Economic Strategies to Synergistically Produce Bioenergy and Optimize Aquifer Life in the US High Plains

Karthik Ramaswamy, Nelson Institute Center for Sustainability and the Global Environment, University of Wisconsin-Madison, karthik.ramaswamy@wisc.edu
Nazli Z. Uludere Aragon, University of Montana, nazli.aragon@mso.umt.edu
Tyler J. Lark, Nelson Institute Center for Sustainability and the Global Environment, University of Wisconsin-Madison, lark@wisc.edu

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ABSTRACT

Irrigated production in most parts of the US High Plains is suffering from declines in the Ogallala aquifer. This study seeks to determine the potential opportunities for replacing irrigated corn (*Zea Mays*) with irrigated sorghum (*Sorghum bicolor (L.) Moench*) as an alternative crop or fully replacing it with bioenergy feedstock on a typical field in the US High Plains. The primary focus of this study was to find the maximum discounted returns from the remaining groundwater, given the market conditions and available groundwater in five pilot counties overlying the Ogallala. Our approach for this study is to: (1) create an economic analysis to estimate the net returns of different farming systems, including irrigated corn, irrigated sorghum, non-irrigated corn, non-irrigated sorghum, switchgrass (*Panicum virgatum L.*), pasture, or CRP for rental; (2) use existing remotely sensed data on the aquifer and well characteristics in the study area; (3) find the minimum saturated thickness to support 90 days of pumping; and (4) use an enterprise budgets approach to figure out the net returns of different irrigated (corn and sorghum) and non-irrigated (corn, sorghum, and switchgrass) farming systems. (5) using a 30-year multiperiod model, determine the optimal irrigated and non-irrigated crop choices for five major irrigated locations across the US High Plains, subject to groundwater constraints. We developed enterprise budgets for the selected agricultural systems in one pilot county from each of the HPA states: Colorado, Kansas, Nebraska, Oklahoma, and Texas. Using aquifer properties and well-drawdown equations, we estimated the amount of groundwater available and irrigation costs for the pilot counties. We entered crop budgets, irrigation amounts, and available groundwater volume into a 30-year mixed-integer linear programming (MILP) model to calculate the net present value of irrigated and non-irrigated crop choices. Early-stage research results suggest that producers switch to irrigated sorghum, which gives the highest production and greatest NPV per unit of groundwater. The study results also show the most economically viable non-irrigated agricultural systems in the five counties. Furthermore, this study demonstrates the optimal well capacities for replacing corn with sorghum which gives higher net returns per unit of water as well capacity are restricted.

1. INTRODUCTION

The agricultural industry is essential to the U.S. High Plains region's economy, as grain production has established the region as the leading supplier of livestock feed in the nation. This agricultural enterprise generates an estimated $35 billion in market sales (Scalon et al., 2012). Crop cultivation comprises 39% of agricultural production in this region, of which about 30% is irrigated by groundwater. Source of this groundwater is the High Plains Aquifer (HPA, that includes the Ogallala Aquifer) covering 174,000 square miles, is the largest aquifer in the US and one that experiences one of the highest rates of groundwater withdrawals in the nation, coupled with limited recharge. With the advent of pumping technology in and center-pivot irrigation systems after World War II, irrigated agriculture expanded rapidly in the region, putting increasing pressure on groundwater resources under conditions now exacerbated by climate change (Hornbeck and Keskin, 2014 and U.S. Geological Survey, 2022). With groundwater withdrawal levels exceeding the recharge rate, producers face decreased well capacities, lower crop yields, and higher extraction costs. These challenges are forcing producers to adopt either by switching to less water-intense crops, transition to dryland production, including pasture for livestock, or cease their cropping operations--either temporarily, by enrolling in Conservation Reserve Program, or permanently.

Today, biomass-derived energy contributes over 37% of the total renewable energy consumption (U.S. Energy Information Administration, 2023). Nearly half of that is supplied by domestically produced biofuels. Nonetheless, the majority of biofuel production in the US still uses food crop-based feedstocks like corn (*Zea Mays*) and the country remains far from meeting its advanced cellulosic biofuel production targets set by the Renewable Fuel Standard (Cui et al., 2018). Several factors play a role in this lag, such as producers' lack of familiarity with growing new perennial feedstocks like switchgrass, uncertainties surrounding biomass and conversion yields (which increase costs), and the dominance of corn ethanol and soy biodiesel in meeting existing transport fuel blending needs that leaves less room for alternative feedstocks. Switchgrass (*Panicum virgatum L.*), a native perennial herbaceous energy crop, is attractive because of its drought tolerance and reliance on fewer inputs, high expected biomass yield, and suitability to marginal and degraded lands. Sorghum (*Sorghum bicolor (L.) Moench*), another candidate energy crop, is an annual that can be used as either animal feed or bioenergy feedstock and might be more readily adopted by farmers due to its familiarity, shorter-term commitment, and multiple uses within existing markets compared to switchgrass. Like switchgrass, biomass sorghum offers high yields with reduced input needs and is also tolerant to drought. In fact, previous studies have shown that irrigated sorghum could be more profitable than irrigated corn as well capacities decline below 5 gallons per minute per acre (Ramaswamy, 2016 & Warren et al., 2015). This is because sorghum can provide higher returns per unit of water than corn.

In this study, we estimate the maximum long-term benefits and opportunities of producing alternative bioenergy feedstocks from agricultural lands over the HPA, subject to groundwater limitations, and representative of expected market conditions. Specifically, we seek to quantify, spatially, the extent to which producers might adopt such cropping systems – biomass sorghum or switchgrass – across the HPA to in relation to available alternatives such as corn grain production, pasture, or enrollment into the CRP. To assess the full scope of production alternatives, we factor in the rental rates for pasture and CRP, alongside the expected net benefits of irrigated corn, irrigated sorghum, dryland corn, dryland sorghum, and switchgrass. The production value of the irrigated lands is determined by finding the optimal extraction path (annual withdrawal amount from the aquifer) of limited groundwater for irrigation of corn and grain sorghum based on the concept of "User Cost" or the profits foregone due to current use. In this preliminary iteration, the study area consists of 5 pilot counties overlying the HPA.

2. METHODS

In the early-stage analysis, we restrict our model to five pilot counties over the HPA and use groundwater characteristics from the literature. Then in subsequent iterations, we will perform analysis over the entire HPA at the (irrigated) field level to maximize economic benefits by choosing the most profitable production following an optimal groundwater extraction path under alternative pumping rates. A broader groundwater model is anticipated to have basis from the studies done by Gleeson et al., 2014 on global hydrogeology maps (GLHYMS), Lin et al., 2024 on irrigation well location from, Xie and Tyler, 2021 on locating irrigated and non-irrigated field locations and Ruess et al., 2024 on irrigation volumes by crop. Our approach is summarized below, and also outlined in Figure 1:

1. Construct an economic analysis to estimate the net returns of growing different agricultural systems.
2. Utilize existing remotely sensed data on aquifer and well characteristics in the study area.
3. Intersect the groundwater permeability and porosity to estimate the minimum saturated thickness to sustain 90-days pumping.

4. Calculate net returns under alternative irrigated (corn and sorghum) and non-irrigated (corn, sorghum and switchgrass) agricultural systems using an enterprise budgets approach.
5. Determine the optimal irrigated and non-irrigated crop choices for five major irrigated locations across the US High Plains, subject to groundwater constraint, using a 30-year multiperiod model.

