Choice of Irrigated Corn or Grain Sorghum and Center Pivot or Subsurface Drip Systems in the High Plains of Oklahoma

Karthik Ramaswamy,
Graduate Research Associate
Department of Agricultural Economics
Oklahoma State University
ramaswk@okstate.edu

Art Stoecker
Associate Professor
Department of Agricultural Economics
Oklahoma State University
art.stoecker@okstate.edu

Jason Warren
Associate Professor
Department of Plant and Soil Sciences
Oklahoma State University
jason.warren@okstate.edu

Rodney Jones
Associate Professor
Department of Agricultural Economics
Oklahoma State University
rodney.jones@okstate.edu

Saleh Taghvaeian
Assistant Professor
Department of Biosystems and Agricultural Engineering
Oklahoma State University
saleh.taghvaeian@okstate,edu

This paper compares the discounted net returns from corn or sorghum, aquifer life, and groundwater use from center pivot and subsurface drip irrigation systems. The irrigated study area in the Oklahoma Panhandle Area (OPA) includes 106,236 acres of corn, 19,457 acres of sorghum, and 64,671 acres of winter wheat (Census of agriculture, 2012). Unfortunately, data from the Oklahoma Water Resources Board (OWRB, 2012) indicates the annual groundwater level of the OPA underlying Ogallala has been declining from 0.94 to 2.59 feet per year since 1995. The annual recharge is estimated to be less than 2.2 inches (Ochsner et al. 2014). The major focus is to find the maximum discounted returns from the remaining water supply given advances in irrigation technology and crop genetics.

Irrigation research at the Oklahoma Panhandle Research Station (Warren, 2013), to determine the yield potential and water use efficiency (WUE) of growing corn and sorghum with center pivot (CP) and subsurface drip (SDI) systems serves as the basis of this study. The CP irrigation application rates and application frequencies were consistent with wells capacities of 1.6 GPM/acre, 3.2 GPM/acre, 4.8 GPM/acre, and 6.4 GPM/acre. The respective minimum days between irrigations were calculated on the amount of time it would take to complete one revolution applying 1.5 gross acre-inches per acre. The experiment also evaluated the performance subsurface drip irrigation (SDI) with similar well capacities used on CP. The conclusions were that sorghum had higher WUE than corn and that SDI had higher WUE than the CP where in line with research from Kansas (Lamm et. al., 2015) and from Texas (Bordovsky et al. 2011). Many of the economic studies (O'Brien et al. 1998 and Lamm et al. 2015), comparing SDI and CP irrigation use

on a single crop (corn), and a static enterprise budget to estimate the net returns per acre. Static budgets are misleading when a primary resource (groundwater) becomes more limiting over the planning period because of the producers' actions. It lacks the concept of "User Cost" or the discounted profits foregone due to increased current use (Hartwick and Olewiler, 1998), because the total groundwater supply is fixed and the overall temporal demand exceeds the total supply. Thus, finding the extraction path (withdrawal amount) of the groundwater in OPA is essential to maximize the profits from the remaining groundwater reserve. The current authors use a calibrated crop simulated model to extend this research to long-term weather conditions in the OPA.

The main objective of this study is to determine producers' actions that will maximize the Net Present Value (NPV) of the remaining groundwater. This includes irrigation system choice between pivot and subsurface drip irrigation system in the Oklahoma Panhandle. To make it clear, the study determines irrigation system choice, irrigated area, dryland area, deficit irrigation, and the crop choices that maximize the net discounted profits from the remaining groundwater supply. The objectives can be sub-divided as,

a. Extend available but limited crop research on irrigated corn and sorghum yields and water use to be more representative of long term weather conditions in the Oklahoma Panhandle.

b. Estimate the impacts of recent USGS published Ogallala parameters on pumping cost considering pumping drawdown on various levels of pumping as the water table declines.

c. Determine the optimal irrigation level and choice between irrigated corn and grain sorghum that maximizes the net benefits from the remaining groundwater supply.

d. Determine the optimal most profitable sequence of pivot and drip investments over the remaining life of the aquifer.

e. Determine the difference in discounted between profits earned by producers who maximizes long-term NPV using pivot system and drip system from the remaining groundwater.

Methods

To extend the irrigation studies in the OPA (objective a), Environmental Policy Impact Calculator (EPIC) crop simulation model was calibrated against available irrigation experimental results and irrigated corn and sorghum variety trials over the period from 2005-2014.

The average market prices were $4.5 for corn and $4.2 for sorghum. Individual crop budgets using vectors of quantity, marginal and fixed costs were prepared to determine the net returns for the crop choice variables. Drip irrigation system size 50 acre, 75 acre, 100 acre, 125 acre, and 150 acre costs $43,000, $58,000, $74,300, $90,700, and $107,000 respectively. The net present value to purchasing a single pivot for a 120-acre field costs about $60,000.

Environmental Policy Impact Calculator (EPIC)

The specific irrigation simulations conducted with each crop (corn and grain sorghum) were designed to estimate yields from a 120-acre center pivot and five sizes of subsurface

drip irrigation at 800, 700, 600, 500, 400, 300, 200 and 100 GPM. The EPIC results were compared against corn and sorghum field experiments conducted at OPA, Texas Panhandle, and southwestern Kansas.

Once the validation was acceptable, the EPIC model was used to generate expected crop yields under 50 years of OPA daily weather from 1965-2014 using the above well capacities and levels of deficit irrigation. EPIC allows specification of the minimum number of days between successive irrigations, the number of days the pivot takes to complete a circle for applying 1.4 acre-inches and drip system irrigation amounts on 120-acre field with 100 to 800 GPM well capacities is shown below in table 1. The effects of deficit irrigation were simulated by not allowing the initiation of the next irrigation until available soil moisture had declined to 90, 80, …, 30 percent available soil-water capacity. This was done in order to take advantage of any rainfall received during the previous pivot rotation or to skip a day for drip application. The 90 percent trigger represents almost continuous irrigation while the 30 percent level represents extreme deficit irrigation.

Simulation validation

Center pivot simulation for corn and sorghum were compared with experimental trials carried out at Oklahoma Panhandle Research and Extension Center, Goodwell, OK from 2005 to 2014. Simulated yields with 600 GPM wells at 90 percent irrigation were able to match with corn variety trial averages and sorghum yields, but missed one up turn and one down turn. However, the ten year (2005-2014) average for corn and sorghum were almost equal to the calibrated yield as shown in figure 1 and figure 2. Estimated yields

were also validated with irrigation experiments performed at southwest Kansas and Texas Panhandle (Ramswamy, 2016 and Klocke, 2012). The relative yield with water use of corn and sorghum was validated with Garden City, KS and Bushland, TX experiments from 1989-2012.

CP simulation results

The 45-year average corn yields obtained for well capacities 800 GPM and 100 GPM wells at 0.90 stress trigger were 213.4 bushels/acre using 19.1 inches and 99.1 bushels/acre using 5.2 inches respectively. For same well capacities at 0.30 stress trigger, corn yields were 159.3 bushels/acre using 12.4 inches and 96.8 bushels/acre using 4.6 inches respectively. Sorghum yields obtained with the 800 GPM and 100 GPM simulations at 0.90 stress trigger were 162.8 bushels/acre using 13.3 inches and 88.5 bushels/acre using 2.4 inches respectively. For 800 GPM and 100 GPM wells at 0.30 stress trigger, sorghum yields were 122.1 bushels/acre with 7.1 inches and 87.5 bushels/acre with 1.9 inches respectively. The irrigation trigger had more effect with higher well capacities than with lower well capacities, because the pivot completes the circle more quickly (fewer days) with the higher GPM well. The next irrigation does not begin until the soil moisture level declines to the set trigger. Conversely, with the lower GPMs it takes more days to complete the entire circle, by which time the soil moisture has already declined, and the pivot remains in motion. The longer time span increases the likelihood of the soil moisture target would have declined to the trigger level before the circle is completed. With 800 GPM and 0.90 stress, corn and sorghum produced at 11.2 bushels and 12.3 bushels per unit of water. However, with lower well capacity and higher

stress, sorghum had much greater WUE than corn. Irrigating 120 acres with 200 GPM at 0.30 stress, corn and sorghum produced 15.9 bushels and 35.5 bushels per unit of water. The 50-year average (expected) corn sorghum yield, water use, and water use efficiency is shown in table 2.

