Irrigation water conservation in Texas Panhandle and Texas South Plains

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Abstract

Texas Panhandle and Texas South Plains rely on the depleting Ogallala Aquifer as their main water source, especially for irrigation water. The paper investigates a variety of water conservation policies including water restriction, conversion to dryland production, the use of more water-efficient technology, and in addition a mixture of these policies. More specifically, our paper analyze different simulations regarding county-specific farmers' net revenues and aquifer saturated thickness over the multiple policy scenarios. Through this investigation, the paper aims at determining the long term economic impacts of these policies for 44 counties in Texas Panhandle and Texas South Plains in responding to the depleting Ogallala aquifer. From evaluating the economic impacts, the paper tries to propose appropriate policies for different counties based on their specific agricultural characteristics and water supply conditions.

Keywords: Simulations, conservation policies, irrigation water, Texas Panhandle, Texas South Plains

1 Introduction

Agriculture plays a crucial part in the Texas High Plains economy. More specifically, farm size within the High Plains Trade Area is substantially larger than in the rest of Texas. In this region, farm size is on average roughly 1,864 acres, while the state average is 511 acres. At the same time, the Texas High Plains - a semi-arid region - has become more and more vulnerable to severe drought conditions. In addition, the region is heavily dependent on the Ogallala Aquifer as a main water source especially for irrigation. Indeed, with irrigators withdrawing most of this water from the Ogallala Aquifer; 74 percent of all groundwater is used for irrigation, or 4.8 million acre-feet per year, and about 36 percent is used to meet municipal demands.[1] Relate the percentage here to the figures in next paragraph.

For both Texas Panhandle and Texas South Plains region, irrigation water makes up a greater proportion than other uses of water. Indeed, for 2011 in the Texas Panhandle, agriculture use was 2,482,135 acre-feet of groundwater as compared to municipal use of 83,881 and the use of 34,474 acre-feet by mining and manufacturing.[2] Acre-feet here is a measure referring to the volume of water sufficient enough to cover an acre of land 1-foot deep. In the same year in the Texas South Plains, agriculture use was 3,655,841 acre-feet of groundwater as compared to municipal use of 85,114 and mining and manufacturing use of 10,445 acre-feet. Indeed, from the table in Figure 1 showing the Ogallala aquifer water withdrawals in 2013, we can see that the share of withdrawal for agriculture in Texas is the highest among the states along the Ogallala Aquifer.[3]

Table 1 Groundwater-based agriculture in the 215 counties over the Ogallala Aquifer

State	Groundwater irrigation withdrawals		Irrigated crop sales from groundwater		Irrigated acres from groundwater		Irrigated farms (all water sources)	
	taf	Share of withdrawals	Million $	Share of State	Million acres	Share of State	Thousand farms	Share of State
NE	7,960	86.6	3,543.8	83.71	7.17	83.75	16.05	93.68
TX	5,601	99.3	1,851.7	3.76	3.54	0.71	6.02	30.51
CO	1,395	63.1	418.8	30.30	0.75	26.21	3.36	21.29
KS	2,845	97.0	1,289.4	87.71	2.44	88.43	4.56	76.50
WY	411	40.9	22.7	12.31	0.12	7.66	1.04	17.92
NM	514	85.6	82.8	16.93	0.21	25.88	0.76	7.43
OK	272	87.1	94.2	24.57	0.23	42.55	0.55	18.11
SD	22	41.3	2.8	.13	0.01	2.53	0.10	6.39
Total Ogallala	19,000	87.9	7,222.6	61.64	14.40	64.02	32.42	40.94
Share of National Total		31.7 %		11.0%		25.4%		10.8%

Figure 1

Unfortunately, groundwater levels, especially in the Central and Southern Ogallala regions that cover Texas, have been steadily declining in recent decades as the rate of irrigation withdrawals gradually exceed the natural recharge rate. The average annual recharge rate throughout the Ogallala Aquifer has been reported to be around three inches for the whole aquifer while some

1. Texas Water Development Board (2016).
2. Texas Water Development Board (2013).
3. Gollehon and Winston (2013).

areas in the Texas Panhandle and South Plain regions have been seeing decline in water levels of around two feet annually (USGS 2017).

Nonetheless, some counties within the Texas High Plains region see significant declines in water levels, while some other counties see negligible reduction. These variations may be due to differences in agricultural production and the extent of its dependency on the Ogallala Aquifer. Given the importance of agriculture in the region and the heavy dependence on irrigation water from Ogallala Aquifer in the two regions of interest, there is a need for conservation policies. With this in mind, we need to look at the multiple conservation policies for a broader range of counties across different agricultural scale and groundwater withdrawal. Our paper, therefore, consider various conservation policies including conversion to dryland production, irrigation technology adoption, water pumping restrictions and analyze how their impacts may vary in terms of farmers' welfare. For example, for regions that see substantial declines in ground water levels, some form of water restriction policies or conversion to dryland production might be more appropriate.

Our paper thus aims at evaluating economic impacts of different irrigation water conservation policies while taking into account the different climatic and production characteristics of each county in the Texas Panhandle and the Texas South Plains. In order to do so we conduct simulations for different policy scenarios and analyze the available data sets to obtain a comprehensive look at recent developments in tackling the water problem within this particular region in Texas.

2 Literature Review

Most of the articles analzying irrigation water conservation policies in Texas region overlying Ogallala Aquifer we investigate use a dynamic optimization model with respect to net present value of returns while accounting for all farmers' welfare and aquifer changes depending on each policy. The impacts of water conservation policies are evaluated through different simulations over time. The simulations vary across different papers regarding the different of interest, different policies to investigate, different time horizon, and different counties to analyze. This variation further shed light on how some policies may be applied to different regions while some others might not.

Almas et al. (2006) analyze the impacts on farmers' welfare of alternative water conservation policies as a response to the depleting Ogallala Aquifer in the Texas Panhandle over the 60-year period. The analysis is conducted by constructing economic optimization models for 23 counties, specifically looking at the production of nine major crops. They evaluate net present value of farmers' income and total water use across multiple policy scenarios in order to determine the optimal crop and irrigation technology in balancing between maximizing farmers revenue and aquifer water level. By running simulations for different policies, the paper represents various trade-offs of switching between policies or switching from no policy to policy implementation through the changing net revenues and groundwater usage. Almas et al. (2006) highlight the increasing conversion to dryland production as the main response of farmers to depleting aquifer. Nevertheless, they propose that beside conversion to dryland production, crop rotation is worth considering as an optimal policy.

