profit objective, allow on-farm reservoirs and all conservation technologies, and there is no constraint on the aquifer magnitude. [a] The farm net returns include the payments to or receipts from the government because of the policy. [b] Groundwater conservation cost is calculated as the policy cost (which is the farm net returns in the baseline less the farm net returns plus government revenue for each policy scenario) divided by the change in aquifer level between the policy option and the baseline. [c] The 60% cost-share for rice package (zero-grade leveling) and soybean package (soil moisture sensors, surge valves, and poly-pipe planner) is based on the rates from the Natural Resource Conservation Service's (NRCS) Agricultural Water Enhancement Program (NRCS 2014). [d] We set the limit on groundwater use at each site to be no greater than the current groundwater use at each site for all periods. [e] We choose a tax on groundwater pumping costs (1%) to achieve groundwater conservation similar to the limits on groundwater use. [e] We choose a subsidy on CRP (1%) to achieve groundwater conservation similar to the limits on groundwater use.

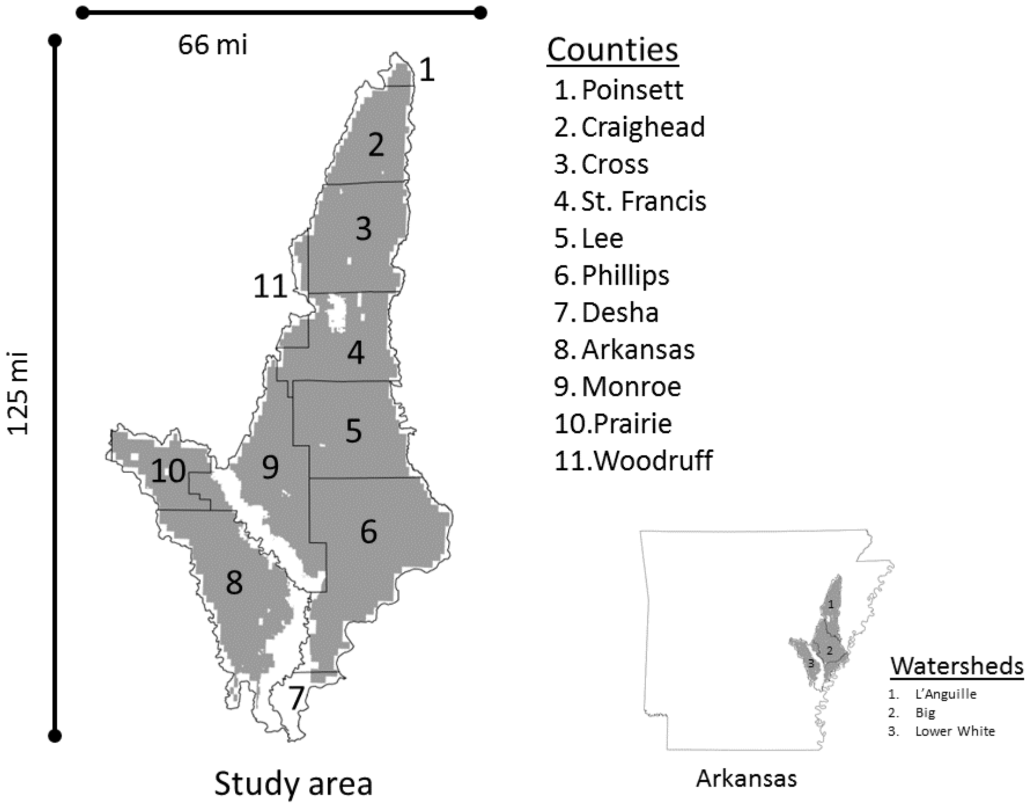

Figure 1. Three eight-digit HUC watersheds in the Mississippi Delta region of eastern Arkansas define the outer boundary of the study area. An eight-digit HUC defines the drainage area of the sub-basin of a river. County lines overlay the study area. Public land and urban areas are excluded. The location of the study area within the state of Arkansas is shown.