Drip simulation results

The simulation model for drip irrigated corn and sorghum was simulated for land sizes of 50, 75, 100, 125, and 150 acres for well capacities 800,…,100 GPM. Yield comparison was made between 120 acre pivot and 125 acre drip irrigation simulations to show the water use efficiency of SDI. The drips emitters were assumed to be placed one foot (300 mm) below the surface.

The results show that, yields for both crops were increased using SDI at 10 percent trigger compared to CP as shown in figure 3. As the irrigation stress triggers were delayed furthermore, both irrigating corn and sorghum using SDI produced less yields than CP but had higher yields per unit of water than CP. Irrigated corn required 11.8 acre inches of water to produce 158 bushels, which signifies SDI's WUE. In addition, as the well capacities declines, irrigation corn and sorghum produced even more bushels per acre unit of water, but had yields lower per-acre.

The Typical Irrigated Farm or 640 acre section

To accomplish the above objectives, the concept of a representative irrigated section of land in Texas County, Oklahoma is visualized. An outline of the representative field is shown below in figure 4.

The irrigation characteristics assumed for this study are, a) Producer's field is a 640-acre square section with four irrigation wells, b) The wells are located at the edge of the field, c) Irrigation systems are connected using underground pipelines, the underground pipelines are in existence before the start of the project, and d) The water table is split into six layers, and wells can produce 600 GPM at the top level.
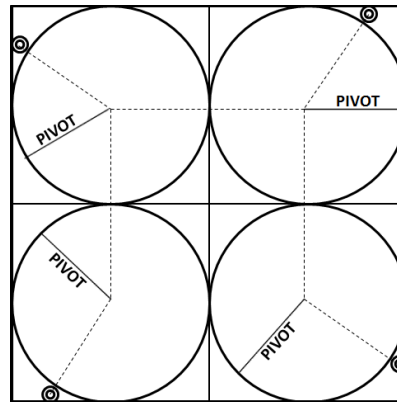
◎ irrigation wells ------ underground pipeline

Figure 4. Typical Section of land equipped with four wells located at edge of the field and connected using an underground pipeline

Well assumptions and pumping estimates

The sizes of each layer were determined by the minimum possible 90-day drawdown. Cooper-Jacob (1946) drawdown equations were modified for this study to calculate the drawdown for each well capacity ranging from 600 to 100 GPM. It is assumed that a producer is surrounded by other producer's, though only 40 percent total land area is irrigated. Current saturated thickness was estimated to be 83 feet. The thickness of aquifer depth and the sizes of the layer depth for each well capacity were determined by

the minimum possible drawdown allowing 35 feet over the pump bowls. Sizes of the layer below the total land area and specific yield of the aquifer gave the amount of water supply available for each well capacity. The amount of water that could be pumped from the water table depends on the depth of the saturated thickness, duration of pumping, and hydraulic conductivity, and specific yield. The drawdown curves were used to determine the minimum saturated thickness that would support each 100 GPM for 90 days of pumping with a hydraulic conductivity of 25 feet per day and specific yield of 0.18. In this analysis, the aquifer was always assumed to be unconfined. When extracting groundwater from an unconfined aquifer, a cone of depression is formed, the depth of the cone of depression from Static Water Level (SWL) is called as the drawdown. The cone of depression varies with the discharge rates. The drawdowns are used to estimate the total head and cost of pumping per unit of water. The well-known and most widely used modified radial flow equation developed by Cooper and Jacob (1946) is used to estimate the drawdowns for single well and multiple wells. The drawdown results are listed in third column in table 3.

When it is time for irrigation system replacement (every 15 years), a producer with a limited water supply can purchase system for one, two, or three quarter sections but continue to use all four wells. Producers can connect the wells together to irrigate one, two, or three quarter sections with an ideal discharge rate that will give the maximum benefit. When the wells are to be connected in various combinations, the number of wells pumped the required GPM at each pivot determine the drawdown. Additional head is required to move the water from a remote well to the irrigation system.

These factors determine the pumping cost. This process of combining wells and delivering higher GPM to fewer quarter sections continues until the water table is exhausted. For example, when each of the four wells has a capacity of 100 GPM, the four wells can be connected to pump 400 GPM and operate one quarter section, or operate two quarter sections with 200 GPM each. This means that the pumping costs are different when two or more wells are combined to supply a quarter sections than when each quarter section is supplied by a single well.

Crop budgets

The expected net return for each possible crop activity with an irrigation treatment for corn and grain sorghum was computed using enterprise budgets of the Oklahoma State University (OSU) and Kansas State University (KSU). The expected output prices for crops were assumed to be constant. Ten-year (2005-2014) Oklahoma average prices for corn were $4.48 per bushel and for grain sorghum $4.16 per bushel according to data from the 2013 Oklahoma Agricultural Statistics. The present value of net returns $\left(C_{gjt}\right)$ calculated for CP activities is expressed as,

$$C_{gjt} = \left[p\mathbf{y}_{gj} - \mathbf{v}_{gj} - \mathbf{w}_{njg}\right]\beta^{-t},$$

where the matrix $\mathbf{w}_{njg}$ is the pumping cost which is denoted by $\mathbf{w}_{njg} = \mathbf{r}_{njg} \times \mathbf{h}_{njg}$, each pumping cost activity are the elements of the matrix $w_{njg} = r_{njg} \times h_{njg}$, g is the index of aquifer level and well capacity, j is the index of irrigated corn and sorghum activities at alternative stress levels, n is the number of quarter sections irrigated using

the irrigation system, $\mathbf{r}_{njg}$ is the irrigation cost per acre-foot from aquifer level and well capacity g, $\mathbf{h}_{njg}$ is the vector of water use at well capacity g at alternative stress level j, $\mathbf{y}_{gj}$ is the vector of crop yields and $\mathbf{v}_{gj}$ is the variable cost vector for the well capacity g at alternative stress levels j, p is the price per bushel of corn or sorghum, β is the discount factor at 4 percent for each time period t.

A similar calculation was made to estimate the present value of SDI activities for varying drip sizes by having an additional index for yield and cost variables which accounts for drip size of 50, 75,…,150 acre. For both SDI and CP, the crop yield and variable costs depend on the well capacity (GPM) and stress levels (delayed irrigations), but do not vary with aquifer depth. This is because the bottom of the drawdown cone is always assumed to be at the top of the safety zone. Cost to irrigate one to four quarter section when acre-foot water is extracted from each layer depth is calculated (Ramaswamy, 2016). If one quarter section is irrigated with 600 GPM, then four 150 GPM wells are combined and served to one quarter section, or when two quarter sections are irrigated with 600 GPM then four 300 GPM wells combine and serve two quarter sections, or when three quarter sections are irrigated with 600 GPM then four 450 GPM wells combine and serve three quarter sections. Final case is when four quarter sections operated at 600 GPM each latter is possible if each well yields 600 GPM. The yields and OVC are extracted from 600 GPM and respective stress factor, what makes the difference with these situations is the pumping cost, since each situation is pumped from different SWL.

An important variable cost difference noted between corn and sorghum was the seeding cost. The seed cost of corn was $3.5 per 1,000 units and sorghum was $0.25 per 1,000 units. Each irrigated corn and sorghum generates 406 pivot activities and 2030 drip activities, and 1 dryland activity each year for both the irrigation systems. Therefore, 24,000 CP and 121,440 SDI activities were generated for the 60-year mixed integer programming (CPLEX) models, after eliminating the negative returns crop activities.

Mixed integer programming (CPLEX)

To compare the optimal crop choice, costs and returns for a producer with 640 cultivated acres with four existing 600 GPM irrigation wells who is considering purchase of either a CP system or SDI, which is determined using individual MIP models for each irrigation system. The amount of total water supply is the water constraint and irrigated land area of 640 acre is the land constraint for each period in the MIP model. Any remaining water not used is transferred to the successive years, and irrigation system life is 15 years.