Amosson et al. (2009) look at the impacts of different irrigation water conservation policies in Texas High Plains over a 60-year horizon considering the changes in both saturated thickness and farmers' income. Their paper addresses a wide range of water conservation policies consisting of both temporary and permanent conversion to dryland, irrigation technology adoption, biotechnology, and water pumping restrictions. Through their analysis, Amosson et al. (2009) propose the use of water pump restrictions with other water conservation policies to enhance the policy impacts on saturated thickness and net revenues. In aligning with Amosson et al. (2009), Almas et al. (2014) evaluate the impacts of different water conservation policies coupled with water pump restrictions, but rather for only four representative counties: Dallam, Sherman, Moore and Hartley in the Texas Panhandle. Almas et al. (2014) argue for the analysis of these policies impact within the bigger context of the regional economy. Almas et al. (2017) focus on analyzing how combining water pump restriction with the rest of the policies may affect farmers' income and aquifer economic life. They argue that biotechnology adoption, the use of newly developed, drought resistant crops, together with water pump restrictions is the most efficient.

Arabiyat et al. (2001), on the other hand, evaluate the impacts of irrigation technology adoption including conventional, sprinkler irrigation, and dryland together with biotechnology adoption in the Texas High Plains. However, the paper analyzes particularly the possible trade-offs between farmers net revenues and aquifer saturated thickness involved in the adoption of different irrigation technologies. They argue that the considerations of these tradeoffs are important for better design of groundwater conservation policies. Arabiyat et al. (2001) propose that even though there are costs to the farmers income when adopting more efficient irrigation technology, when comparing to the benefits of extending economic life of Ogallala Aquifer, irrigation technology and advanced biotechnology adoption is worth considering. Leatham et al. (2006), on the contrary, take a different analysis approach, focuses particularly on irrigation technology adoption. They evaluate whether each of the irrigation systems available in the Texas High Plains including low energy precision application (LEPA) sprinkler irrigation, subsurface drip irrigation (SDI), and variable rate irrigation (VRI) is worth adopting by comparing farmers revenues of each irrigation technology with respect to the current crop prices. Leatham et al. (2006) then conclude that sprinkler irrigation is profitable under the current crop prices while variable rate irrigation is profitable with higher cotton price or higher yield. On the other hand, subsurface drip irrigation is the least profitable across different yield and crop price scenario despite having the most efficient use of water.

Terrell et al. (2002) look into three policies that respond to the depletion of the Ogallala Aquifer in the Texas South Plains region over a 30-year horizon: an increase in the adoption of sprinkler irrigation, the substitution of higher-yield corn for other grain crops, and the conversion to dryland production. They argue that the increased conversion to dryland agriculture is the best response to declining water levels and saturated thickness in the region. Additionally, they argue that the economic impact of these policies should be analyzed both within the agricultural sector and in the context of the economic performance of the region as a whole. They highlight cotton irrigated and dryland production as the optimal policy choices in balancing farmers' net revenues and aquifer saturated thickness. Moreover, due to the decreasing irrigated acreage in the region, the contribution of agricultural production to regional economy may decline which might require other non-agricultural sector to thrive to sustain regional economic growth.

Johnson et al. (2009) evaluate the economic outcomes of a water pumpage fee policy and a water pumpage quota policy in the Texas South Plains and Eastern New Mexico by comparing these two policies with the baseline scenario where no policy is being implemented. They emphasize the need to tailor policies according to varying hydrologic conditions and agricultural production characteristics across different regions. More specifically, the paper argues for an immediate focus on implementing water conservation on the most heavily irrigated counties where saturated thickness is relatively low. Johnson et al. (2009) conclude that water pumpage quota is more effective in terms of conserving water, especially for those counties with serious aquifer depletion problem. Nevertheless, the water pumpage quota negatively affects regional economy due to decreasing irrigated acre and in turn reducing agriculture's contribution to regional economy.

Feng (1992) looks at the intertemporal efficiency of groundwater allocation for irrigation in The Texas High Plains. Using dynamic programming, profit maximization and quadratic programming models, Feng (1992) tries to derive the optimal crop combination, irrigation technology and groundwater extraction rates. He found that irrigated cotton and switching to more water-efficient LEPA irrigation technology is optimal in conserving and sustaining revenue for the counties studied in the Texas High Plains.

Das et al. (2010) evaluate the impacts of two water conservation policies in the Texas High Plain: groundwater extraction tax and groundwater extraction quota by analyzing agricultural costs together with groundwater withdrawal. Through their analysis, they propose that the two policies are similar in managing the groundwater extraction amount, neither significantly curb groundwater withdrawal, but the tax policy may impose higher cost on farmers. Deciding which policy to implement, therefore, depends on water managers' objective. The quota policy would be better to minimize the cost of conservation if the enforcement cost for the quota is not too high. Otherwise, the tax policy might be preferable (Das et al. 2010). Moreover, they emphasize that the tax policy effectiveness varies depending on the crop market prices.

In consistent with previous literature, our paper also looks at simulations for different policy scenarios considering both farmers' net revenues and aquifer saturated thickness. Our paper specifically considers policies such as conversion to dryland production, conversion to water-efficient irrigation technology and the implementation of different pumping water restriction percentage. On the other hand, our paper attempts to make contributions in several ways. First, we investigate policy impacts in both Texas Panhandle and Texas South Plains. The paper additionally consider the possibilities of mixing water restriction policy with conversion to water-efficient irrigation technology while also considering different level of water pumpage restriction. Furthermore, the paper looks at all counties in the two regions of interest across different degree of saturated thickness depletion and agricultural production.

2.1 Current agricultural practices in the study area

In Texas, Groundwater Conservation Districts currently handle the local management of groundwater resources. Along with the establishment of management districts, multiple policies have been designed and/or implemented to achieve short- and long-run objectives with respect to groundwater management. These policies include water use fees, water pump restrictions, the adoption of more drought tolerant crops, enhanced irrigation technology, and temporary and permanent conversion to dry land production (Amosson et al., 2009; Wang et al., 2015). The goals of these policies is to respond to the depletion of the Ogallala Aquifer by reducing water used for agriculture so as to extend the economic life of the Ogallala Aquifer while sustaining farmers' net revenues in the region. Amosson et al. (2009) mentions a biotechnology policy scenario referring to the adoption of drought-tolerant cotton that increases production per unit of water. However, there is not much data indicating the implementation of any drought tolerant crops to the farmers in our study area. As a result, we do not consider this policy scenario in our paper.

Consequently, our paper analyzes forty four counties in the Texas Panhandle and South Plains regions. These two regions' main crops include corn, wheat, cotton, and grain sorghum and as a result, these four crops will be the main crops being used in our analysis.