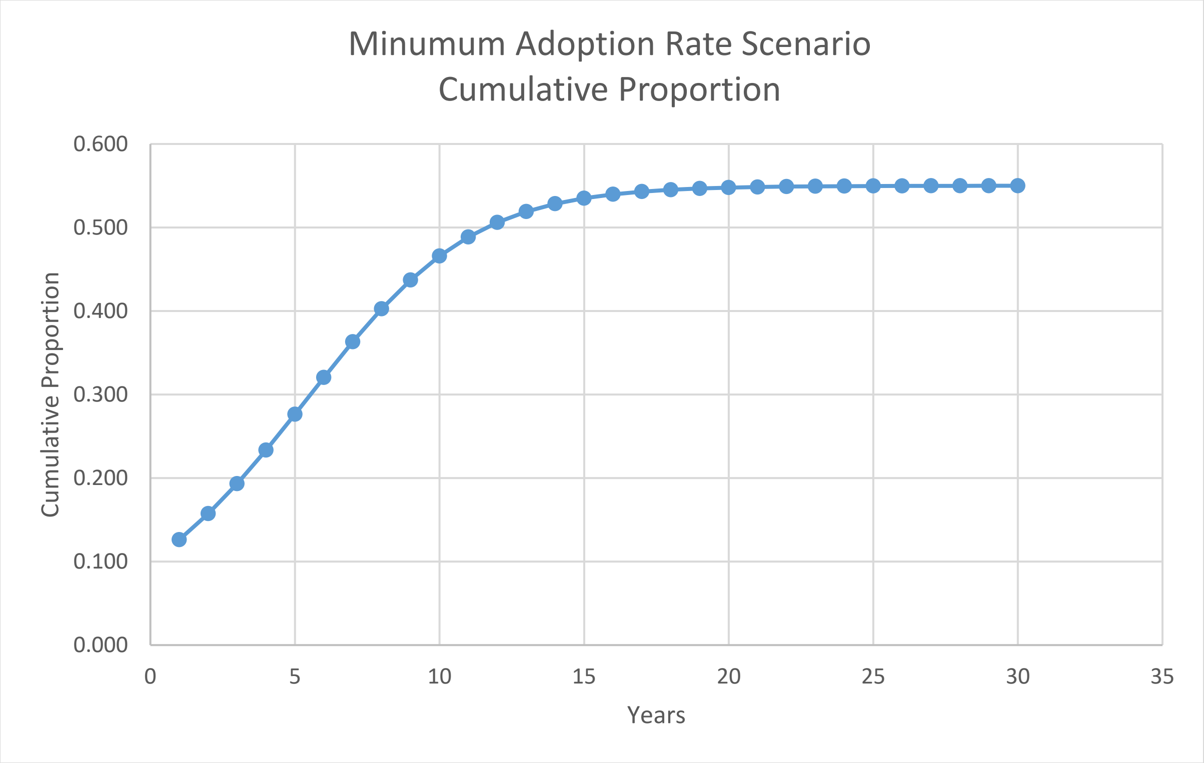

Figure 2. Cumulative proportion for minimum adoption rate scenario

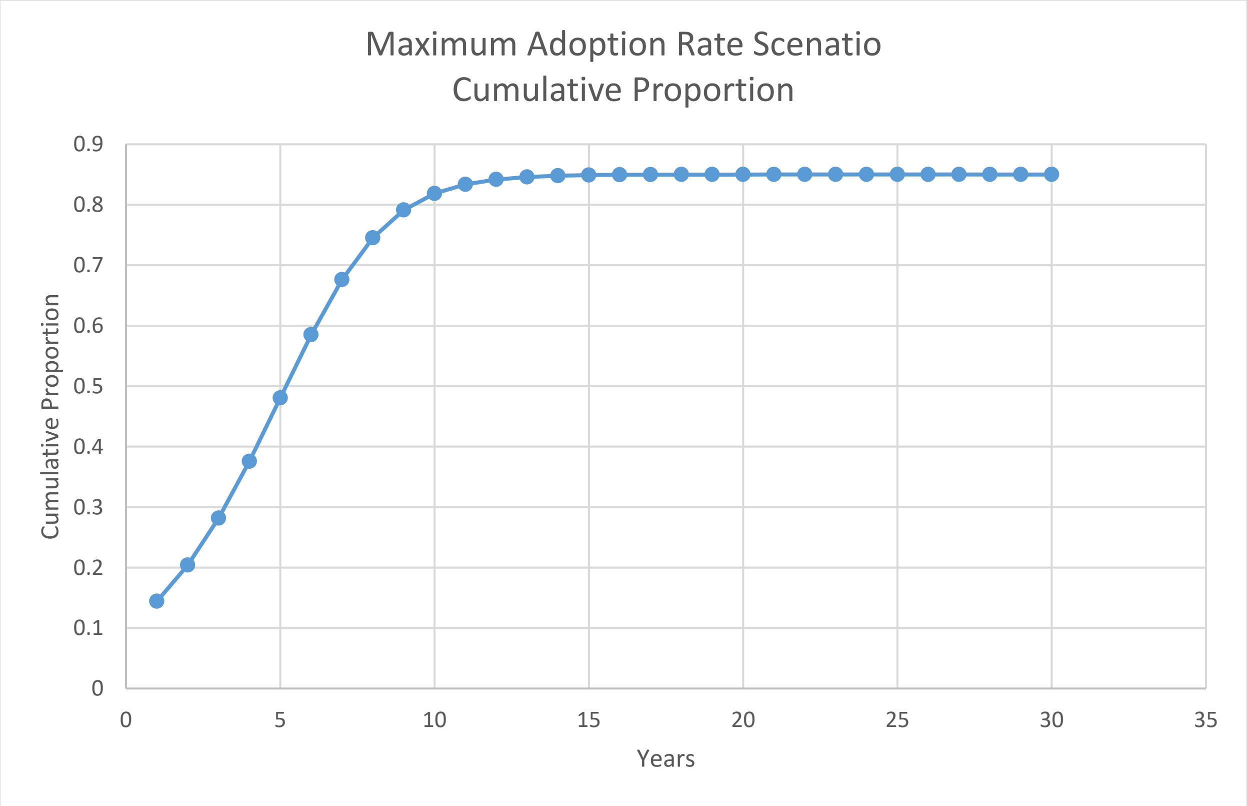

Figure 3: Cumulative proportions for maximum adoption rate scenario