The crop net returns calculated from the budgets were set as coefficients of the objective function, and the irrigation purchase activities were made as integer choices on the MIP model. The pivot variables name are expressed in seven characters, crop takes the value of C or S, total GPM/acre is defined as $a,b,...,f$, the irrigation stress levels are 3, 4, ..., 9, the activity period is from 1,...,60, number of operating pivots takes value 1, 2, ..., 4, and the aquifer is defined by the 1,2,..., 6. An example activity for pivot system is Cd50522: the pivot activity can be defined as in period 5 (character 4 and 5), corn (C) irrigated at 400 (d) GPM at stress level at 0.50 (5) operating with two (2) pivots from

aquifer level with maximum well capacity of 200 (2) GPM. Intuitively, the CP activity

means it combines two 200 GPM wells to irrigate one pivot at 400 GPM. For drip

activity Std41722: it can be expressed as, in period 17 (character 5 and 6), sorghum (S)

irrigated on at 400 (d) GPM at stress level at 0.60 (4) on two quarter sections (2) from

aquifer level with maximum well capacity of 200 (2) GPM.

The mathematical definition of the MIP will give a clear understanding of the

activities and constraints used in this model. The CP and SDI model follows the same

algorithm, but SDI model assumes five different sizes of drip investments. NPV

maximization over a 60-year using MIP for CP model is expressed as,

$$\max \text{NPV} = \sum_{r=1}^{4} \left[\sum_{t=1}^{15} \left[\left(\sum_{g=1}^{8} \sum_{j=1}^{n} (C_{gjt} I_{gjt}) + d_t D_t \right) - K_r P_r \right] \right],$$

Subject to:

Total Land: $\sum_g \sum_j I_{gjt} + D_t \leq 640$ for all t,

Irrigated Land: $\sum_g \sum_j I_{gjt} - 120 \times P_r \leq 0, P_r \in \{0,4\}$ integer for all t, g, r,

and, Water Supply: $\sum_r \sum_t \sum_g \sum_j W_{gjt} I_{rgj} \leq WS_g$ for all t,

where j is the index of irrigated corn and sorghum activities at alternative stress levels, g

is the index of aquifer level and well capacity, t is the index of crop land allocation time

period, r is the index of irrigation purchase period 0-15, 15-30, 30-45 and 45-60, C_{gjt} is

the present value of net revenue from irrigation in year t, I_{gjt} is the acres irrigated and

W_{gjt} is the water use at aquifer level g with GPM in year t, d_t is the present value of

dryland production per acre at year t, D_t is the land allocated for dryland production, K_r

is the present value of pivot investment in period r, P_r is the pivots investment in period r.

Results

The results section addresses the objective (c, d, and e) of deciding the optimal crop choice, irrigation system size that will maximize the discounted net returns from remaining groundwater for CP and SDI. These details are total NPV, choice of and irrigation system investments in the optimal irrigated area, and dryland area (area not covered by the irrigation system). By default, CP dryland area is 160 acres and SDI dryland area is 40 acres. The dryland area produces grain sorghum, which is assumed to be the marginal value or opportunity cost of an acre land in OPA.

Crop Budgets

Crop budget results indicate that irrigated corn give diminishing returns by increasing irrigation water for each acre. This would imply it will be optimal to spread water supplies over more acres with grain sorghum. However, spreading the water requires more capital investment. If spreading is more expensive respective to remaining water supply, dryland becomes competitive and remaining groundwater is applied to fewer acres. This is clearly obeyed and satisfied by the model results. The budgets show that, with CP and SDI sorghum becomes profitable when the capacity of the well serving one quarter section declines below 600 GPM. The graph shown in figure 5 and 6, shows the net return override by irrigated sorghum. As the well capacities declines, investing irrigating system for each well is capital intensive. Under such circumstances, producers

may connect the underground pipeline and irrigate fewer acres at higher GPM that could maximize the net revenue. Therefore, crop budgets for irrigating corn and sorghum under one, two and three with CP and SDI are shown in Table 4 and 5. The summary of the crop budgets show that, irrigating corn at 600 GPM on all the four quarter sections is more profitable using both the CP and SDI than irrigating sorghum. However, as the well capacities to 400 GPM, spreading the irrigated corn becomes less profitable than sorghum. When the well capacities reaches 200 GPM range, the crop budgets for CP and SDI show that it is profitable to irrigate corn under one pivot using 800 GPM well. In the 100 GPM range, the budgets indicates that irrigating sorghum with 400 GPM under one pivot gives higher returns than irrigating corn. The crop budgets can be used to determine the recursive use to maximize the annual returns when resource is not limited, if groundwater is a limited, investing on more irrigation systems becomes expensive respective to the remaining water supply. Thus, a long-term profit maximization method was developed using MIP to determine the use of remaining groundwater that yielded maximum discounted net returns.

Crop choice and system investment size

For a 60-year planning horizon with maximum well capacity of 600 GPM per well, investing in three pivots in the first 15 years was the most profitable. The shadow price (SP) per irrigated acre under four pivots was always less than the SP of investing in three pivots. When wells are capable to deliver 600 GPM per well, the value of water (SP) was high of $53.4, thus irrigating corn was able to replace the total opportunity cost at the 600 GPM level of the aquifer. In year 4, the water level declines to maximum

capacity of 500 GPM, and the SP of water reduced to $31.4 and reduced irrigated acres

SP leads to choose sorghum and replaces corn fully until year 15 (see table 8). By the

year 16, the aquifer level was declined to 300 GPM level. It was most profitable to invest

in only one pivot, which increased the value of the irrigated acres. This was because

spreading the irrigated diminishes the SP of the irrigated acres, since four 300 GPM wells

combined and producing corn at 800 GPM was more profitable choice from year 16

through 32. In year 32, the water level was reached 100 GPM level, thus it was profitable

to irrigate sorghum under one pivot till end of the project life, which is shown in figure 7.

The results of SDI follow the similar characteristics, but SDI produced more

bushels by irrigating grain sorghum on a more acres than CP. The results of SDI crop

choice, irrigated area, and drip sizes are shown in figure 8. Investing in SDI system

begins the 60-year project with 600 acres of irrigated sorghum. At 600 GPM range

though irrigating 150 acre of corn on all four quarter sections had higher net returns

($209/acre) than sorghum net returns ($196) per acre, sorghum was irrigated on 150 drip

size on all four quarter sections. Irrigating corn would require 0.6 acre-feet of water per

to spread over 600 acres, which would create a reduced cost to the objective function.

Because the SP of the water in year 1 is $73 and thus it causes $31/acre in the overall

profit by using 360 acre-feet of water in year 1. Under Euler theorem, if the marginal

value is paid to the input of the optimal output, the profit from the output is equal to the

distributed shares from the input. Theoretically, if all the resources are their Value of

Marginal Product (VMP), all the net revenue would be exhausted. Thus, irrigating 150

acres of sorghum on all the four quarters from 600 GPM through 300 GPM first 15 years

was optimal and profitable crop choice to maximize the overall benefits from the remaining groundwater. In year 16, the total irrigated sorghum is reduced to 125 acres on two quarters, as well capacity reduces to 300 GPM per well, two wells are combined to supply 600 GPM to each quarter section. Irrigated sorghum on 250 acres continues until year 30, and well capacity declines to 200 GPM per well when it is time to replace the drip systems in year 31.

In year 31, the total irrigated area was reduced to 125 acres on one quarter section. With well capacity with 200 GPM, it was most profitable to combine the all the four wells and irrigate 125 acres for four years. When well capacities increases above 5 GPM/acre, corn is the profitable crop choice. However, the well capacity declined to 100 GPM in year 35 and it was optimal to combine all the four wells and irrigate sorghum at 400 GPM on 125 acres. The shadow prices and present value of the optimal activities for CP and SDI model are shown in table 8 and table 9.

The final objective is to compare the net benefits and affect of aquifer life between CP and SDI investment decision. The results show that, in the beginning of the project, the expensive SDI system may have reduced benefits compared to CP investment, but on a long-term profit maximization axiom, investing drip system incentives increase rapidly by giving greater profits. This is seen in the cumulative net present value results in figure 9. The unexpected result is both CP and SDI water use trends were similar, this is mostly because the aquifer was not exhausted and the limitation is water supply was not entirely exhausted over the 60-year planning horizon. Remaining water supply over a 60-year for CP and SDI is show in figure 10.

The following table 6 shows the NPV obtained when irrigating corn and sorghum using pivot and drip irrigation. The results show that investing SDI system on a 640-acre land increases the value of the land by. $255,219. One major advantage of the SDI is, irrigated sorghum production increased by replacing the corn and dryland sorghum. By producing more irrigating sorghum using SDI, the NPV value of a 640 acre section increases by $255,219. The total bushels sorghum increased is 1,237,108 bushels, corn reduced by 544,264 bushels, and dryland sorghum reduced by 342,150 bushels. Total bushel production is listed in table 7.