Across the Texas Panhandle and Texas South Plains, conservation policies are limited by the type of crop production technology. More especially, crops are produced using particular types of technology for delivering water. In the Texas Panhandle counties, the production of corn, wheat and grain sorghum tend to use furrow and sprinkler irrigation Low Energy Precision Application(LEPA) technology. On the other hand, the production of cotton only applies sprinkler irrigation. In the Texas South Plains, the production of corn, wheat, and grain sorghum apply only pivot irrigation while the production of cotton applies pivot and drip irrigation technology. As a result, the policy regarding switching between different irrigation technology can only be implemented for cotton in the Texas South Plains region. Furrow irrigation and sprinkler irrigation has been the main irrigation systems in the Texas High Plains (Leatham et al. 2006). However, due to the water scarcity problem in the region, other irrigation systems have also been adopted such as pivot and drip irrigation. Furrow irrigation is a method of irrigation that capitalizes on a natural, soil physical phenomenon. Water in the furrow can infiltrate back to soil during off season, which would lower the deep percolation loss at the top of the fields. The idea of LEPA sprinkler irrigation system is to minimize the evaporation loss. Drip irrigation is a process of delivering precise amounts of water and nutrients directly to the plant's root zone, drop by drop, and offers farmers more irrigation control and more efficient use of the limited water resource. In the context of this paper, we specifically consider the conversion between currently available irrigation technology with each county rather than adopting complete new technology.

When comparing among counties in terms of both net revenues and saturated thickness, we also need to acknowledge the different characteristics between multiple crops when applying the current irrigation technology. Indeed, regarding the different crops when applying irrigation technology, corn is more water intensive than cotton. Indeed, profitable cotton yields are possible with more limited irrigation, unlike corn as represented in Schneider and Howell, 1998; Howell et al., 2004; Almas et al. 2007.

Due to the increasingly serious aquifer depletion in Texas Panhandle and Texas South Plains, dryland crop production has been adopted widely beside irrigated production. Dryland farming produces crops using precipitation as the main source of soil moisture, which in turn would better address groundwater shortage.[4] The method can result in successful yields for certain crops in a variety of regions in Texas. In the two regions we study, dryland production is implemented for wheat, cotton, and grain sorghum. Switching to dryland farming can also help reduce cost of production as compared to irrigated farming. Nevertheless, the yield from dryland farming may be lower so the amount of profit would be less than that using irrigation production technology.[5] Furthermore, we want to look at whether the irrigation technology's idiosyncratic characteristics may make their impacts crop and county-specific.

3 Research questions

Our paper aims at comparing water conservation policies for various counties in both the Texas Panhandle and South Plains regions, while accounting for the heterogeneity in counties' agricultural production, hydro-logical and climatic characteristics.

By analyzing and running simulations on our data set, we attempt the following:

1. To determine the long term economic and conservation impacts of different water conservation policies to see if these various policies can sustain farmers' revenue while responding to the increasing depletion of the Ogallala Aquifer.

2. To propose the appropriate policies based on the different characteristics of the counties. In order to be considered as appropriate and worth implementing, the policies should be able to balance between conserving water and sustaining farmers' profits in the long run.

4 Datasets and Empirical methods

4.1 Model specification

For our paper, we construct a model to analyze crop production with respect to a variety of water conservation policies involving changing irrigation technology and water pumping restrictions. The two crucial variables in the study are farmers' net revenue and saturated thickness since these reflect the dual mandate of sustaining farmers' revenues while also maintaining groundwater levels in the Ogallala Aquifer. Indeed, saturated thickness of an aquifer is a crucial indicator of the availability of its groundwater stock. Even though the two variables are the main focus, our analysis also requires the consideration of other variables such as crop yield, water pumped per acre, harvest and labor cost per acre among a variety of others.

4. Land Management Systems, TWDB (2013).
5. Land Management Systems, TWDB (2013).

The study is conducted with the objective of investigating farmers' revenues and the status of the aquifer on an individual county basis, using a model to simulate the path of net returns from crop production with varying irrigation technology over a time horizon of 60 years. The 60-year period was chosen because according to Rajan et al. (2015), it has been projected given the current extraction rates that the aquifer might have a usable lifetime of less than 60 years before being depleted to levels incapable for irrigation water use. For this paper, I adopt the model of Johnson et al. (2003).

Across different policies, revenue and cost vary. For example, if we consider the conversion to dryland production, the cost of irrigation decreases but revenues also decrease because of decreasing yields. On the other hand, some irrigation technology might yield higher revenue but may also come at higher cost. Since the irrigation systems vary across counties, so will changes in net revenue.

In the model, i represents the crop grown and k reflects the irrigation systems used. One important controlling variable to look at is Ω_{ikt}, which represents the percentage of each crop using a certain irrigation technology at a particular time along with WP_t, the water pump rate.

$$WT_t = \sum_i \sum_k \Omega_{ikt} * WP_{ikt}, \tag{1}$$

Equation (1) represents the total amount of water pumped per acre, WT_t, as the sum of water pumped on each crop across its irrigation technology.

$$WAikt = a * \Omega_{ikt} * WPikt \tag{2}$$

Equation (2) represents the relationship between water application rate and water pumped rate where a is a constant for each irrigation technology with respect to each crop. As WA_{ikt} is a proportion of water pumped rate, water application rate is also being affected by Ω_{ikt}.

The following equations reflecting the change in the two variables that reflecting the status of the aquifer on a county basis:

$$ST_{t+1} = ST_t - [(\sum_i \sum_k \Omega_{ikt} * WP_{ikt}) - R]A/s, \tag{3}$$

$$X_{t+1} = X_t + [(\sum_i \sum_k \Omega_{ikt} * WP_{ikt}) - R]A/s, \tag{4}$$

Equation (3) and (4) update the variables of saturated thickness ST_t and pump lift X_t where R represents the annual recharge rate of the aquifer (in feet per acre), A represents the percentage of irrigated acres expressed as the initial number of irrigated acres in the county divided by the county area overlying the aquifer, and s represents percentage of the saturated thickness that yield water. The percentage of irrigated acres and specific well yield variables are county specific. In both equations, the second term represents the county specific net water pumped for irrigation use. Assuming that the recharge rate and the specific water yield is constant for the whole

Ogallala Aquifer, the county-specific factor here is the percentage of irrigated acres A. Under those assumptions, the ratio A/s help convert the total water pumped per acre to reflect the status of the county area overlying the aquifer.

Following Johnson et al. (2008), I also calculate saturated thickness as the difference between the base of the aquifer and the water level. On the other hand, pump lift is calculated as the difference between surface to ground water table. Both saturated thickness and pumping lift depends on not only the water pumped for each crop and each irrigation technology but also the initial water level values. Both saturated thickness and pumping lift also depend on the recharge rate of the aquifer. The saturated thickness would increase with higher recharge rate as higher recharge rate would partially offset the amount of water pumped for irrigation. On the other hand, the recharge rate negatively affects the pump lift in the sense that it reduces the burden of pump lift on other factors, especially the cost of crop production. Pump lift is considered here because it is an essential determinant of the pumping cost, and in turn the total cost.

$$PC_{ikt} = [[EF(X_t + 2.31 * PSI)EP] * WP_{ikt}]/EFF, \tag{5}$$

$$C_{ikt} = VPC_{ik} + PC_{ikt} + HC_{ikt} + MC_k + DP_k + LC_k \tag{6}$$

Equations (5) and (6) represent the cost functions in the model. In Equation (5), PC_{ikt} represents the cost of pumping, EF represents the energy use factor for electricity, EP is the price of energy, EFF represent pump efficiency, and 2.31 feet is the height of a column of water that will exert a pressure of 1 pound per square inch.