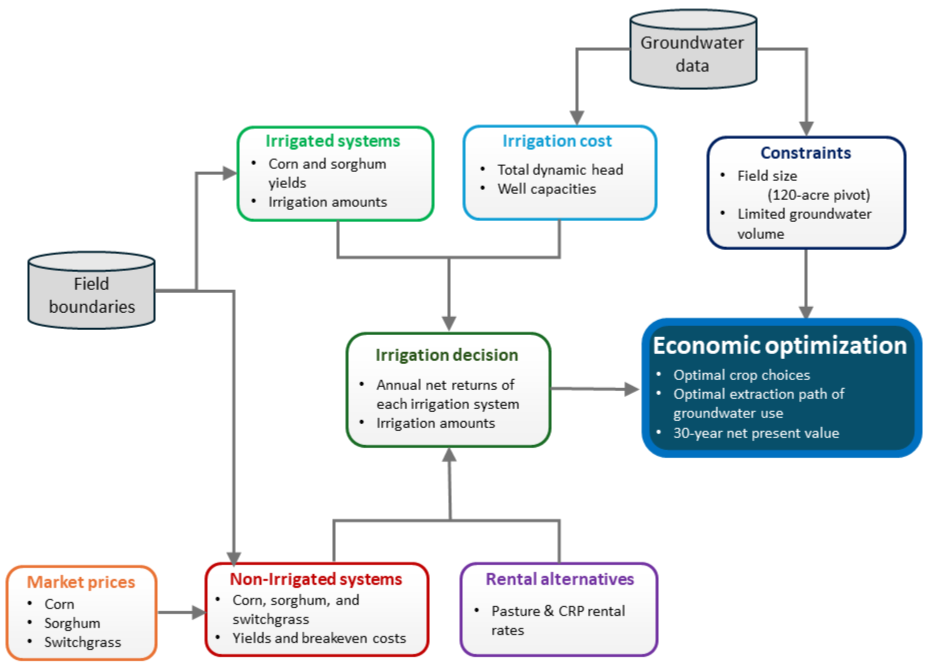

Figure 1. Flowchart showing the outline of the methods of the present study

2.1 Selecting the counties for economic analysis

We selected one county from five major HPA states-- Colorado, Kansas, Nebraska, Oklahoma and Texas-- based on previous studies (Deines et al., 2020; Hacker et al., 2016) and data availability. Hacker et al., 2016 and Deines et al., 2109 located regions in HPA where groundwater pumping is likely to become uneconomical if saturated thickness is less than 30 feet. In the case of unconfined HPA, the saturated thickness is defined as the vertical distance between the bedrock surface and the water table. Furthermore, Deines et al., 2020 used a random forest method to identify and rank the highest percentage of irrigated lands that would transition to dryland or pasture production by county. To test this hypothesis, we selected the same counties, and used a well drawdown method to calculate the minimum saturated thickness required to pump 600 gallons per minute (GPM) for a growing season. The five counties used in the pilot study are shown in Figure 2.

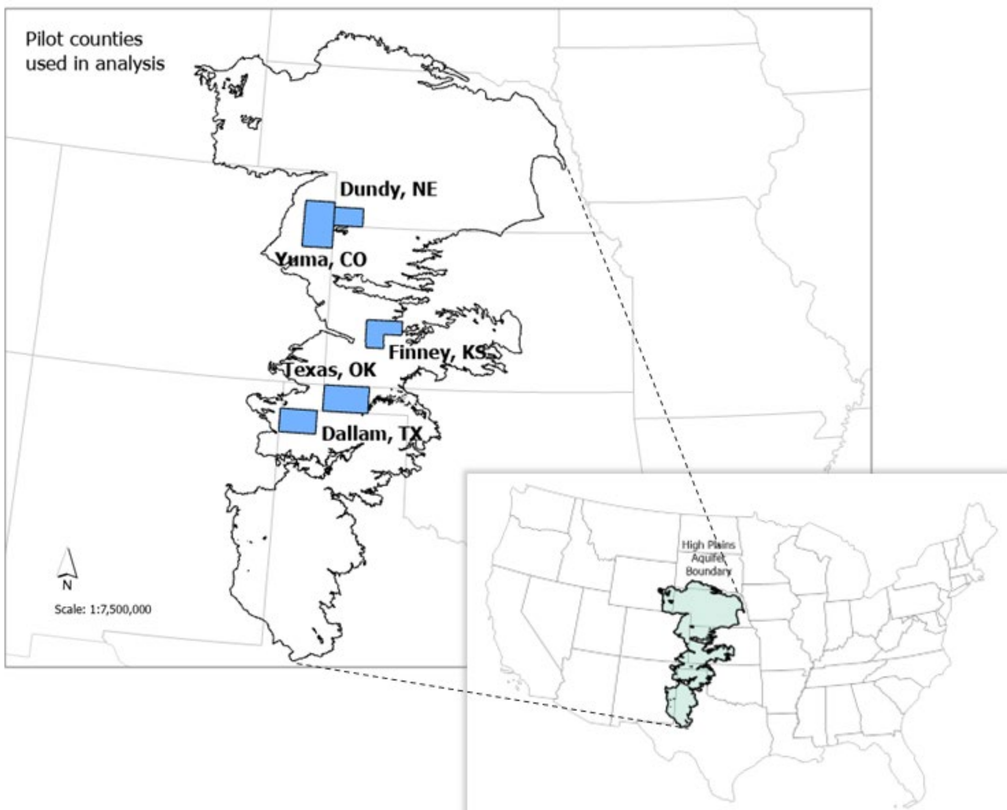

Figure 2. Selected counties for the pilot study in the HPA

2.2 Representative field and irrigation methods

This study analyzes the potential for irrigated crop selections on 120-acre pivot field under the general assumption of maximum well capacity, which may sustain irrigation for ninety days. In this study, farm characteristics assumed are, a) 120-acre pivot field is irrigated using a center pivot on a quarter section (160-acre, ¼ square mile), b) the pivot is connected to a groundwater well and pump system with capacity of 600 GPM. A representative farm is shown in Figure 3.

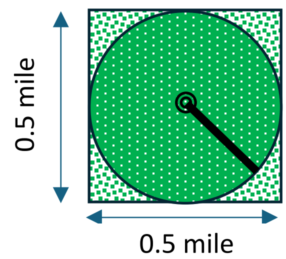

Figure 3. Showing the representative center pivot on a typical field dimension in the HPA region

Table 1 shows the groundwater characteristics of the selected counties. The minimum saturated thickness required to sustain 600 GPM is calculated based on approximation of well drawdown equation to determine the depth of 90-day cone of depression for the well capacities 100, 200, ..., 600 GPM (Cooper-Jacob, 1946, Theis, 1935, and Hecox et al., 2008). Saturated thickness is then split into layers which are assumed as minimum thickness required to sustain 90 days of pumping for the mentioned well capacities (Ramaswamy, 2016). Furthermore, there was no observed well interference at ¼ mile, indicating that the wells are operating independently. The specific yield is an important factor in estimating the actual groundwater available, the volume of groundwater available for a 160-acre field is calculated as Volume = 160 x porosity x saturated thickness. Porosity gives the capacity of a rock formation to absorb and store ground water (Buddemeier and Schloss, 2000). Porosity ranges between 0 to 100%. To irrigate the 120-acre pivot field, the only supply of groundwater is beneath the 160-acre land, and there is no horizontal movement between the adjacent lands. Figure 4 shows the permeability, porosity, and change of water level in the High Plains region.

Table 1. Aquifer characteristics and groundwater volume data for the five pilot counties in the HPA

		Hydraulic conductivity		Groundwater supply	
	Porosity	(ft/day)	(m/day)	Saturated thickness[1] (ft)	Remaining groundwater supply[2] (MMCF)
Yuma, CO	0.27	25.92	7.90	50	94.18
Finney, KS	0.15	25.04	7.63	53	55.41
Dundy, NE	0.19	24.36	7.43	53	70.26
Texas, OK	0.22	25.63	7.81	51	78.28
Dallam, TX	0.22	25.63	7.81	51	78.28

[1]Safety zone 35 ft.