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Table 1. Application amounts and intervals used in simulation for CP and SDI system

Well capacity			Irrigation schedule	
GPM/well	GPM/ac		Pivot[1] (days)	Drip[2] (ac-in)
800	6.7		4	8.6
700	5.8		5	7.5
600	5.0		6	6.5
500	4.2		7	5.4
400	3.3		8	4.3
300	2.5		11	3.2
200	1.7		16	2.2
100	0.8		32	1.1

[1]Pivot system applied 1.4 acre inches per application, and
[2]Drip system applied irrigation amounts on daily basis
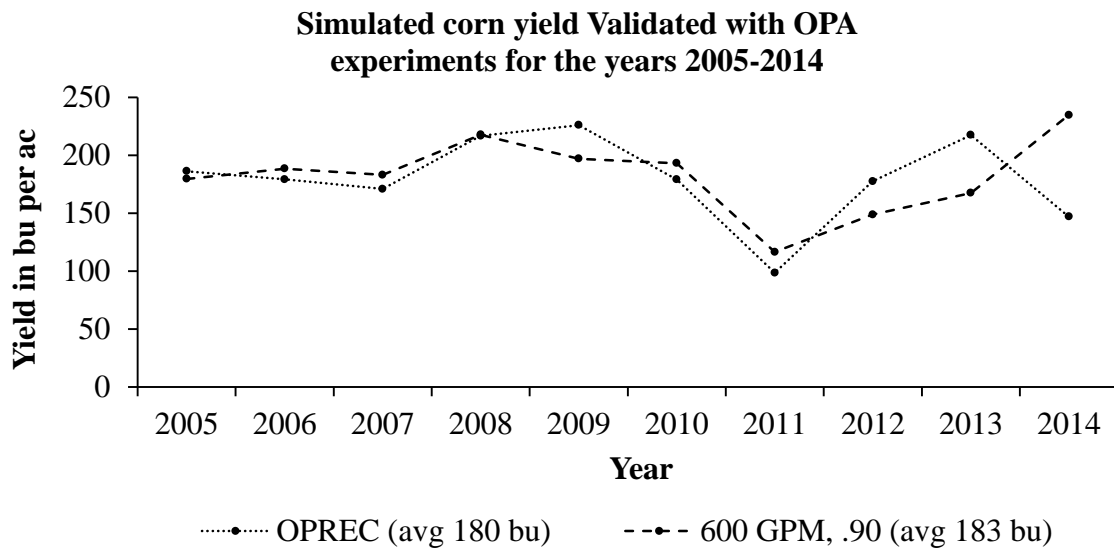
Figure 1. Simulated Corn yields are validated with the variety trials conducted at the Oklahoma Panhandle Research and Experiment Center, Goodwell, OK from 2005-2014

Simulated sorghum yield Validated with OPA experiments for the years 2005-2014
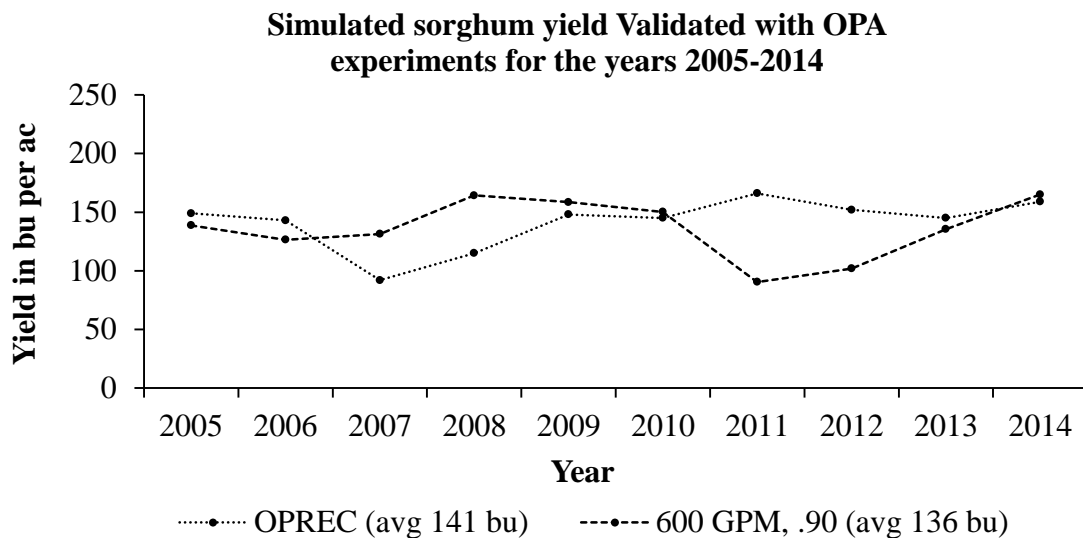
Figure 2. Simulated Sorghum yields are validated with the variety trials conducted at the Oklahoma Panhandle Experimental Research Center, Goodwell, OK from 2005-2014

Table 2. Expected CP irrigated Corn and Sorghum results for selected well capacities and irrigation stress levels from 50 years of simulation on a 120-acre

Crop	GPM/ac	Yield (bu./ac)			Irrigation[1] (ac-in)			bu./ac-in		
		30%	60%	90%	30%	60%	90%	30%	60%	90%
Corn	6.7	159	181	213	14.6	18.8	22.5	11	10	9
	5.0	157	171	187	14.6	17.2	21.6	11	10	9
	3.3	148	155	164	13.5	15.0	17.6	11	10	9
	1.7	117	119	122	8.7	9.4	10.3	14	14	12
Sorghum	6.7	122	139	163	8.3	9.2	15.6	15	15	10
	5.0	122	134	148	8.2	10.0	12.6	15	14	12
	3.3	117	125	134	7.7	8.6	10.4	15	14	13
	1.7	88	90	92	2.9	3.3	4.1	30	27	23

[1]Frequency is the number of days to complete a 120-acre field using a pivot system with 85 percent

WUE of SDI on Corn and Sorghum compared with CP yields and water use
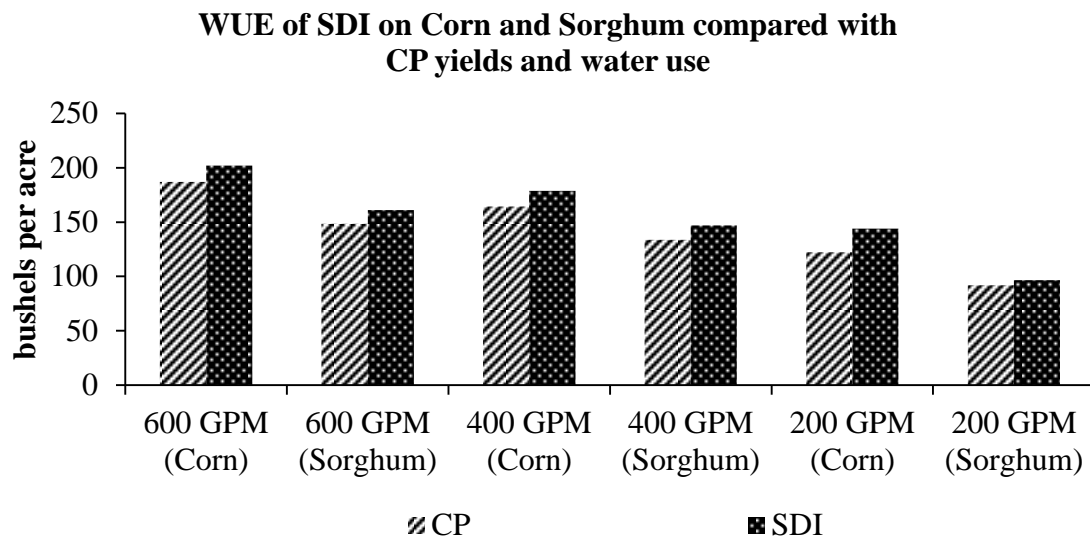
Figure 3. Comparing the 45-year simulated average of Corn and Sorghum using CP and SDI
Note: SDI efficiency was 95 percent and CP efficiency was 85 percent