Equation (6) expresses the cost of production, C_{ikt}, in terms of VPC_{ik}, variable cost of production per acre; HC_{ikt}, harvest cost per acre; PC_{ikt}, cost of pumping; MC_k, irrigation system maintenance cost per acre; DP_k, per acre depreciation of the irrigation system per year; and LC_k, cost of labor per acre for the irrigation systems being applied.

$$\sum_i \sum_k \Omega_{ikt} + \sum_i \beta_{it} \leq 1 \text{for all t}, \tag{7}$$

Equation (7) limits the fractional sum of crops i produced by irrigation systems k for time period t per acre to be less than or equal to one. Here, the β_{it} variable is also included to account for the fraction of dryland production for each crop.

$$\Omega_{ikt} \geq \alpha \Omega_{ik(t-1)}, \tag{8}$$

Equation (8) is a constraint placed in the model to limit the annual shift to a certain percent change (α) from previous year's acreage depending on different policy scenarios. For the first scenario, we let omega decrease 3 percent every year after the initial year to reflect water pump restriction. On the other hand, for the second scenario, we let omega decrease 5 percent every year after the initial year. Moreover, we can alternate omega to reflect changes in the use of irrigation technology, change the proportion of different technology usage after each year. More specifically, there is a scenario where sprinkler LEPA irrigation use is increasing year by year.

$$\Omega_{ikt} \geq 0 \tag{9}$$

Equation (9) is a non-negativity constraint to assure variables in the model take on positive values.

The NPV is defined as below:

$$NPV = \sum_{t=1}^{60} NR_t (1+r)^{-t} \tag{10}$$

where NPV represents the net present value of net returns, r represents the discount rate, which in the context of this study, we use the discount rate of 3 percent, as followed Almas et al. (2006); and NR_t represents net revenue at time t and is defined as:

$$NR_t = \sum_i \sum_k P_i Y_{ikt}[WA_{ikt}(\Omega_{ikt})] - \sum_i \sum_k C_{ikt}(VPC_{ikt}, PC_{ikt}, HC_{ikt}, MC_{ikt}, DP_k, LC_k) \tag{11}$$

P_i represents the output price of crop i and WA_{ikt} represents irrigation water application per acre. Y_{ikt} represents per acre yield production function, C_{ikt} represents the costs per acre. The bounds of summation are 1 to 5 and 1 to 3 for i and k respectively.

The water application rate is represented as a percentage of the water pumped for each crop and irrigation technology. Moreover, the yield for each crop, which considerably affects the revenue, is a function of this water application rate. Indeed, the yield given in the model's data is already being optimized based on the changing water application rate and the amount of water pumped. This is derived from the Crop Production and Management Model (CROPMAN).

Changing prices for agricultural water use may also be a means to conserve irrigation water. However, given the data constraint, here we focus more on analyzing the other water restriction policies' impacts through considering net revenues and saturated thickness. Net revenues and saturated thickness are the two important factors when evaluating water conservation policy impacts in these regions as they are interconnected and together affect the sustainability of farming. Net revenues constructed in this paper represent closely the actual net revenues the farmers may earn given the crop prices, different water supply and crop yield conditions. Saturated thickness is equally important as the decreasing saturated thickness, or decreasing groundwater stock, would penalize all the farmers withdrawing water from the aquifer as it is getting more and more difficult to pump the remaining water level. It, in turn, leads to higher groundwater pumping cost and decreases the net revenues for all farmers in the county or region of interest. This decreasing saturated thickness, without any policy being enacted, can be considered as an externality for all counties in the regions of interest and therefore should be addressed. The paper's main purpose is to analyze how different policies may address this externality and find out the most appropriate policies for different counties in the study.

4.2 Datasets

Our paper follows Johnson et al. (2002)'s model specification closely but with a few differences in the empirical methods and policy evaluation. Our paper consider some different policy scenarios and also certain combination of multiple policies. Rather than finding the optimal crop combination and optimizing net revenue over the changing crop combination and irrigation technology, our paper aims at investigating the varying net revenues and saturated thickness depending on different policies and their combination. Therefore, our analysis would aspire to find the optimal policy depending on the objectives of the water managers, conserving water or sustaining farmers' net revenue or balancing between the two. Specific data was obtained for each county within the study region of the Texas Panhandle and the Texas South Plains regions over the years 2011 to 2018. The simulation in the paper makes use of all the 2011-2018 data in guiding the simulations' initial values. The county specific data include the planted acreage of corn, cotton, grain sorghum and wheat. The planted acreage includes dryland and the irrigated lands from different irrigation technology such as furrow irrigation, sprinkler irrigation using LEPA, pivot irrigation and drip irrigation. The total operating costs for the four crops associated with these different crop production techniques are also included. The data set from NASS are also used to check our modeling and simulated revenues and costs.

The hydrological data including saturated thickness and groundwater pumpage are also included. Specifically, saturated thickness by county data is obtained from the Texas Water Development Board groundwater database reports over the study period. The groundwater pumpage, on the other hand, is obtained directly from the groundwater database provided by Texas Water Development Board. The amount of recharge in the Ogallala Aquifer overlying Texas Panhandle and South Plains regions is not consistent across different data sources. However, to simplify our analysis we would consider the recharge rate of 3 inches annually as followed USGS(2017).

The irrigated versus dryland utilization data is also used to reflect whether there are significant changes in crop yields between irrigated crops and crops using dryland production techniques. Moreover, through the Cropman simulation software, we can get information regarding the relationship between the crop yields and the different irrigation technologies, specifically the efficiency of each irrigation technology. Indeed, we are able to obtain the county specific production yield by crops from the CropMan model for LEPA, furrow, pivot and drip irrigation for varying water application rates. All of this information is obtained by assuming a certain soil and weather conditions that is typical for the county.

The prices and cost of production for corn, cotton, grain sorghum, and wheat are collected from the AgriLife Extension Texas Crop and Livestock Budgets over the study period. In addition, the costs of production are irrigation technology specific.

The crop yield data is collected from the Texas Crop and Livestock Budgets. The corn yield is in bushels/acre. The cotton and wheat yield are in lb/acre. The grain sorghum yield is in cwt/acre.

It is also important to break down the statistics between the two regions regarding the yield and production costs across different irrigation technology, saturated thickness, and water level.

From Table 2, we can see that costs vary across different irrigation technology. Following Feng (1992), the differences in costs would be assumed to be equal to the conservation cost from one irrigation technology to another. There are some missing variables in the Table 2 because some specific irrigation technologies are only applied in one region or the other. Specifically, the Panhandle applies furrow and sprinkler irrigation while the South Plains applies pivot and drip irrigation.

4.3 Empirical methods

In the paper, we use the General Algebraic Modeling System (GAMS) with Matlab to run simulations for farmers' revenues variations depending on different policy scenarios while accounting for varying climatic conditions across counties over the 60-year horizon from 2021.