[2]Assuming 100% of area is irrigated.

[3]Million cubic feet (MMCF)

a) b)

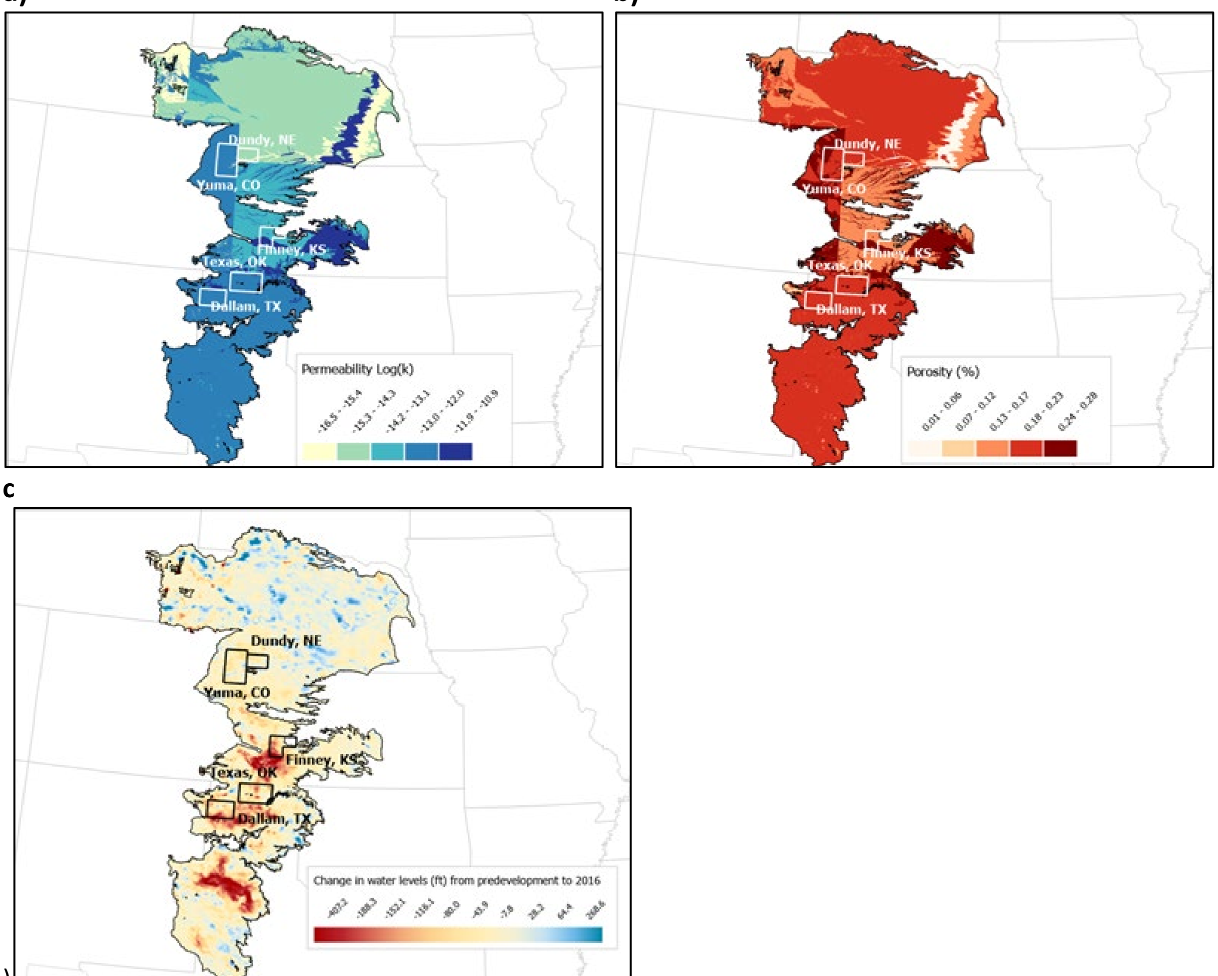

Figure 4. Estimates of High Plains aquifer properties and groundwater level change since 1950 in the study area. a) permeability map of High Plains region extracted from Gleeson et al.,

2014, b) porosity maps of High Plains region extracted from Gleeson et al., 2014, and c) change of groundwater levels in the High Plains region from predevelopment (1950) to 2016 following McGuire and Strauch, 2022

2.3 Economic analysis

Economic analysis consists of two major steps: (1) constructing an economic analysis and incorporating crop activities, irrigation amounts, pumping costs, and groundwater supply constraints into a 30-year mixed integer linear programming (MILP) model to determine the optimal crop choices, groundwater use, and (2) determining the net present value (NPV) for a typical 120-acre field over 30 years. The MILP model has the option to invest in 120-acre pivot in the beginning of the planning period and choose optimal irrigated crop choices until the groundwater is exhausted and switches to dryland cropping systems that give the greatest net returns.

2.3.2 Static enterprise (crop) budgets

We developed expected crop budgets for irrigated corn and non-irrigated sorghum, and switchgrass as follows. First, (county average crop yield data were collected from NASS (National Agricultural Statistics Service) over a representative timeframe (2000–2018). We also obtained (annual average state-level) prices for corn and sorghum from 2009–2023. The expected irrigated yields and market prices are shown in Figure 5 and 6, respectively. Where we had issues with gaps in county-level average yield data, an issue mainly for sorghum, we substituted them by the agricultural district average yields or mimic the yield trend of corn. We also document a possible anomaly associated with sorghum yields where the predicted sorghum yields using corn yield trend can vary from the actual performance of sorghum hybrid development in the High Plains region.

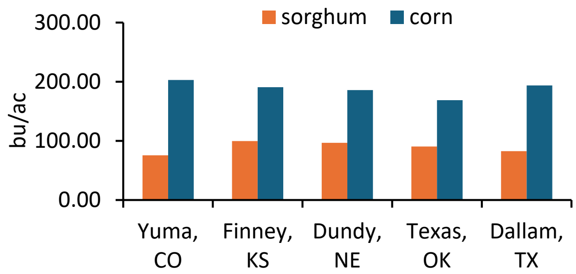

Figure 5. Average expected crop yields of corn and sorghum in Colorado, Kansas, Nebraska, Oklahoma, and Texas from 2000-2018

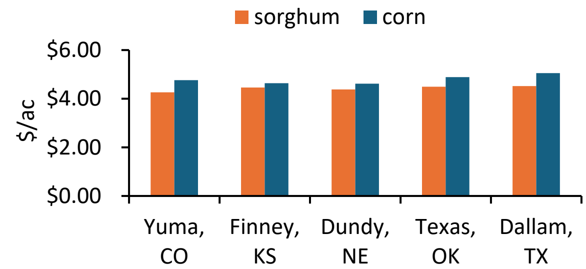

Figure 6. Annual average market prices of corn and sorghum in Colorado, Kansas, Nebraska, Oklahoma, and Texas from 2009-2023

Considering the observed yield averages from NASS as response to irrigation at 800 GPM with no deficit or delayed irrigation. Crop yields and gross irrigation amounts were extended to determine the yield responses for well capacities ranging from 100 to 800 GPM in increments of 100 GPM using the relative yield response to irrigation identified in Ramaswamy et al, 2017. Crop yields for well capacities mentioned above are shown in Table A2.