Table 3. Drawdown estimates for well capacities and amount of water available for each well capacity to pump

Level	GPM/well	Drawdown (ft)	Layer size (ft)	Water supply (ac-ft)
6	600	58	6.0	1,680
5	500	52	7.0	1,960
4	400	45	7.0	1,960
3	300	37	7.0	1,960
2	200	28	9.0	2,520
1	100	16	12.0	3,360

[a]Cooper-Jacob method was used to estimate the drawdown, the aquifer characteristics are as follows, specific Yield is 0.18, Hydraulic Conductivity is 25 feet/day, Saturated Sand is 93 feet, and no well interference were considered in this study. Difference in the drawdown in the available saturated sand layer thickness aquifer to pump

Expected net returns per acre by irrgated corn and sorghum with CP using single well at 0.90 stress on a 120-acre
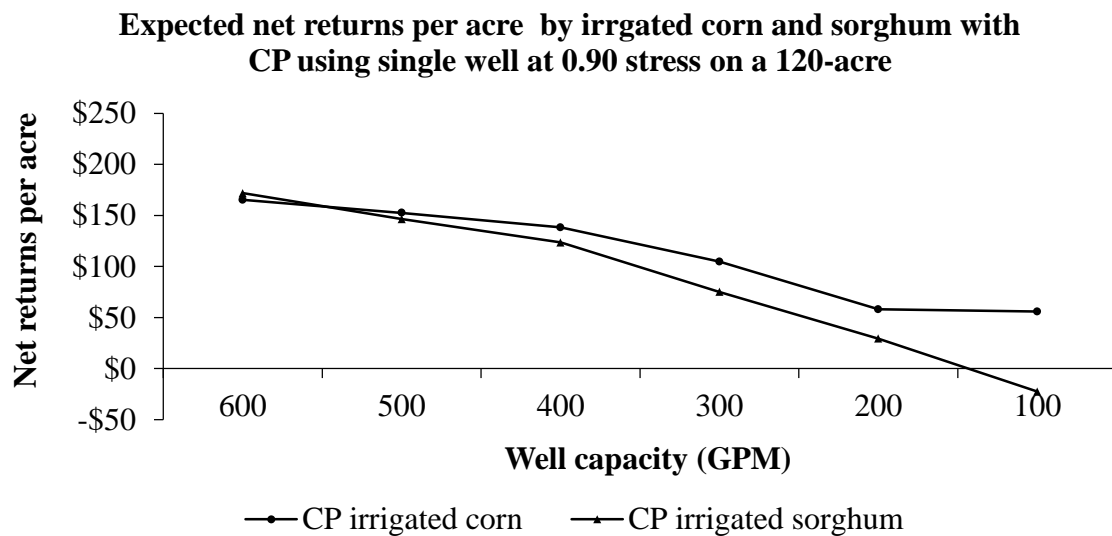
Figure 5. Expected net returns per acre by irrigating corn and sorghum on a 120-acre with CP using single 600 GPM well

Expected net returns of SDI irrgated corn and sorghum using single well at 0.90 stress on a 150-acre
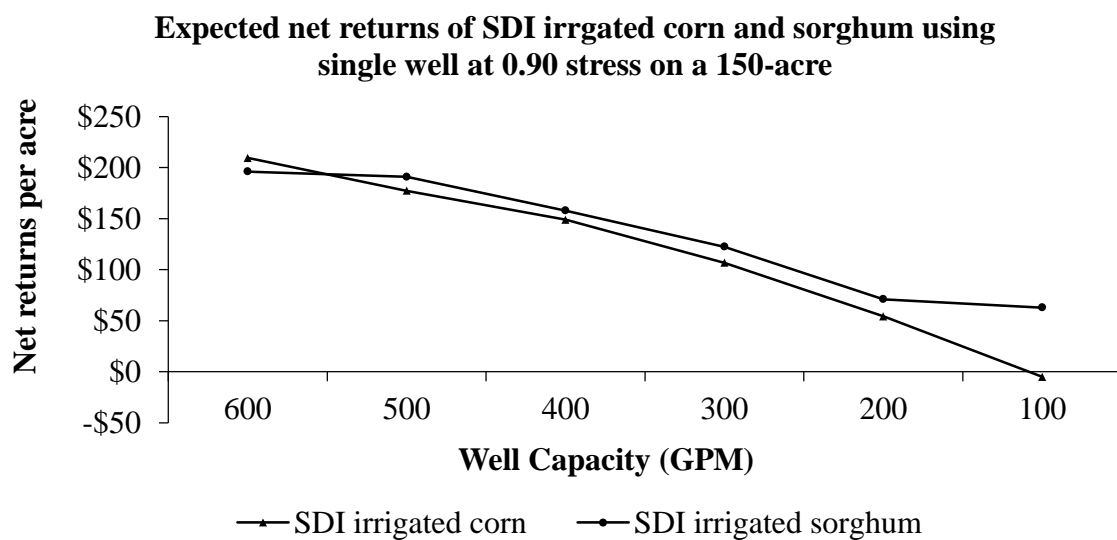
Figure 6. Expected net returns per acre by irrigating corn and sorghum on a 120-acre with SDI using single 600 GPM well

Table 4. Crop Budgets showing Expected Net Returns of Irrigated Corn and Sorghum with CP using various combination of Well capacities

	Units	Irrigated Corn				Irrigated Sorghum			
CROP ACTIVITY									
Maximum GPM/well		600	400	200	100	600	400	200	100
Number of operating pivots		4	4	1	1	4	4	2	1
GPM at each pivot		600	400	800	400	600	400	400	400
PRODUCTION									
Grain Yield	(bu./ac)	187	164	213	164	148	134	134	134
Nitrogen	(lb./ac)	172	151	197	151	165	149	149	149
Phosphorus Cost	(lb./ac)	25	22	29	22	27	24	24	24
Irrigation	(ac-in/ac)	22	18	22	18	13	10	10	10
Revenue	($/ac)	837	736	956	736	619	558	558	558
OPERATING COST									
Nitrogen Cost	($/ac)	95	83	108	83	91	82	82	82
Phosphorus Cost	($/ac)	13	11	15	11	14	13	13	13
Seeding Cost	($/ac)	113	113	113	113	16	16	16	16
Herbicide Cost	($/ac)	61	61	61	61	52	52	52	52
Insecticide Cost	($/ac)	15	15	16	15	0	0	0	0
Crop Consulting Cost	($/ac)	7	7	7	7	6	6	6	6
Drying Cost	($/ac)	24	21	28	21	19	17	17	17
Miscellaneous Cost	($/ac)	10	10	10	10	10	10	10	10
Custom Hire Cost	($/ac)	150	140	162	140	126	120	120	120
Non Machinery Labor Cost	($/ac)	18	18	18	18	18	18	18	18
Interest Cost	($/ac)	18	16	20	16	14	13	13	13
Sub Total Operating Cost	($/ac)	523	495	556	495	368	348	348	348
Crop Insurance Cost	($/ac)	25	24	27	24	18	17	17	17
Irrigation Cost	($/ac)	117	94	119	92	68	55	54	54
Total Operating Cost	($/ac)	665	613	702	611	453	420	419	419
Total Net Returns	($/ac)	172	124	254	125	165	138	139	139