For all the scenarios, the crop variety is the same with the gradual transition of less corn farming and more wheat, cotton and sorghum farming. Moreover, for all the scenarios, there is no biological change to the crops. The baseline scenario assumes no water conservation policy is implemented. In the baseline scenario, the farmers stick with the existing crop combination and irrigation technology for each crop depending on the region we consider. The paper also analyzes four alternative scenarios: scenario (1) with 3 percent reduction in groundwater pumpage, scenario (2) with 5 percent reduction in groundwater pumpage, scenario (3) with increasing use of water-saving irrigation technology and scenario (4) with increasing conversion to dryland. For scenario (1) and (2), they require a 3 and 5 percent decrease in groundwater pumpage annually, respectively. Other things including the crop variety, the combination of irrigation technology for each crop are the same. For scenario (3), we adjust the omega, which is the fraction of water pumped for each irrigation technology so that there is a 1 percent increase in the use of a more water-efficient irrigation technology while decreasing the use of less efficient irrigation technology by 1 percent. For scenario (4), we decrease the groundwater pumpage for every irrigation technology by 2 percent so that there would be a 2 percent equivalent increase in dryland farming. We also include scenario (5) which assumes a combination of a 3 percent reduction in water use and a two percent gradual transition to the relatively more water-saving irrigation technology.

In order to further investigate how the changing in irrigation affects the yield and in turn net revenues, it is important to have a better understanding of the irrigation technologies themselves. The irrigation technology adoption opportunities are different between the Texas Panhandle and Texas South Plains. In the Texas Panhandle, the irrigation technology presently being adopted include furrow irrigation, and sprinkler LEPA irrigation, with LEPA irrigation being more efficient (at 90 percent). On the other hand, the Texas South Plains currently adopts either pivot and

Table 1: Variables explanation

Variable	Definition
gpump	Annual groundwater pumpage (gal/year)
WL	water level (ft)
dwl	change in water level (ft)
WA	water application rate (percent)
ST	saturated thickness (ft)
WHEATI	wheat irrigated land (acres)
WHEATNI	wheat non-irrigated land (acres)
CI	corn irrigated land (acres)
CNI	corn non-irrigated land (acres)
CTI	cotton irrigated land (acres)
CTNI	cotton non-irrigated planted (acres)
GSI	grain sorghum irrigated land (acres)
GSNI	grain sorghum non-irrigated land (acres)
pWheat	wheat price (US dollars)
pC	corn price (US dollars)
pCT	cotton (upland) price (US dollars)
pGS	grain sorghum price (US dollars)
CORNYIF	corn yield furrow irrigation (bushels/acre)
CORNYIS	corn yield sprinkler irrigation (bushels/acre)
CORNYIP	corn yield pivot irrigation (bushels/acre)
WHEATYIF	wheat yield furrow irrigation (lb/acre)
WHEATYIS	wheat yield sprinkler irrigation (lb/acre)
WHEATYIDRY	wheat yield dryland (lb/acre)
WHEATYPI	wheat yield pivot irrigation (lb/acre)
COTYIDRY	cotton yield dryland (lb/acre)
COTYIS	cotton yield sprinkler irrigation (lb/acre)
COTYIPI	cotton yield pivot irrigation (lb/acre)
COTYIDRIP	cotton yield drip irrigation (lb/acre)
GSYIF	grain sorghum yield furrow irrigation (cwt/acre)
GSYIS	grain sorghum yield sprinkler irrigation (cwt/acre)
GSYIDRY	grain sorghum yield dryland (cwt/acre)
GSYIPI	grain sorghum pivot irrigation (cwt/acre)
CCF	corn furrow irrigation cost (US dollars/acre)
CCS	corn sprinkler irrigation cost (US dollars/acre)
CCPI	corn pivot irrigation costs (US dollars/acres)
WCF	wheat furrow irrigation cost (US dollars/acre)
WCS	wheat sprinkler irrigation cost (US dollars/acre)
WCDRY	wheat dryland costs (US dollars/acres)
WCPI	wheat pivot irrigation cost (US dollars/acres)
CTCDRY	cotton dryland costs (US dollars/acre)
CTCS	cotton sprinkler irrigation costs (US dollars/acre)
CTCPI	cotton pivot irrigation costs (US dollars/acre)
CTCDRIP	cotton drip irrigation costs (US dollars/acre)
GSCF	grain sorghum furrow irrigation costs (US dollars/acre)
GSCS	grain sorghum sprinkler irrigation costs (US dollars/acre)
GSCDRY	grain sorghum dryland costs (US dollars/acre)
GSCPI	grain sorghum pivot irrigation costs (US dollars/acre)

Table 2: Variables by region (average)

Variable	**Panhandle**	**South Plains**
gpump	114832.76	99109.58
WL	242.35	147.95
ST	93.5	53.35
pWheat	5.89	6.03
pC	4.82	4.68
pCT	0.701	0.704
pGS	7.64	7.74
CORNYIF	200	
CORNYIS	225	
CORNYIPI		180
WHEATYIF	60	
WHEATYIS	65	
WHEATYIDRY	20	18
WHEATYPI		60
COTYIDRY	433	433
COTYIS	1100	
COTYIPI		1000
COTYIDRIP		1500
GSYIF	65	
GSYIS	80	
GSYIDRY	25	18
GSYIPI		79
CCF	752.53	
CCS	700.09	
CCPI		927.496
WCF	402.91	
WCS	358.73	
WCDRY	165.61	169.11
WCPI		362.75
CTCDRY	314.15	322.55
CTCS	680.77	
CTCPI		697.31
CTCDRIP		730.55
GSCF	394.92	
GSCS	399.59	
GSCDRY	186.42	
GSCPI		397

drip irrigation, with drip irrigation being more efficient (at 95 percent) (Johnson et al. 2009). Irrigation application efficiency represents a function of quantity of water emitted from a system that is being stored in the root zone for crop water uptake (Rajan et al. 2015). Accounting for the irrigation water application efficiency is also important since the problem of estimation bias may be worsen as there are larger gaps between irrigation water pumped and irrigation water applied (Kim and Schaible 2000).

In scenario (3) for the Texas Panhandle, there is an increase in sprinkler irrigation (LEPA) together with a decrease in furrow irrigation since LEPA is more water-efficient. On the contrary, for the Texas South Plains, there is an increase in drip irrigation with a decrease in pivot irrigation.

Besides the irrigation technology and crop combination, we also look at the role of agricultural production in each county. Since the importance of agricultural production would determine whether these policies would be relevant for each county. We calculate the agriculture percentage in Table 3 by taking the percentage of irrigated and non-irrigated crop farming land with respect to the total land for each county. Based on the agricultural percentage of each county, we can also evaluate the county-specific policy impact.