Next, we derive county average yields for switchgrass using modeled pixel level yields from Daly et al., 2018. For switchgrass production, we assume that the land is owned, and the crop has a productive lifespan of 10 years (though this can extend up to 20 years). Establishment is done via conventional tillage. The projected farm gate price for switchgrass biomass is $55/ton (Brandes et al., 2018). Pasture and conservation reserve program (CRP) county rental rates are collected from US Department of Agriculture Farm Service Agency (USDA FSA) for the year 2021.

Static crop budgets were developed based on current Kansas State University Enterprise budgets. Specific irrigation cost for total depth and well capacities was calculated using NPC (Nebraska pumping criteria) approach subject to total dynamic head and the well capacities. We assumed that the nozzle pressure (psi), the lateral discharge, and the field elevations would remain constant across all well capacities to simplify the calculation process.

2.3.2 Multiperiod programming model

Utilizing an optimization model helps us effectively test / determine feasible profit-maximizing choices of farm enterprise subject to a set of fixed groundwater and land constraints. Optimization models are good at representing the profit maximizing objective and resource costs / constraints of a typical farm enterprise and can make considerably accurate predictions about producers' crop choices.

For each pilot county groundwater characteristics, independent 30-year models mixed integer programming model (MILP) were formulated to invest in a center pivot ($60,000) that will maximize the NPV from the limited groundwater. The MILP determines the NPV, crop selections, and rate of groundwater use, the purchase of pivot or not is taken by the integer variable. The MILP model is constraints from land with 160 acres with 120-acre allocated to irrigation crop activity, water supply is constrained to the pumping capacity/aquifer level. The NPV maximization for pivot investment is expressed as,

$$\max NPV = \sum_{t=1}^{30} (R_{iwt} I_{iwt} - N_{it} D_{jt}) - P,$$

s.t.,
Total Land,

$$\sum_{i,j}\sum_{w} I_{iwt}+D_{jt} = 160 \text{ is true } \forall t,$$

Irrigated Land,

$$\sum_{i}\sum_{W} I_{iWt} - 120\times P\leq 0, \text{ is true } \forall t; P\in\{0,1\}$$

Water Supply,

$$\sum_{i}\sum_{W}\sum_{t} W_{iWt}I_{iWt}\leq WS_f \text{ for all } t,$$

where, R_{iwt} is the discounted net returns per acre for the irrigated crop i (corn or sorghum) at well capacity w in year t, I_{iwt} is the net irrigated area of crop i (corn or sorghum) at well capacity w in year t, N_{jt} is the discounted net returns of non-irrigated system choices j in year t, D_{jt} is the area allocated to dryland practice for system j in year t, W_{iwt} is the amount of irrigation required per acre to allocate the irrigated crop i using the well capacity j in year t, the pivot investment in year zero is decided on whether the integer variable P takes 0 or 1.

3. RESULTS

3.1 Static budgets

The results section discusses irrigated crop budgets, non-irrigated system budgets, optimal groundwater use, and NPV. Under the myopic (annual profit maximization) strategy and assuming groundwater factors, producers in Yuma, Colorado, and Dallam, Texas, would prioritize irrigating corn over sorghum using a 120-acre pivot, regardless of the capacity of the wells. In a similar short-term maximization scenario, a producer in Finney County, Kansas, Dundy County, Nebraska, and Texas County, Oklahoma, would irrigate corn under well capacities of 500–200 GPM, opting to irrigate sorghum only at 100 GPM.

A representative budget for irrigated corn and irrigated sorghum at 600 GPM are shown in Figure 7a-7e. Static budgets are the most common and widely used approach in crop decision making with absence of “Users Cost”. In the limited groundwater scenario, user’s cost is the opportunity cost of delaying the extraction.

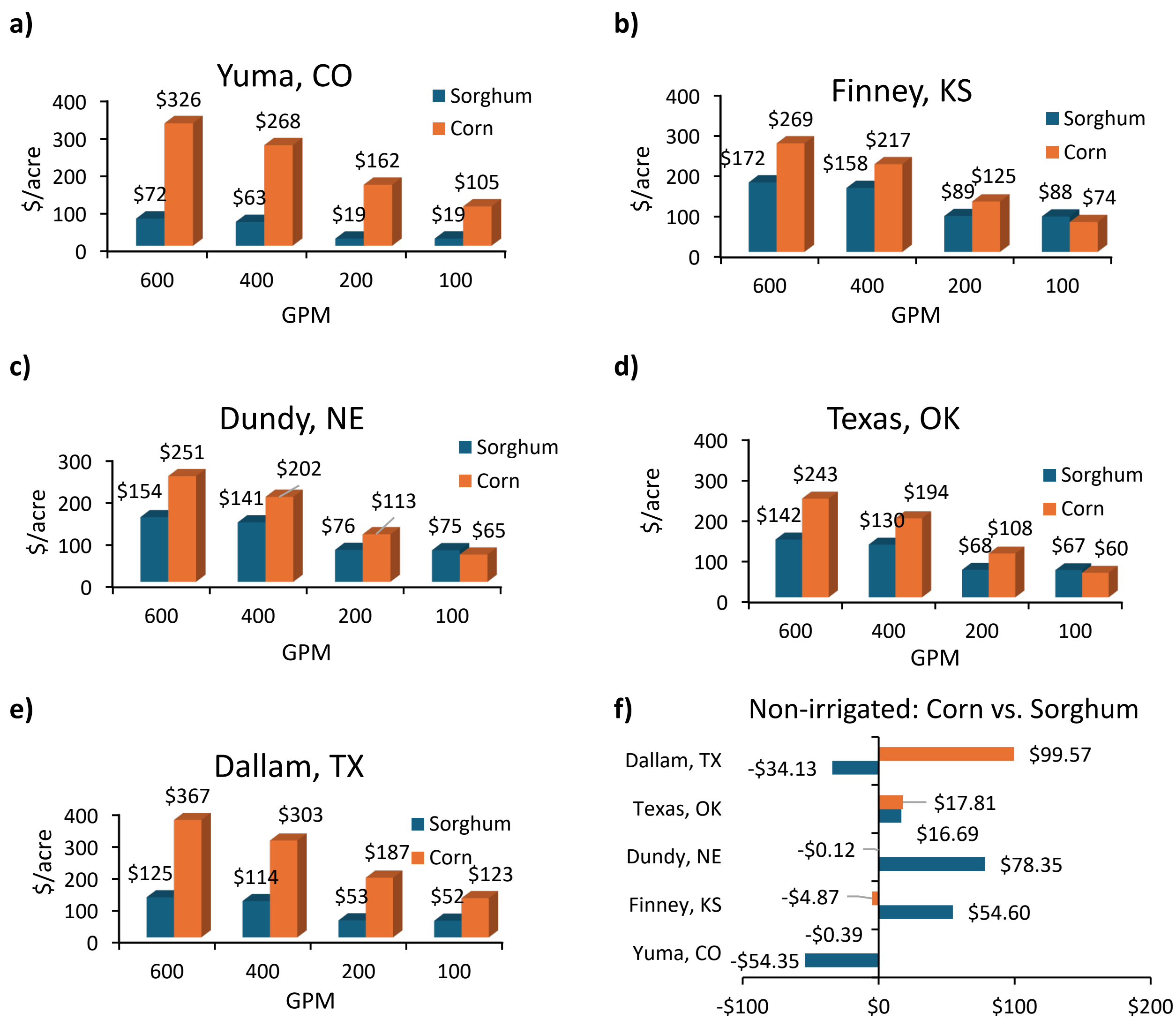

Figure 7. Static budgets showing undiscounted net returns for irrigated corn and sorghum by county (panels a-e), panel f) showing the non-irrigated corn and sorghum net returns by county

3.2 MILP results

Preliminary results show the effects of groundwater decline and benefits of alternative crop selections in the five pilot counties. The results follow the Euler theorem in the constant returns to scale of homogenous degree one. The results are shown in Figure 8.