Table 5. Crop Budgets showing Expected Net Returns of Irrigated Corn and Sorghum with SDI using various combination of ideal well capacities

|	Units	Irrigated Corn				Irrigated Sorghum			
CROP ACTIVITY									
Maximum GPM/well		600	400	200	100	600	400	200	100
Number of operating SDI systems		4	4	1	1	4	4	2	1
GPM at each SDI system		600	400	800	400	600	400	400	400
SDI size per quarter section		150	150	150	125	150	150	125	125
PRODUCTION									
Grain Yield	(bu./ac)	194	166	211	179	155	135	147	147
Nitrogen	(lb./ac)	184	157	201	170	173	151	164	164
Phosphorus Cost	(lb./ac)	27	23	29	24	28	24	27	27
Irrigation	(ac-in/ac)	18	13	22	16	10	8	9	9
Revenue	($/ac)	869	742	947	800	647	565	613	613
OPERATING COST									
Nitrogen Cost	($/ac)	101	86	111	93	95	83	90	90
Phosphorus Cost	($/ac)	14	12	15	13	15	13	14	14
Seeding Cost	($/ac)	113	113	113	113	16	16	16	16
Herbicide Cost	($/ac)	61	61	61	61	52	52	52	52
Insecticide Cost	($/ac)	16	15	16	15	0	0	0	0
Crop Consulting Cost	($/ac)	7	7	7	7	6	6	6	6
Drying Cost	($/ac)	25	22	27	23	20	18	19	19
Miscellaneous Cost	($/ac)	10	10	10	10	10	10	10	10
Custom Hire Cost	($/ac)	153	141	161	146	129	120	126	126
Non Machinery Labor Cost	($/ac)	18	18	18	18	18	18	18	18
Interest Cost	($/ac)	19	17	20	18	15	13	14	14
Sub Total Operating Cost	($/ac)	536	500	558	516	377	350	366	366
Crop Insurance Cost	($/ac)	26	24	27	25	18	17	18	18
Irrigation Cost	($/ac)	98	69	114	82	56	40	47	47
Total Operating Cost	($/ac)	660	593	699	623	451	407	431	431
Total Net Returns	($/ac)	209	149	248	178	196	158	183	183

Optimal CP acres allocated between Corn and Sorghum by maximizing NPV from limited groundwater over 60 years
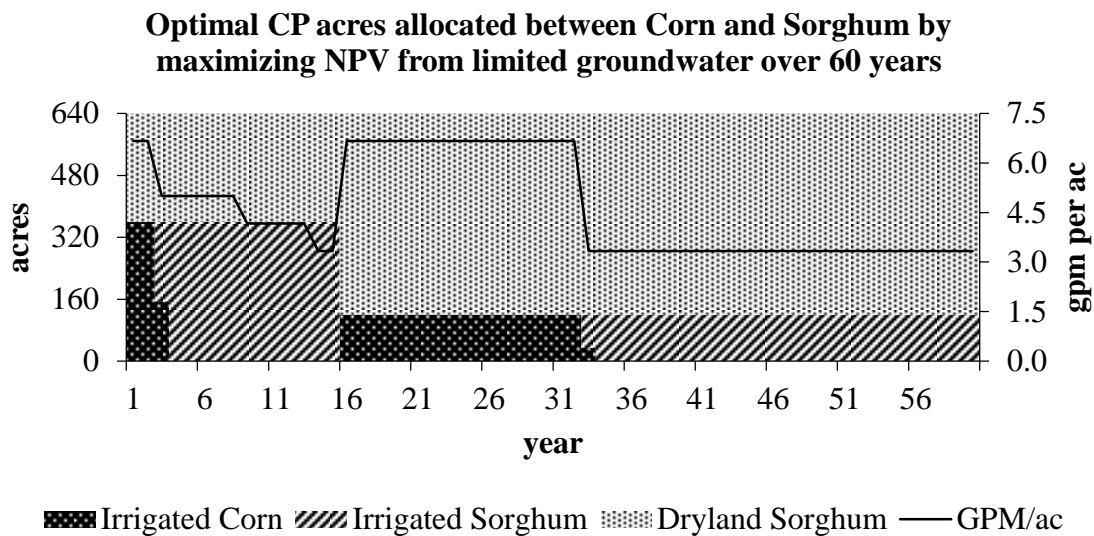
Figure 7. Crop choice and number of pivot investments for a long-term profit maximation over a 60-year period

Optimal SDI acres allocated between Corn and Sorghum by maximizing NPV from limited groundwater over 60 years
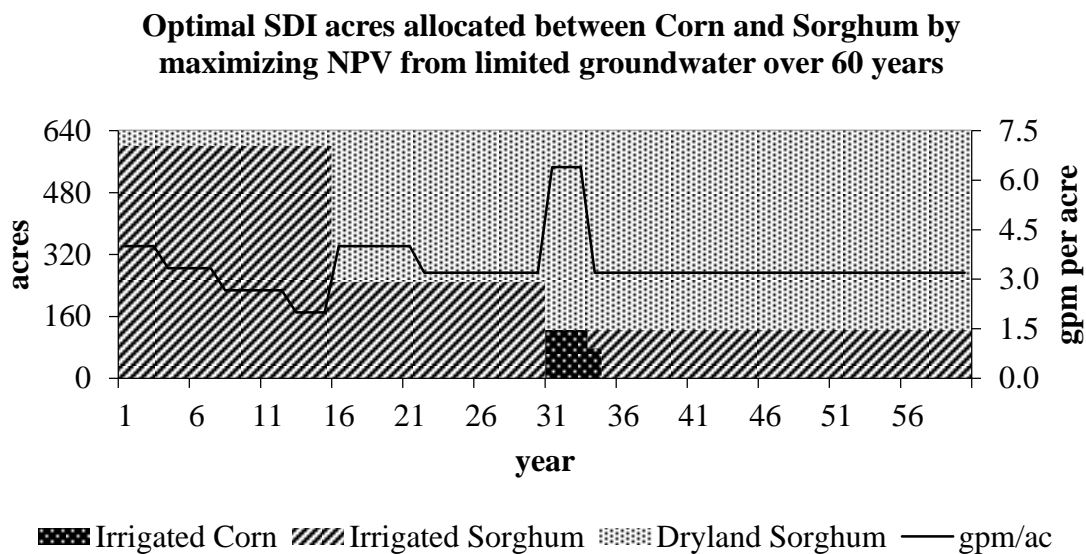
Figure 8. Crop and SDI size investment choice by maximizing NPV from limited groundwater over a 60-year period

Remaining groundwater decline rate by investing CP and SDI and maximizing NPV over a period of 60 years

Beginning water supply = 13,440 ac-ft
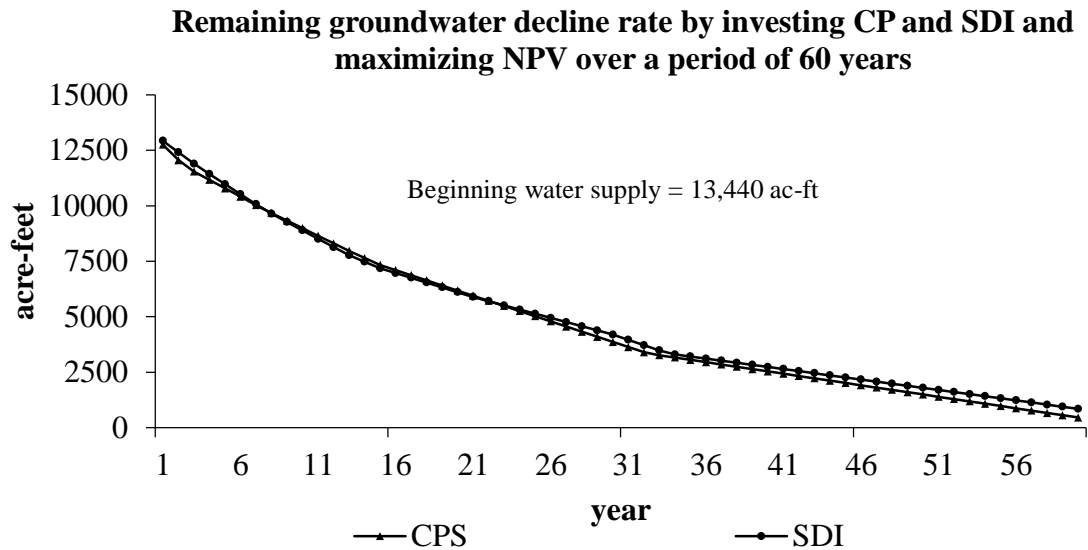
Figure 9. Remainning water supply decline rate for investing CP and SDI and mximizing NPV over the project life of 60 years

CNPV maximizing long term profits by investing CP and SDI and irrigate corn and sorghum over a period of 60 years