Table 3: County-specific percentage of agricultural production

CountyPanhandle	**Agrip**	**CountySouthPlains**	**Agrip**
Andrews	66.72	Bailey	67.87
Armstrong	6.39	Borden	9.36
Briscoe	40.53	Cochran	56.72
Carson	35.53	Crosby	71.67
Castro	96.92	Dawson	80.56
Dallam	80.65	Dickens	24.67
Deaf Smith	87.13	Floyd	76.75
Donley	54.4	Gaines	69.39
Gray	24.86	Garza	25.54
Hansford	61.83	Glasscock	33.59
Hartley	89.2	Hale	70.04
Hemphill	14.5	Hockley	77.69
Hutchinson	54.26	Howard	10.84
Lipscomb	47.14	Lamb	61.14
Moore	82.97	Lubbock	57.4
Ochiltree	72.61	Lynn	82.2
Oldham	8.97	Martin	75.91
Parmer	60.38	Midland	21.93
Potter	2.06	Terry	69.73
Randall	22.32	Yoakum	64.83
Roberts	44.81		
Sherman	81.85		
Swisher	64.28		
Wheeler	27.12		

4.4 Hypotheses

In this paper, we focus on investigate the impacts of different policies on the counties across the Texas Panhandle and Texas South Plains. We hypothesize that the impacts may vary depending on and the demographics, agricultural production and aquifer conditions.

First of all, it is important to highlight the influence of county-specific crop production since this factor may change the impact of each policy on the counties. Some crops might not be adaptable under certain policies due to their costs of production and the degrees of water usage. More specifically, some crops may be more adaptable under water restrictions and dryland production than others as in the case of cotton vs. corn.

Moreover, across the different policy scenarios, some crop production might have much greater impact than others on net revenues and saturated thickness for within a specific policy scenarios. Also, some crop production might only work with certain policies.

Additionally, some policies might have more impact on net revenues and saturated thickness than others. Indeed, the two water restriction policies might have larger impact on decreasing net revenues and conserving saturated thickness as compared to others. Therefore, the impact of each dependent variables on net revenues and saturated thickness under policy (1) and (2) might be hypothesized to be larger than other policies. However, these differences in impact may also vary across the counties depending on their agricultural production.

Besides crop combination, other county specific characteristics like population growth, and aquifer-related conditions may also have impacts on net revenues and saturated thickness.

We also try to classify the counties into different groups based on their changes in saturated thickness. More specifically, we divide the counties into two groups of (1) the lower 50th percentile of saturated thickness reduction, (2) the upper 50th percentile of saturated thickness reduction. Following such group classification across different scenarios, since the changes in saturated thickness vary across the different scenarios we consider, the threshold for classifying the counties would also vary from one scenario to another. From these changing groups classifications, we can further see the impact of different policies on conserving groundwater level through the changing thresholds and the potential shifting of counties between groups.

5 Results

In order to represent the comprehensive approach of explaining the results, we add a diagram showing the relationship between saturated thickness and net revenue together with the consideration of crop combination, location along the aquifer and the agricultural production percentage.

Following previous literature, we will study different counties in detail depending on each region's characteristics. It is crucial to compare among different counties not just in terms of producers' income but also in terms of hydro-logical outcomes. Therefore, we compare the results for farmers' net revenues and saturated thickness across the different scenarios.

To better evaluate the policy impacts on net revenues and saturated thickness, we also construct

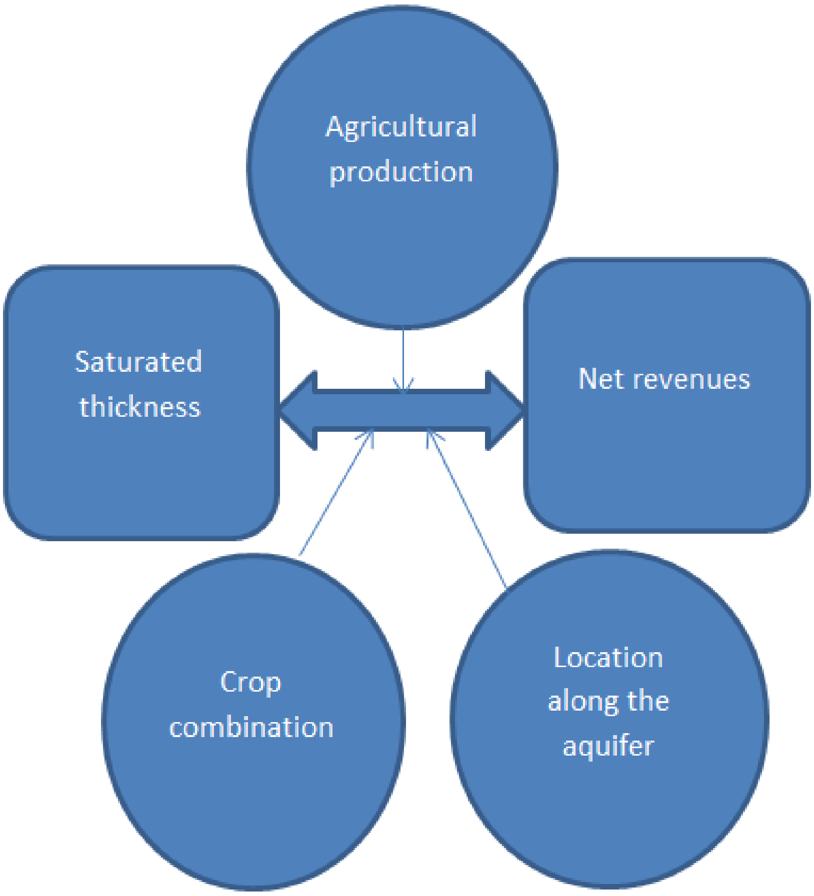

Figure 2: Diagram for the relationship between ST and NR

sustainable thresholds to detect whether the policies might be too severe for either factor. From income perspective, the sustainable threshold for net revenue reduction is 75 percent of the initial values, according to Carlisle et al. (2019). Also, in the case of the Texas Panhandle and Texas South Plains, decreasing the net revenues by more than 75 percent would lead the revenues to fall below 75 (US dollars) per acre for some counties. This number is based on the average net income of farmers across the four crops we consider: corn, wheat, cotton, and sorghum. [6]

Regarding water conservation purpose, water level must not be reduced to below the 60 percent of initial water level after the 60-year period as followed the High Plains Underground Water Conservation District goal in Rajan et al. (2015), which is equivalent to losing no more than one percent of the saturated thickness annually. This threshold is based on the idea that in a lot of counties surrounding the aquifer, losing more than one percent of saturated thickness annually over the period is not sustainable. The general annual recharge rate of the Ogallala Aquifer is only around 3 inches or 0.25 ft, which is less than 1 percent of the saturated thickness level for most of the counties we consider in the region.