3.2.1 Typical 120-acre field in Yuma, Colorado with 600 GPM well capacity and 94.18 MMCF of available groundwater

In Yuma, Colorado, it is profitable to irrigate continuous corn for the first 18 years and then transition to the CRP program in year 19. This is because the total net returns for irrigating corn were higher than irrigating sorghum and these profits covered the marginal value of land, the shadow price of water and the pivot investment. At 600 GPM, the net returns per acre for irrigating corn and sorghum were $332.14 and $77.55, respectively. The value of resources (land and water) at 600 GPM was satisfied by the irrigating corn. However, the cost of resources of irrigating sorghum was $212.95 per acre which is short by $135.40 per acre ($212.50–$77.55). During the period from year 2 to year 18, the maximum pumping rate at which water could be drawn from the well decreased from 500 to 100 GPM while irrigating corn. By the thirteenth year, the well's capacity had reached its maximum of 100 GPM. The discounted net returns for corn were $66.13 per acre and for irrigating sorghum in year 13 were $12.82 per acre, which fell short of the value of resources by $31.84 per acre ($44.66 minus $12.82). In year 19, the field has used all the allocated groundwater, and the CRP was the most profitable option for dryland practices. During years 19 to 30, it was economically advantageous to lease the land to CRP for $40 per acre.

3.2.2. Typical 120-acre field in Finney, Kansas with 600 GPM well capacity and 55.41 MMCF available groundwater

Irrigated sorghum becomes more profitable than irrigated corn when the well capacities decline to 600 GPM and below, and non-irrigated sorghum gives net returns among the dryland system choices. In year one, the net returns of corn were $277.01 per acre, and sorghum were $173.28 per acre. In year 2, the withdrawal capacity was still 600 GPM, and it was profitable to fully replace irrigated corn with irrigated sorghum until year 26. Even though the net returns of irrigated corn per acre ($266.36) were significantly higher than those of irrigated sorghum per acre ($166.61), the value of using groundwater resources is greater than the attainable returns from 120 acres. This is because the value of corn production is $277.80 per acre and stayed above the expected returns until year 26. In year 27, non-irrigated sorghum became the system that gave the maximum benefit among the dryland options.

3.2.3 Typical 120-acre field in Dundy County, Nebraska with 600 GPM well capacity and 70.26 MMCF available groundwater

In Dundy County, Nebraska, it is profitable to irrigate 120-acre field for first two years and fully replace with irrigated sorghum as the well capacity reduces to 500 GPM in year three. The MILP results suggest that it is optimal to irrigate sorghum from year 3 through 30 without transition to dryland production. The static budgets for well capacity 500 to 200 GPM show that the discounted return for irrigating corn is always greater than sorghum. Example: At 300 GPM, corn is $120.12 per acre vs. sorghum is $112.88 per acre. However, irrigating sorghum becomes a profitable choice because the value of marginal product (VMP) of groundwater for each input ($58.44 per acre-feet) and land constraint ($54.44 per acre) is paid by the net returns of sorghum ($112.88 per acre). The VMP of each input of groundwater for producing corn at 300 GPM is $113.09 per acre, and VMP for one acre is $54.44 which exceeds the profit of the producing corn ($167.53 > $112.88 per acre).

3.2.4 Typical 120-acre field in Texas County, Oklahoma with 600 GPM well capacity and 78.28 MMCF available groundwater

The irrigated crop choices in Texas County, Oklahoma are like Dundy County, Nebraska, where irrigated corn was replaced by irrigated sorghum until the end of year 30 and no transition to dryland. However, in Texas, Oklahoma the corn was irrigated until year 6 before fully replacing it with corn. It was profitable to irrigate corn from year 1-5 until the well capacities declined to 300 GPM and fully replaced with irrigated sorghum in year 6.

With 300 GPM capacity wells, it required 1.19 acre-feet of irrigation to produce 140.9 bushels per acre to generate net returns of $130.01 per acre, while it requires 0.61 acre-feet of irrigation to produce 90.1 bushels per acre to give net returns of $109.95 per acre. The VMP of one unit of groundwater (acre-feet) at 300 GPM at year 6 is $89.17 and one acre is $55.56. Even though the yield and net returns of irrigating corn gives the highest yield and net returns, sorghum exhausts the distributive shares of the inputs (0.61*$89.17 + 1*$55.56 = $109.95 per acre) is paid by producing sorghum. However, producing corn at 300 GPM in year 6 does not pay the distributive shares of land and water (1.19*$89.17 + 1*$55.56 = $161.67 per acre), which is greater than the potential net returns of $109.95 per acre.

3.2.5. Typical 120-acre field in Dallam County, Texas with 600 GPM well capacity and 78.28 MMCF available groundwater

According to the MILP results, producing irrigated corn is profitable until the groundwater runs out in year 15. In year 16, it was time to transition to non-irrigated system choices, and dryland corn gave the greatest net return from years 15–30. Based on the MILP analysis results, irrigated corn production remains economically viable until groundwater depletion occurs in the 15th year. Due to continuous corn production choices, the 78.28 MMCF of groundwater runs out by year 15. In the 16th year, a shift towards non-irrigated system options was necessary, and dryland corn proved to be the most profitable alternative from the 16th to the 30th year. Among the dryland corn production in five counties, dryland corn net returns in Dallam, Texas, gave the greatest net returns of $99.57 per acre, which is also higher than the net returns of irrigating sorghum with a 300 GPM well capacity.

In this situation, sorghum irrigation at a rate of 300 GPM in year 6 was not able to achieve competitiveness with corn. Results show that the value of the groundwater per acre-foot is $84.58 and one acre is $93.25. To produce corn in Dallam County, Texas, under the current groundwater conditions with a 300 GPM capacity well, it requires 1.19 acre-feet of water. In the same case, sorghum requires about 0.61 acre-feet of water. The allocation of resources for corn, which accounts to $100.65 acre-feet for groundwater and $93.25 per acre for land, totals $193.90 per acre. This allocation is sufficient to generate a profit of $193.90 per acre from corn irrigation at a discharge rate of 300 GPM. However, distributive shares of sorghum at 300 GPM (0.61 multiplied by $84.58 plus $93.25 equals $144.85 per acre) does not meet the profitability achieved by irrigating sorghum at a rate of 300 GPM, which is only about $67.58 per acre.