SDI = $1,027,053

CP = $771, 834
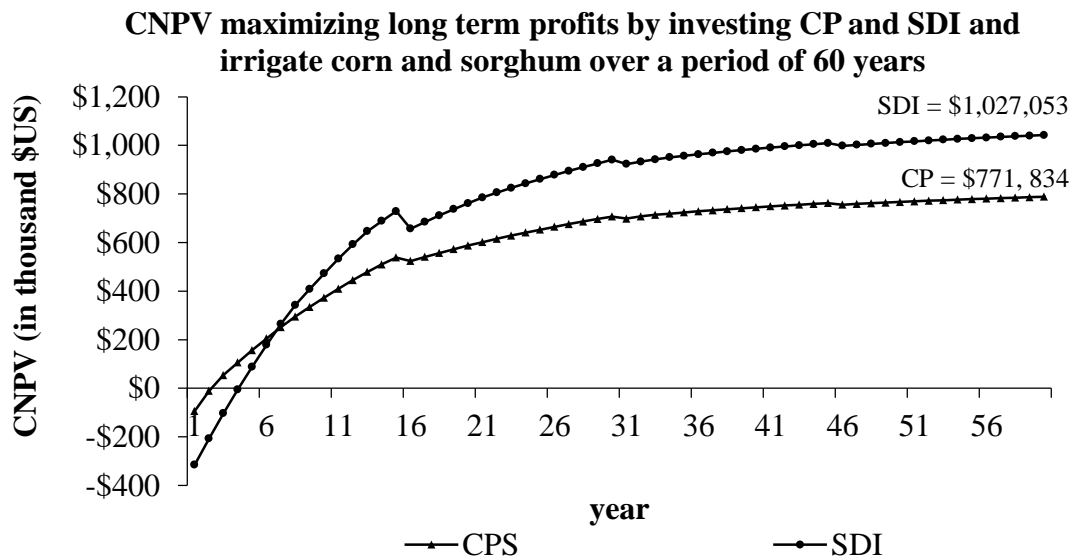
Figure 10. Cummulative net present value (CNPV) growth between CP and SDI from the remaining groundwater over a 60-year period

Table 6. NPV for investing on CP and SDI and irrigate Corn and Sorghum or dryland over a project life of 60 years on 640 acres

Irrigation System	NPV at 4 percent
CP	$771,834
SDI	$1,027,053
Change (+/−)	$255,219

Table 7. Total Bushels of Corn and Sorghum produced in 60 years by investing on CP and SDI on 640 acres

Irrigation Method	Irrigated		Dryland	Total
	Sorghum (bu.)	Corn (bu.)	Sorghum (bu.)	Grain (bu.)
CP	1,092,795	629,254	1,741,560	3,463,609
SDI	2,329,903	84,990	1,399,410	3,814,304
Change (+/−)	1,237,108	− 544,264	− 342,150	− 350,695

Table 8. Results of MIP model for CP system with Annual Lagrangian Multiplier Undiscounted Values

year	VAR X	level	pivot	PV	ac-ft	S.Wat	S.Land	S.Pivot	V of ac-ft	SP	PV-SP
01	Ch90136	6	3	235.9	1.9	53.4	4.0	129.4	102.7	236.1	0
02	Ch90236	6	3	226.8	1.9	53.4	3.8	120.5	102.7	227.0	0
03	Ch90336	6	3	218.1	1.9	53.4	3.7	111.9	102.7	218.3	0
03	Sf90335	5	3	148.6	1.0	31.4	3.7	111.9	33.0	148.6	0
04	Sf90435	5	3	142.9	1.0	31.4	3.5	106.4	33.0	142.8	0
05	Sf90535	5	3	137.4	1.0	31.4	3.4	101.0	33.0	137.4	0
06	Sf90635	5	3	132.1	1.0	31.4	3.3	95.8	33.0	132.1	0
07	Sf90735	5	3	127.0	1.0	31.4	3.1	90.9	33.0	127.0	0
08	Sf90835	5	3	122.1	1.0	31.4	3.0	86.1	33.0	122.1	0
08	Se90834	4	3	112.5	0.9	24.8	3.0	86.1	23.5	112.6	0
09	Se90934	4	3	108.2	0.9	24.8	2.9	81.9	23.5	108.3	0
10	Se91034	4	3	104.0	0.9	24.8	2.8	77.9	23.5	104.1	0
11	Se91134	4	3	100.0	0.9	24.8	2.7	74.0	23.5	100.1	0
12	Se91234	4	3	96.2	0.9	24.8	2.6	70.2	23.5	96.3	0
13	Se91334	4	3	92.5	0.9	24.8	2.5	66.6	23.5	92.6	0
14	Se91434	4	3	88.9	0.9	24.8	2.4	63.2	23.5	89.0	0
14	Sd91433	3	3	80.2	0.9	16.8	2.4	63.2	14.6	80.1	0
15	Sd91533	3	3	77.1	0.9	16.8	2.3	60.2	14.6	77.1	0
16	Ch91613	3	1	136.0	1.9	16.8	2.2	101.5	32.4	136.1	0
17	Ch91713	3	1	130.8	1.9	16.8	2.1	96.3	32.4	130.9	0
18	Ch91813	3	1	125.8	1.9	16.8	2.0	91.4	32.4	125.8	0
19	Ch91913	3	1	120.9	1.9	16.8	2.0	86.6	32.4	121.0	0
20	Ch92013	3	1	116.3	1.9	16.8	1.9	82.1	32.4	116.3	0
21	Ch92113	3	1	111.8	1.9	16.8	1.8	77.7	32.4	111.9	0
22	Ch92213	3	1	107.5	1.9	16.8	1.7	73.4	32.4	107.6	0
22	Ch92212	2	1	105.7	1.9	15.9	1.7	73.4	30.6	105.8	0
23	Ch92312	2	1	101.6	1.9	15.9	1.7	69.4	30.6	101.7	0
24	Ch92412	2	1	97.7	1.9	15.9	1.6	65.6	30.6	97.8	0
25	Ch92512	2	1	94.0	1.9	15.9	1.6	61.9	30.6	94.0	0
26	Ch92612	2	1	90.4	1.9	15.9	1.5	58.3	30.6	90.4	0
27	Ch92712	2	1	86.9	1.9	15.9	1.4	54.9	30.6	86.9	0
28	Ch92812	2	1	83.5	1.9	15.9	1.4	51.6	30.6	83.6	0
29	Ch92912	2	1	80.3	1.9	15.9	1.3	48.5	30.6	80.4	0
30	Ch93012	2	1	77.2	1.9	15.9	1.3	45.4	30.6	77.3	0
31	Ch93112	2	1	74.3	1.9	15.9	1.2	42.5	30.6	74.3	0
32	Ch93212	2	1	71.4	1.9	15.9	1.2	39.7	30.6	71.5	0
33	Ch93312	2	1	68.7	1.9	15.9	1.1	37.0	30.6	68.7	0
33	Sd93311	1	1	38.1	0.9	0.0	1.1	37.0	0.0	38.1	0
34	Sd93411	1	1	36.7	0.9	0.0	1.1	35.6	0.0	36.7	0
35	Sd93511	1	1	35.3	0.9	0.0	1.1	34.2	0.0	35.3	0
36	Sd93611	1	1	33.9	0.9	0.0	1.0	32.9	0.0	33.9	0
37	Sd93711	1	1	32.6	0.9	0.0	1.0	31.6	0.0	32.6	0
38	Sd93811	1	1	31.3	0.9	0.0	0.9	30.4	0.0	31.3	0
39	Sd93911	1	1	30.1	0.9	0.0	0.9	29.2	0.0	30.1	0
40	Sd94011	1	1	29.0	0.9	0.0	0.9	28.1	0.0	29.0	0
41	Sd94111	1	1	27.9	0.9	0.0	0.8	27.0	0.0	27.9	0
42	Sd94211	1	1	26.8	0.9	0.0	0.8	26.0	0.0	26.8	0
43	Sd94311	1	1	25.8	0.9	0.0	0.8	25.0	0.0	25.8	0
44	Sd94411	1	1	24.8	0.9	0.0	0.7	24.0	0.0	24.8	0
45	Sd94511	1	1	23.8	0.9	0.0	0.7	23.1	0.0	23.8	0
46	Sd94611	1	1	22.9	0.9	0.0	0.7	22.2	0.0	22.9	0
47	Sd94711	1	1	22.0	0.9	0.0	0.7	21.4	0.0	22.0	0
48	Sd94811	1	1	21.2	0.9	0.0	0.6	20.5	0.0	21.2	0
49	Sd94911	1	1	20.4	0.9	0.0	0.6	19.8	0.0	20.4	0
50	Sd95011	1	1	19.6	0.9	0.0	0.6	19.0	0.0	19.6	0
51	Sd95111	1	1	18.8	0.9	0.0	0.6	18.3	0.0	18.8	0
52	Sd95211	1	1	18.1	0.9	0.0	0.5	17.6	0.0	18.1	0
53	Sd95311	1	1	17.4	0.9	0.0	0.5	16.9	0.0	17.4	0
54	Sd95411	1	1	16.7	0.9	0.0	0.5	16.2	0.0	16.7	0
55	Sd95511	1	1	16.1	0.9	0.0	0.5	15.6	0.0	16.1	0
56	Sd95611	1	1	15.5	0.9	0.0	0.5	15.0	0.0	15.5	0
57	Sd95711	1	1	14.9	0.9	0.0	0.4	14.4	0.0	14.9	0
58	Sd95811	1	1	14.3	0.9	0.0	0.4	13.9	0.0	14.3	0
59	Sd95911	1	1	13.8	0.9	0.0	0.4	13.3	0.0	13.8	0
60	Sd96011	1	1	13.2	0.9	0.0	0.4	12.8	0.0	13.2	0