Table 4: Farmers' net revenues for Texas Panhandle counties in baseline scenario (in US dollars)

County	Year 2021	Year 2080	Percentage change
Andrews	336.89	236.90	-29.68
Armstrong	324.97	229.02	-29.53
Briscoe	347.88	252.11	-27.53
Carson	433.55	329.71	-23.95
Castro	422.33	220.04	-47.90
Dallam	376.13	180.70	-51.96
Deaf Smith	433.79	233.18	-46.25
Donley	439.49	339.96	-22.65
Gray	358.74	256.15	-28.6
Hansford	435.84	225.10	-48.35
Hartley	485.46	260.79	-46.28
Hemphill	353.03	253.86	-28.09
Hutchinson	352.09	253.09	-28.12
Lipscomb	366.21	271.52	-25.86
Moore	427.85	224.91	-47.43
Ochiltree	399.23	204.29	-48.83
Oldham	383.37	285.35	-25.57
Parmer	370.43	182.43	-50.75
Potter	393.53	299.75	-23.83
Randall	479.52	369.92	-22.86
Roberts	433.79	337.68	-22.16
Sherman	390.27	227.61	-41.68
Swisher	479.52	252.52	-47.34
Wheeler	347.56	259.54	-25.33
Avg change			-35.02

6. Polk et al. (2010); Langemeier and Purdy (2019); Schintkey et al. (2020); Wilde (2021).

Table 5: Saturated Thickness for Texas Panhandle counties baseline scenario (in ft)

County	Agriculturepercentage	Year 2021	Year 2080	Percentage change
Andrews	66.72	50.24	43.36	-13.68
Armstrong	54.99	40.04	37.42	-6.54
Briscoe	69.72	26.6	19.72	-25.84
Carson	35.53	116.51	81.93	-29.69
Castro	96.92	70.09	19.44	-72.26
Dallam	80.65	185.11	77.64	-58.06
Deaf Smith	87.13	76.64	23.72	-69.06
Donley	54.4	80.68	68.96	-14.53
Gray	24.86	166.06	150.62	-9.3
Hansford	61.83	138.14	60.14	-56.47
Hartley	89.2	131.45	34.1	-74.06
Hemphill	14.5	69.57	67.21	-3.39
Hutchinson	54.26	160.96	138.65	-13.87
Lipscomb	47.14	203.1	177.59	-12.65
Moore	82.97	30.78	12.95	-57.93
Ochiltree	72.61	34.84	13.36	-61.17
Oldham	42.52	104.33	102.27	-1.98
Parmer	60.38	34.87	12.88	-63.06
Potter	2.06	125.12	124.38	-0.6
Randall	22.32	45.95	38.8	-15.65
Roberts	44.81	22.7	19.59	-13.78
Sherman	81.85	57.97	12.42	-78.58
Swisher	64.28	60.02	26.07	-56.56
Wheeler	48.45	310.81	307.04	-1.21
Avg change				-31.82

In the baseline scenario, even though there is no change to the production regarding water restriction, or irrigation methods, the net revenues still decrease over time due to the reduction of saturated thickness and the increasing pumping cost. Referring to Table 4, in the baseline scenario, we can see that the average reduction in net revenues is around 35 percent. There are some counties see decreases much more considerably than average, seeing over 40 percent decrease, such as Castro, Dallam, Deaf Smith, Hansford, Hartley, Moore, Ochiltree, Parmer, Sherman and Swisher.

From Table 5, we can see that saturated thickness levels are also decreasing in the baseline but the changes vary across counties. Some counties do not see their saturated thickness changing so much while others see much more considerably decrease in saturated thickness. This may be due to the difference in the initial saturated thickness, their annual groundwater pumpage and also their agricultural production composition. Some counties starts out with higher saturated thickness but they sustain high groundwater pump to facilitate the production of all the crops. These counties see much larger decrease in saturated thickness. On the other hand, some other counties, even though they do not have high initial saturated thickness, manage to sustain low groundwater pumpage to just facilitate the use of more water-efficient crops like wheat and cotton. These counties, as a result, see insignificant decrease in saturated thickness.

Furthermore, there are 6 out of 24 counties that see reduction in saturated thickness of over 60 percent. Indeed, based on the threshold mentioned previously of no more than 60 percent decrease in saturated thickness, the baseline scenario would not be sustainable from water conservation perspective like Castro, Deaf Smith, Hartley, Ochiltree, Parmer, and Sherman counties. Dallam, Hansford, Moore and Swisher counties see the reduction in saturated thickness that nearly exceeding the threshold. These counties have relatively higher agricultural production percentage. Moreover, these are the counties with more serious aquifer depletion problem.

Regarding the change in saturated thickness, we follow the criteria for group classification of group (1) being the counties on the lower 50th percentile reduction in saturated thickness and group (2) being the counties on the upper 50th percentile reduction in saturated thickness to divide up the counties. As a result, in the baseline, group (1) would include Andrews, Armstrong, Briscoe, Carson, Donley, Gray, Hemphill, Hutchinson, Lipscomb, Oldham, Potter, Randall, Roberts, and Wheeler, group (2) would include Dallam, Deaf Smith, Hansford, Hartley, Moore, Ochiltree, Parmer, Sherman and Swisher.

Comparing to the baseline scenario, the different policy scenarios might bring about different impacts on saturated thickness and net revenues. The water restriction and the conversion to dryland policies do a better job at preserving the saturated thickness even though farmers' net revenue may be negatively affected. On the other hand, the changing in irrigation technology might improve net revenues at the cost of saturated thickness for some counties.

Policy (1) refers to a 3 percent decrease in irrigation water use. This policy aims at improving saturated thickness levels from the baseline, however, may be at the cost of revenue reduction. Referring to Table 6 and 7, as opposed to the baseline scenario, policy (1) decreases net revenues significantly, while increase saturated thickness levels. Indeed, with 3 percent reduction in

Table 6: Farmers' net revenues for Texas Panhandle counties scenario 1 with 3 percent decrease in water irrigation use

County	**Year 2021**	**Year 2080**	**Percentage change**	**Baselinecompare**
Andrews	336.89	101.39	-69.90	-40.22
Armstrong	324.97	96.69	-70.25	-40.72
Briscoe	347.88	75.16	-78.40	-50.87
Carson	433.55	105.67	-75.63	-51.68
Castro	422.33	77.95	-81.54	-33.64
Dallam	376.13	68.87	-81.69	-29.73
Deaf Smith	433.79	80.57	-81.43	-35.18
Donley	439.49	120.78	-72.52	-49.87
Gray	358.74	88.42	-75.35	-46.76
Hansford	435.84	80.65	-81.50	-33.14
Hartley	485.46	89.84	-81.49	-35.21
Hemphill	353.03	103.99	-70.54	-42.45
Hutchinson	352.09	85.12	-75.83	-47.71
Lipscomb	366.21	82.79	-77.39	-51.54
Moore	427.85	77.66	-81.85	-34.42
Ochiltree	399.23	73.93	-81.48	-32.65
Oldham	383.37	86.93	-77.33	-51.76
Parmer	370.43	66.06	-82.17	-31.42
Potter	393.53	108.82	-72.35	-48.52
Randall	479.52	116.47	-75.71	-52.86
Roberts	433.79	105.29	-75.73	-53.57
Sherman	395.58	71.96	-81.81	-40.13
Swisher	433.79	86.93	-81.87	-34.53
Wheeler	347.56	96.86	-72.13	-46.81
Avg change			-77.33	-42.31