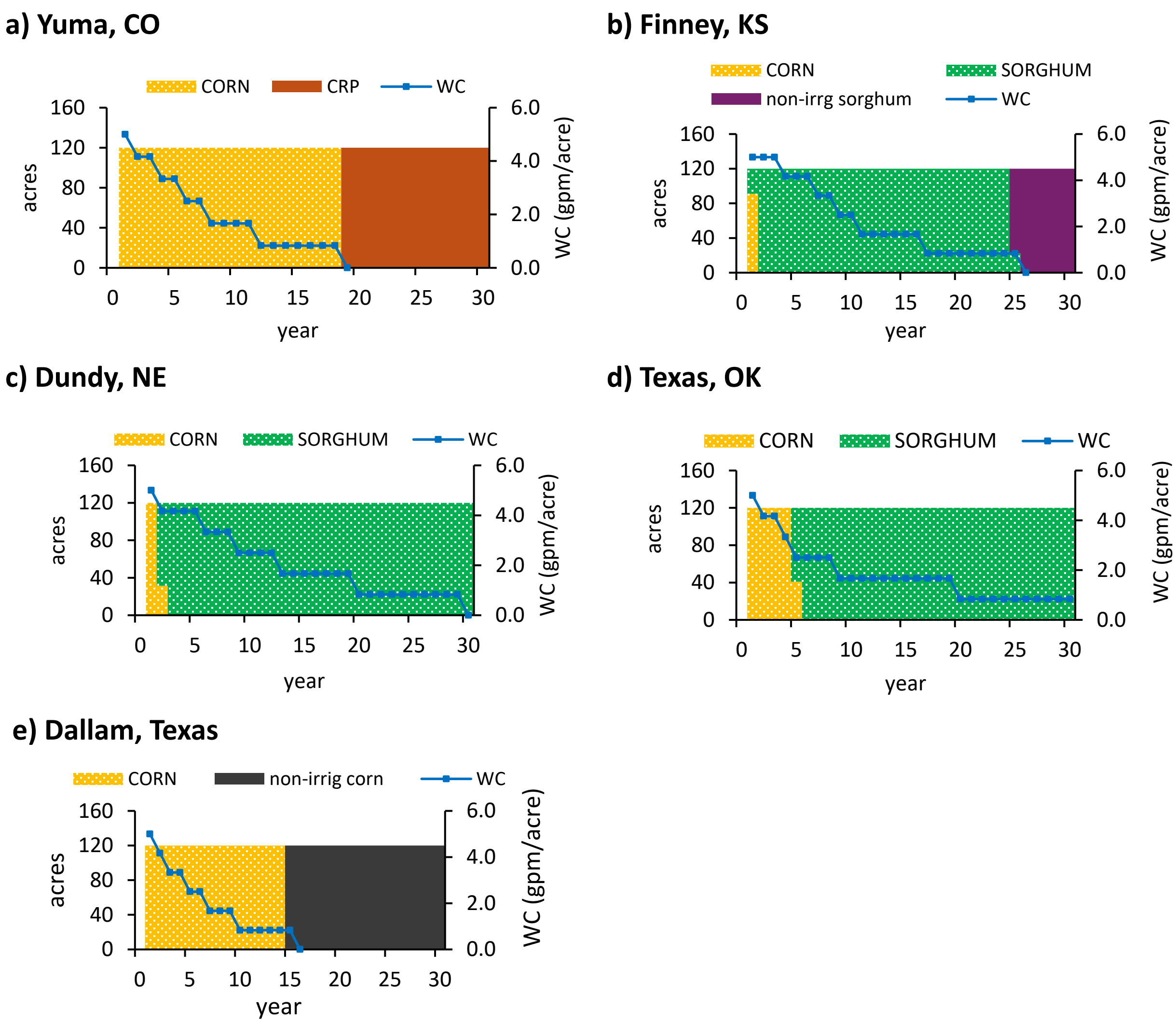

Figure 8. Optimal crop choices followed by dryland activities as the well capacities decline for a) Yuma, Colorado for 120-acre pivot with WC 600 GPM and 94.18 MMCF, b) Finney, Kansas for 120-acre pivot with WC 600 GPM and 55.41 MMCF, c) Dundy, Nebraska for 120-acre pivot with WC 600 GPM and 70.26 MMCF, d) Texas, Oklahoma for 120-acre pivot with WC 600 GPM and 78.28 MMCF, e) Dallam, Texas for 120-acre pivot with WC 600 GPM and 78.28 MMCF

3.3 Non-irrigated crop budgets

The Figure 9 shows the non-irrigated agricultural systems enterprise budgets. The non-irrigated enterprise budgets are conducted for corn, sorghum, and switchgrass, and rental rates were used for pasture and CRP. The budgets indicate that, according to a deterministic approach, leasing the land to CRP in Yuma County was a more profitable than adopting dryland agricultural methods or renting the land for pasture. According to estimations, the highest net return per acre in Finney, Kansas, could be obtained by implementing dryland sorghum practices (approximately $54.60 per acre). Switchgrass production, yielding $35 per acre, is ranked second, followed by leasing the land to CRP for $35 per acre annually. Among the dryland practices evaluated in Dundy, Nebraska, producing sorghum at a cost of $78.35 per acre is the most profitable option, followed by switchgrass at $33.06 per acre, or leasing the land to CRP for $43 per acre. The most economically beneficial dryland practice in Texas County, Oklahoma is to establish switchgrass production with net returns of $22.11 per acre per year. Dryland corn emerges as the next best option at $17.81 per acre; however enrolling into the CRP could return up to $23 per acre per year. The most economically viable dryland practice in Dallam County, Texas, is to implement corn production with returns of $99.57 per acre. Establishing switchgrass, which yields $18.37 per acre annually, or leasing to CRP at $30 per acre annually, is the subsequent most profitable alternative.