Table 9. Results of MIP model for SDI system with Annual Lagrangian Multiplier Undiscounted Values

year	VAR X	level	Q.sec	size	PV	ac-ft	S.Wat	S.Land	S.Drip	V of ac-ft	SP	PV-SP
01	Swf90146	6	4	w	187.1	0.86	70.1	5.4	121.4	60.4	187.2	0
02	Swf90246	6	4	w	179.9	0.86	70.1	5.2	114.5	60.4	180.0	0
03	Swf90346	6	4	w	173.0	0.86	70.1	5.0	107.7	60.4	173.1	0
04	Swf90446	6	4	w	166.4	0.86	70.1	4.8	101.3	60.4	166.4	0
04	Swe90445	5	4	w	162.0	0.75	74.7	4.8	101.3	56.3	162.3	0
05	Swe90545	5	4	w	155.8	0.75	74.7	4.6	95.2	56.3	156.1	0
06	Swe90645	5	4	w	149.8	0.75	74.7	4.4	89.4	56.3	150.1	0
07	Swe90745	5	4	w	144.0	0.75	74.7	4.2	83.8	56.3	144.3	0
08	Swe90845	5	4	w	138.5	0.75	74.7	4.1	78.4	56.3	138.8	0
08	Swd90844	4	4	w	114.4	0.63	50.6	4.1	78.4	31.9	114.4	0
09	Swd90944	4	4	w	110.0	0.63	50.6	3.9	74.2	31.9	110.0	0
10	Swd91044	4	4	w	105.7	0.63	50.6	3.8	70.1	31.9	105.7	0
11	Swd91144	4	4	w	101.7	0.63	50.6	3.6	66.2	31.9	101.7	0
12	Swd91244	4	4	w	97.8	0.63	50.6	3.5	62.4	31.9	97.8	0
13	Swd91344	4	4	w	94.0	0.63	50.6	3.4	58.8	31.9	94.0	0
13	Swc91343	3	4	w	72.9	0.49	21.9	3.4	58.8	10.7	72.9	0
14	Swc91443	3	4	w	70.1	0.49	21.9	3.2	56.1	10.7	70.1	0
15	Swc91543	3	4	w	67.4	0.49	21.9	3.1	53.6	10.7	67.4	0
16	Sve91623	3	2	v	110.7	0.86	21.9	3.0	89.0	18.8	110.8	0
17	Sve91723	3	2	v	106.5	0.86	21.9	2.9	84.8	18.8	106.5	0
18	Sve91823	3	2	v	102.4	0.86	21.9	2.8	80.8	18.8	102.4	0
19	Sve91923	3	2	v	98.5	0.86	21.9	2.7	77.0	18.8	98.5	0
20	Sve92023	3	2	v	94.7	0.86	21.9	2.5	73.3	18.8	94.7	0
21	Sve92123	3	2	v	91.0	0.86	21.9	2.5	69.8	18.8	91.0	0
22	Sve92223	3	2	v	87.5	0.86	21.9	2.4	66.4	18.8	87.5	0
22	Svd92222	2	2	v	76.4	0.75	10.2	2.4	66.4	7.7	76.4	0
23	Svd92322	2	2	v	73.4	0.75	10.2	2.3	63.5	7.7	73.5	0
24	Svd92422	2	2	v	70.6	0.75	10.2	2.2	60.8	7.7	70.7	0
25	Svd92522	2	2	v	67.9	0.75	10.2	2.1	58.2	7.7	67.9	0
26	Svd92622	2	2	v	65.3	0.75	10.2	2.0	55.6	7.7	65.3	0
27	Svd92722	2	2	v	62.8	0.75	10.2	1.9	53.2	7.7	62.8	0
28	Svd92822	2	2	v	60.4	0.75	10.2	1.9	50.8	7.7	60.4	0
29	Svd92922	2	2	v	58.0	0.75	10.2	1.8	48.6	7.7	58.1	0
30	Svd93022	2	2	v	55.8	0.75	10.2	1.7	46.4	7.7	55.8	0
31	Cvh93112	2	1	v	75.3	1.88	10.2	1.7	54.4	19.2	75.3	0
32	Cvh93212	2	1	v	72.4	1.88	10.2	1.6	51.6	19.2	72.4	0
33	Cvh93312	2	1	v	69.6	1.88	10.2	1.5	48.9	19.2	69.6	0
34	Cvh93412	2	1	v	66.9	1.88	10.2	1.5	46.2	19.2	66.9	0
34	Svd93411	1	1	v	47.7	0.75	0.0	1.5	46.2	0.0	47.7	0
35	Svd93511	1	1	v	45.9	0.75	0.0	1.4	44.5	0.0	45.9	0
36	Svd93611	1	1	v	44.1	0.75	0.0	1.4	42.8	0.0	44.1	0
37	Svd93711	1	1	v	42.4	0.75	0.0	1.3	41.1	0.0	42.4	0
38	Svd93811	1	1	v	40.8	0.75	0.0	1.3	39.5	0.0	40.8	0
39	Svd93911	1	1	v	39.2	0.75	0.0	1.2	38.0	0.0	39.2	0
40	Svd94011	1	1	v	37.7	0.75	0.0	1.2	36.5	0.0	37.7	0
41	Svd94111	1	1	v	36.3	0.75	0.0	1.1	35.1	0.0	36.3	0
42	Svd94211	1	1	v	34.9	0.75	0.0	1.1	33.8	0.0	34.9	0
43	Svd94311	1	1	v	33.5	0.75	0.0	1.0	32.5	0.0	33.5	0
44	Svd94411	1	1	v	32.2	0.75	0.0	1.0	31.2	0.0	32.2	0
45	Svd94511	1	1	v	31.0	0.75	0.0	1.0	30.0	0.0	31.0	0
46	Svd94611	1	1	v	29.8	0.75	0.0	0.9	28.9	0.0	29.8	0
47	Svd94711	1	1	v	28.7	0.75	0.0	0.9	27.8	0.0	28.7	0
48	Svd94811	1	1	v	27.5	0.75	0.0	0.9	26.7	0.0	27.6	0
49	Svd94911	1	1	v	26.5	0.75	0.0	0.8	25.7	0.0	26.5	0
50	Svd95011	1	1	v	25.5	0.75	0.0	0.8	24.7	0.0	25.5	0
51	Svd95111	1	1	v	24.5	0.75	0.0	0.8	23.7	0.0	24.5	0
52	Svd95211	1	1	v	23.5	0.75	0.0	0.7	22.8	0.0	23.6	0
53	Svd95311	1	1	v	22.6	0.75	0.0	0.7	21.9	0.0	22.6	0
54	Svd95411	1	1	v	21.8	0.75	0.0	0.7	21.1	0.0	21.8	0
55	Svd95511	1	1	v	20.9	0.75	0.0	0.6	20.3	0.0	20.9	0
56	Svd95611	1	1	v	20.1	0.75	0.0	0.6	19.5	0.0	20.1	0
57	Svd95711	1	1	v	19.4	0.75	0.0	0.6	18.8	0.0	19.4	0
58	Svd95811	1	1	v	18.6	0.75	0.0	0.6	18.0	0.0	18.6	0
59	Svd95911	1	1	v	17.9	0.75	0.0	0.6	17.4	0.0	17.9	0
60	Svd96011	1	1	v	17.2	0.75	0.0	0.5	16.7	0.0	17.2	0