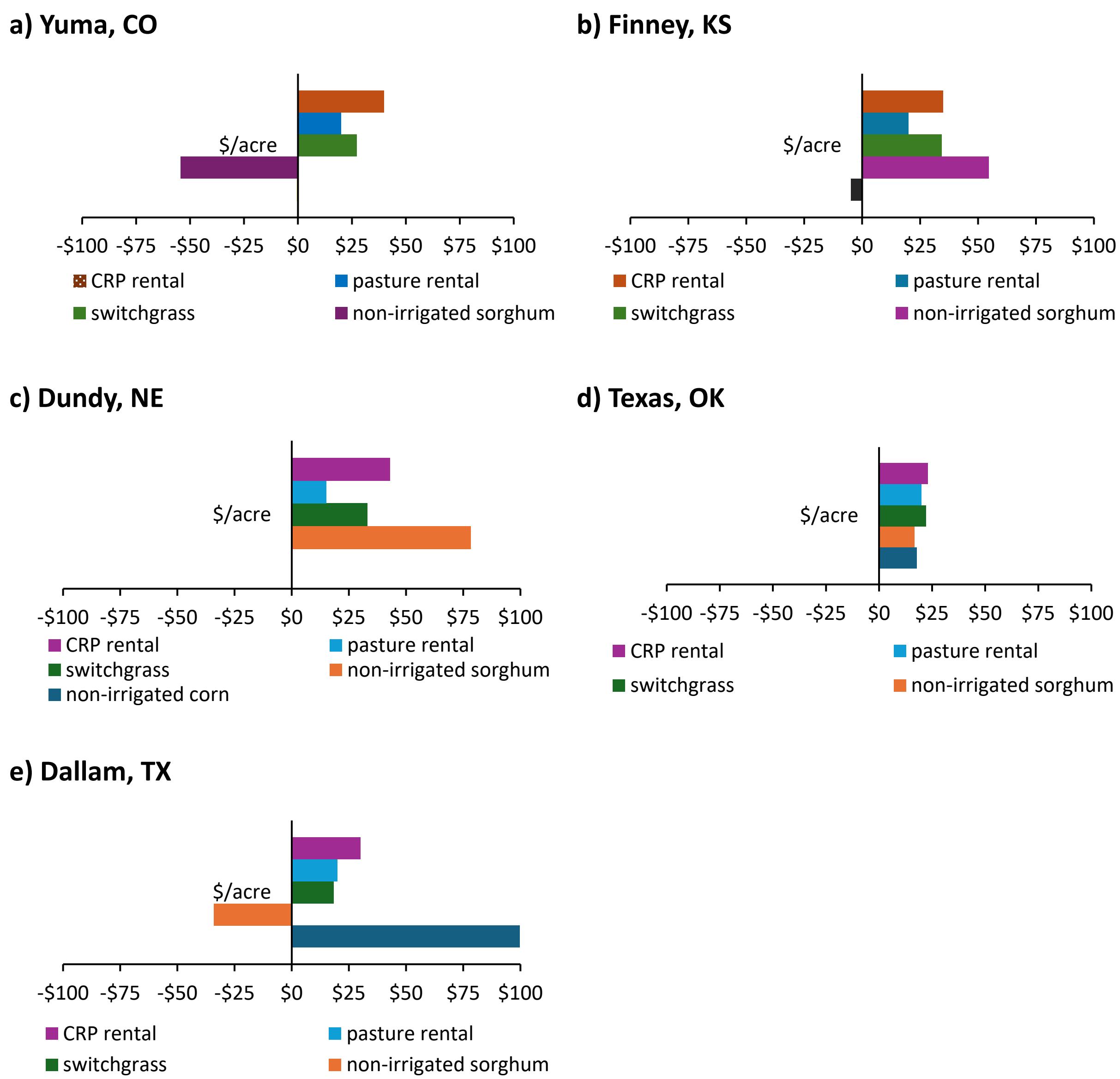

Figure 9. Net returns per acre of non-irrigated corn, non-irrigated sorghum and switchgrass, and rental rates for pastureland and CRP, a) Yuma, Colorado, b) Finney, Kansas, c) Dundy, Nebraska, d) Texas, Oklahoma, and 3) Dallam, Texas

3.4 NPV results

Table 2 lists the optimal NPV of the remaining groundwater in each of the five counties. The present value and the quantity of bushels produced over the lifespan of the aquifer's life are contrasted in the table. Of the five counties, Yuma County, Colorado, had the highest cumulative present value, earning $321,695 from a 120-acre field that produced corn continuously for eighteen years. When the well capacity reduces to 500 GPM in year 2, however, replacing maize with sorghum until year 26 had a greater present value ($4,489.73 per MMCF) and production efficiency ($4,250 bushels per MMCF) per unit of water.

The largest production from the remaining groundwater is produced by a 120-acre field in Dundy, Nebraska with 70.26 MMCF of available groundwater, followed by Texas, Oklahoma with 277,471 bushels from 78.28 MMCF. A contributing factor to increased production in Texas, OK and Dundy, NE is the adoption of less water-demanding sorghum and longer irrigation periods. However, many factors influence the quantity of production and the value of groundwater. Remaining groundwater, yield per unit of water, price (market demand), and production costs are a few of the most important variables.

Table 2. NPV, production, value of production, efficiency of groundwater for the selected counties and its respective groundwater availability

	Groundwater (MMCF)	NPV[2] (US $)	Production[3] (bushels)	Value of production (PV/MMCF)	Production Efficiency (bushels/MMCF)
Yuma, CO	94.18	$321,695	268,221	$3,415.75	2,848
Finney, KS	55.41	$248,776	235,516	$4,489.73	4,250
Dundy, NE	70.26	$297,865	297,186	$4,239.47	4,230
Texas, OK	78.28	$257,810	277,471	$3,293.43	3,545
Dallam, TX	78.28	$300,426	210,873	$3,837.84	2,694

[1] one million cubic feet (MMCF) ~ 28,316.85 cubic meters
[2]Cummulative net present value from the irrigated area; pivot cost = $60,000
[3]Corn and sorghum grain production in bushels from irrigation operations; one bushel = 56 lbs. or 0.0254 Mg

4. DISCUSSION and CONCLUSION

Our preliminary findings show that investing in a center pivot system and irrigating grain sorghum in the HPA could maximize the value of the remaining groundwater resources. Corn is sensitive to drought and requires large irrigation amounts compared to sorghum. As irrigation capacity declines, an increase in well depth raises the irrigation cost per unit of yield to grow corn. Grain sorghum has higher water use efficiency at lower well capacities, and therefore irrigating sorghum emerged as the more profitable alternative. Therefore, crop producers in the High Plains could choose to irrigate corn when the irrigation capacity is sustainable to cover the costs of the groundwater resources.

One of the challenges we need to address in our next iteration is obtaining a more spatially complete and representative sorghum yield data to carry out the study for all the counties and arrive at realistic economic results when sorghum goes head-to-head with corn. Due to gaps in county level yield data from NASS, we may need to substitute modeled sorghum yields (e.g., from Billion Ton Study Update) Except Texas, all the states included in this analysis lacked complete data on irrigated and non-irrigated sorghum yields at the county level. It is expected that simulated and validated yield data will be utilized to substitute the missing data.

Another data gap we will work to fill is to estimate irrigation amounts (water use) . It was challenging to obtain the specific irrigation amounts applied for the yield data used from NASS agricultural survey. The irrigation amounts we assume are based on the average weather and typical agronomic crop water needs. As an alternative, irrigation amounts applied and yield responses from field trials can be used to estimate the relative irrigation amounts for the yields in this study. We will also explore leveraging remotely sensed datasets, like OpenET (https://etdata.org/), to gauge water use. Lastly, because there is not an established market for switchgrass, we have assumed the switchgrass farm gate price as $55/ton for all the counties in the HPA. In our next iteration, we will consider alternative farmgate price levels (e.g., breakeven) and consider and distance to biorefineries for assessing switchgrass profitability.

The groundwater remaining in HPA is a finite resource. Despite implementing optimal conservation practices, areas with low recharge rates and crop water demands, such as the Southern High Plains and western parts of the Central and Northern High Plains regions, are expected to experience continued decline in groundwater levels. However, in the Northern High Plains, where groundwater recharge is attained, sustainable groundwater pumping levels are achieved. Thus, our future research is to include the amount of annual recharge in locations where groundwater replenish is observed. Furthermore, at times, multiple wells are located within the same aquifer and in close proximity to each other. As a result, it is possible that their depression cones may intersect. Pumping interference occurs when the depression cones of two or more proximate pumping wells intersect. Interference occurs when the span of influence of one well overlaps with another. Including multiple well pumping scenarios in this study can improve the exact nature of groundwater flow predictions.

This study uses a deterministic model, which does not allow for flexibility to alternate between different decisions farmers can make (e.g., deciding to irrigate during a dry year and using less irrigation during a wet year, or experimenting with different crop rotations to conserve soil moisture). For our next, more comprehensive (field-scale) modeling exercise, we will evaluate additional scenarios incorporating variability in economic drivers, groundwater availability, yields , and land quality where we plan to perform sensitivity analysis (comparative statics) or utilize stochastic programming to better represent uncertainty in some parameters. Lastly, looking at the cost and lifespan of different irrigation methods when making multistage investment decisions can help find prospects when it is time to replace center pivot with new and more efficient alternative methods of irrigation to optimal groundwater extraction path.

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APPENDIX

Table A1. Expected yield for corn and sorghum, and switchgrass biomass

	Crop Yield							
	Irrigated ($bu\ ac^{-1}$)		Non-Irrigated ($bu\ ac^{-1}$)		Irrigated ($Mg\ ha^{-1}$)		Non-Irrigated ($Mg\ ha^{-1}$)	
	corn	sorghum	corn	sorghum	corn	sorghum	corn	sorghum
Yuma, CO	203.0	75.7	12.74	4.75	53.6	33.0	3.36	2.07
Finney, KS	190.8	99.7	11.97	6.26	54.2	61.6	3.40	3.86
Dundy, Nebraska	186.0	96.8	11.67	6.07	56.0	69.8	3.51	4.38
Texas, Oklahoma	168.7	90.4	10.58	5.67	56.8	24.7	3.56	1.55
Dallam, Texas	193.7	82.7	12.15	5.19	76.6	36.2	4.81	2.27

Table A2. Average market price (2009-2023) data from NASS

	(US dollars per bushel)		(US dollars per metric ton)	
	corn	sorghum	corn	sorghum
Yuma, CO	$4.76	$4.26	$187.39	$167.71
Finney, KS	$4.64	$4.46	$182.67	$175.58
Dundy, Nebraska	$4.62	$4.38	$181.88	$172.43
Texas, Oklahoma	$4.89	$4.49	$192.51	$176.76
Dallam, Texas	$5.05	$4.52	$198.81	$177.94

Table A3. Annual rental rates for CRP and grassland

	Rental rates (US dollars ac^{-1})		Rental rates (US dollars ha^{-1})	
	CRP	Pasture	CRP	Pasture
Yuma, CO	$40.00	$20.00	$98.84	$49.42
Finney, KS	$35.00	$20.00	$86.49	$49.42
Dundy, NE	$43.00	$15.00	$106.25	$37.07
Texas, OK	$43.00	$20.00	$56.83	$49.42
Dallam, TX	$30.00	$20.00	$74.13	$49.42

Table A4. Estimated static budgets for irrigated corn and sorghum for well capacities 100 to 800 GPM for Yuma, Colorado

	GPM	Yield (bu/ac)	Revenue ($/ac)	Variable Costs ($/ac)	Net Returns ($/ac)
Irrigated corn	800		966.28	570.68	395.60
	700		911.06	553.28	357.78
	600		856.32	530.25	326.07
	500		807.30	508.85	298.45
	400		754.94	487.27	267.67
	300		661.16	445.72	215.44
	200		567.39	404.94	162.45
	100		463.15	358.45	104.70

		Yield (bu/ac)	Revenue ($/ac)	Variable Costs ($/ac)	Net Returns ($/ac)
Irrigated sorghum	800		322.48	249.89	72.59
	700		320.35	249.04	71.31
	600		321.20	248.85	72.35
	500		314.81	246.71	68.10
	400		305.87	242.49	63.38
	300		271.79	230.58	41.21
	200		224.08	204.99	19.09
	100		219.82	200.61	19.21

Non-irrigated

	Yield (bu/ac)	Revenue ($/ac)	Variable Costs ($/ac)	Net Returns ($/ac)
Corn	53.6	255.14	255.53	(0.39)
Sorghum	33.0	140.58	194.93	(54.35)

Table A5. Estimated static budgets for irrigated corn and sorghum for well capacities 100 to 800 GPM for Finney, Kansas

	GPM	Yield (bu/ac)	Revenue ($/ac)	Variable Costs ($/ac)	Net Returns ($/ac)
Irrigated corn	800		885.31	554.74	330.57
	700		834.74	538.27	296.47
	600		784.62	516.12	268.50
	500		739.62	495.46	244.16
	400		691.82	474.76	217.06
	300		605.98	434.69	171.29
	200		520.14	395.40	124.74
	100		424.56	350.51	74.05

		Yield (bu/ac)	Revenue ($/ac)	Variable Costs ($/ac)	Net Returns ($/ac)
Irrigated sorghum	800		444.66	272.20	172.46
	700		441.54	271.18	170.36
	600		442.88	271.06	171.82
	500		434.40	268.55	165.85
	400		421.92	263.66	158.26
	300		375.09	249.42	125.67
	200		309.08	220.37	88.71
	100		303.28	215.68	87.60

Non-irrigated

	Yield (bu/ac)	Revenue ($/ac)	Variable Costs ($/ac)	Net Returns ($/ac)
Corn	54.2	251.49	256.36	(4.87)
Sorghum	61.6	274.74	220.14	54.60

Table A6. Estimated static budgets for irrigated corn and sorghum for well capacities 100 to 800 GPM for Dundy, Nebraska

	GPM	Yield (bu/ac)	Revenue ($/ac)	Variable Costs ($/ac)	Net Returns ($/ac)
Irrigated corn	800		859.32	548.06	311.26
	700		810.35	531.99	278.36
	600		761.38	510.12	251.26
	500		717.95	489.88	228.07
	400		671.29	469.44	201.85
	300		588.13	430.06	158.07
	200		504.50	391.31	113.19
	100		412.10	347.24	64.86

		Yield (bu/ac)	Revenue ($/ac)	Variable Costs ($/ac)	Net Returns ($/ac)
Irrigated sorghum	800		423.98	269.55	154.43
	700		420.92	268.53	152.39
	600		422.23	268.42	153.81
	500		413.91	265.90	148.01
	400		402.52	261.20	141.32
	300		357.41	247.13	110.28
	200		294.34	218.46	75.88
	100		289.08	213.86	75.22

Non-irrigated

	Yield (bu/ac)	Revenue ($/ac)	Variable Costs ($/ac)	Net Returns ($/ac)
Corn	56	258.72	258.84	(0.12)
Sorghum	69.8	305.72	227.37	78.35

Table A7. Estimated static budgets for irrigated corn and sorghum for well capacities 100 to 800 GPM for Texas, Oklahoma

	GPM	Yield (bu/ac)	Revenue ($/ac)	Variable Costs ($/ac)	Net Returns ($/ac)
Irrigated corn	800		824.94	523.28	301.66
	700		778.00	508.60	269.40
	600		731.06	488.15	242.91
	500		689.00	469.05	219.95
	400		644.50	450.04	194.46
	300		564.80	413.09	151.71
	200		484.60	376.77	107.83
	100		395.60	335.28	60.32
Irrigated sorghum	800		405.90	263.43	142.47
	700		403.20	262.51	140.69
	600		404.55	262.39	142.16
	500		396.47	259.98	136.49
	400		385.24	255.38	129.86
	300		342.14	242.00	100.14
	200		281.97	214.34	67.63
	100		276.58	209.78	66.80

Non-irrigated

	Yield (bu/ac)	Revenue ($/ac)	Variable Costs ($/ac)	Net Returns ($/ac)
Corn	56.8	277.75	259.94	17.81
Sorghum	45.5	204.3	187.61	16.69

Table A8. Estimated static budgets for irrigated corn and sorghum for well capacities 100 to 800 GPM for Dallam, Texas

	GPM		TX	TX	TX
Irrigated corn	800	193.7	978.19	558.09	420.10
	700	182.7	922.64	541.49	381.15
	600	171.7	867.09	519.12	347.97
	500	161.8	817.09	498.24	318.85
	400	151.3	764.07	477.32	286.75
	300	132.6	669.63	437.08	232.55
	200	113.8	574.69	397.48	177.21
	100	92.9	469.15	352.30	116.85

		Yield (bu/ac)	Revenue ($/ac)	Variable Costs ($/ac)	Net Returns ($/ac)
Irrigated sorghum	800	82.7	373.80	256.41	117.39
	700	82.1	371.09	255.48	115.61
	600	82.4	372.45	255.37	117.08
	500	80.8	365.22	253.14	112.08
	400	78.5	354.82	248.72	106.10
	300	69.7	315.04	236.07	78.97
	200	57.4	259.45	209.41	50.04
	100	56.4	254.93	205.03	49.90

Non-irrigated

	Yield (bu/ac)	Revenue ($/ac)	Variable Costs ($/ac)	Net Returns ($/ac)
Corn	76.6	386.83	287.26	99.57
Sorghum	36.2	163.62	197.75	(34.13)

Table A9. Static budgets of Switchgrass analyzed in this study

	Yield (Mg/ha)	Net revenue ($/ac)	Variable cost ($/ac)	Net returns ($/ac)
Yuma, CO	7.04	156.69	129.43	27.26
Finney, KS	7.59	168.94	134.59	34.35
Texas, OK	7.49	166.71	133.65	33.06
Dundy, NE	6.64	147.79	125.68	22.11
Dallam, TX	6.35	141.34	122.97	18.37