Table 7: Saturated Thickness for Texas Panhandle counties scenario 1 with 3 percent decrease in water irrigation use

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Andrews	50.24	46.80	-6.85	+6.83
Armstrong	40.04	38.77	-3.16	+3.38
Briscoe	26.6	23.14	-12.98	+12.86
Carson	116.51	99.49	-14.62	+15.07
Castro	70.09	48.26	-31.15	+41.11
Dallam	185.11	133.22	-28.03	+30.02
Deaf Smith	76.64	54.00	-29.53	+39.52
Donley	80.68	75.38	-6.57	+7.96
Gray	166.06	158.12	-4.79	+4.51
Hansford	138.14	97.82	-29.18	+27.28
Hartley	131.45	85.79	-34.74	+39.32
Hemphill	69.57	68.39	-1.69	+1.70
Hutchinson	160.96	149.88	-6.89	+6.98
Lipscomb	203.1	195.99	-3.60	+9.05
Moore	30.78	20.09	-34.75	+23.19
Ochiltree	34.84	24.84	-28.73	+32.94
Oldham	104.33	103.48	-0.82	+1.16
Parmer	34.87	24.80	-28.89	+34.17
Potter	125.12	124.8	-0.26	+0.34
Randall	45.95	42.36	-7.91	+7.73
Roberts	22.7	21.38	-5.9	+7.89
Sherman	57.97	21.38	-59.9	+18.68
Swisher	60.02	38.05	-36.60	+19.95
Wheeler	310.81	309.26	-0.5	+0.72
Avg change			-17.42	+16.35

irrigation water use, net revenues decrease by 77.33 percent, on average. The reduction varies across the counties, with some reducing by lower than 75 percent while others seeing above 80 percent decrease in net revenues. On the other hand, the reduction in saturated thickness falls significantly as compared to the baseline, with most of the counties experience much less than 50 percent decrease in saturated thickness except Sherman county. Moreover, as compared to the baseline, the saturated thickness levels increase by around 16.35 percent, on average.

Based on our threshold, net revenues for most counties under policy (1) by the end of the 60-year period are below the benchmark of 75 percent of initial revenue except for Andrews, Armstrong, Donley, Hemphill, Potter, and Wheeler. These counties are also the ones seeing relatively smaller reduction in saturated thickness. Regarding the water conservation perspective, the saturated thickness levels of most counties are all falling within the sustainable benchmark. As we can see from the results of policy (1)'s simulation, this policy might be bad for all the counties from revenues perspectives.

Using the same group classification as in the baseline, under policy (1), group (1) will include the counties with lower 50th percentile reduction in saturated thickness (2) will include the counties with the upper 50th percentile reduction in saturated thickness. According to this criteria, group (1) will include Andrews, Armstrong, Briscoe, Carson, Donley, Gray, Hemphill, Hutchinson, Lipscomb, Oldham, Potter, Randall, Roberts, and Wheeler counties. On the other hand, group (2) will include Castro, Dallam, Deaf Smith, Hansford, Hartley, Moore, Ochiltree, Parmer, Sherman and Swisher. Under policy (1), the members of the groups stay the same as compared to the baseline.

Policy (2) requires a 5 percent decrease in irrigation water use. The policy aims at conserving water level more considerably but also at the cost of higher revenue reduction. This is also being reflected through the results. Indeed, referring to Table 8 and 9, policy (2) does a better job in conserving water, for most of the counties, the decrease in saturated thickness falls significantly, with all counties having saturated thickness falling within the 60-percent sustainable benchmark. Indeed, policy (2) increases saturated thickness levels by around 21.66 percent as compared to the baseline, on average.

Nevertheless, it is too severe for most of the counties in terms of revenues, decreasing net revenue by more than 89 percent, on average. The counties seeing relatively lower reduction in net revenues are also seeing their saturated thickness decreasing by only a small amount like Andrews, Armstrong, Donley, Hemphill, Potter and Wheeler. Based on our benchmark, this policy leads to a severe reduction in net revenues that exceed the point of sustainable benchmark of 75 percent reduction.

For group classification under policy (2), we would use the same group classification of the top 50th and lower 50th percentile in saturated thickness reduction as in the baseline. According to this classification, group (1) will include Andrews, Armstrong, Briscoe, Carson, Dallam, Donley, Gray, Hansford, Hemphill, Hutchinson, Lipscomb, Oldham, Potter, Randall, Roberts, Swisher and Wheeler counties. Group (2) will include Castro, Deaf Smith, Hartley, Moore, Ochiltree, Parmer, and Sherman counties. Under policy (2), we can see that Dallam, Castro, Hansford and

Table 8: Farmers' net revenues for Texas Panhandle counties with scenario 2 of 5 percent decrease in water use for irrigation

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Andrews	336.89	52.48	-84.42	-54.74
Armstrong	324.97	43.97	-86.47	-56.94
Briscoe	347.88	44.28	-87.27	-59.74
Carson	433.55	47.19	-89.12	-65.16
Castro	422.33	33.18	-92.14	-44.24
Dallam	376.13	28.94	-92.31	-40.35
Deaf Smith	433.79	33.84	-92.20	-45.95
Donley	439.49	53.30	-87.87	-65.23
Gray	358.74	41.01	-88.57	-59.97
Hansford	435.84	35.60	-91.83	-43.48
Hartley	485.46	38.35	-92.1	-45.82
Hemphill	353.03	48.34	-86.31	-58.22
Hutchinson	352.09	41.02	-88.35	-60.23
Lipscomb	366.21	45.88	-87.47	-61.62
Moore	427.85	33.48	-92.18	-44.74
Ochiltree	399.23	31.81	-92.03	-43.20
Oldham	383.37	48.87	-87.25	-61.69
Parmer	370.43	29.86	-91.94	-41.19
Potter	393.53	49.09	-87.53	-63.70
Randall	479.52	52.70	-89.01	-66.15
Roberts	433.79	46.42	-89.30	-67.14
Sherman	395.58	38.61	-90.24	-48.56
Swisher	433.79	41.24	-91.40	-44.06
Wheeler	347.56	45.62	-86.88	-61.55
Avg change			-89.34	-54.32

Table 9: Saturated Thickness for Texas Panhandle counties with scenario 2 of 5 percent decrease in water use for irrigation

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Andrews	50.23	47.75	-4.96	+8.72
Armstrong	40.04	39.2	-2.09	+4.46
Briscoe	26.6	23.61	-11.23	+14.61
Carson	116.51	105.81	-9.19	+20.49
Castro	70.09	56.61	-19.23	+53.03
Dallam	185.11	151.34	-18.24	+39.81
Deaf Smith	76.64	60.92	-20.5	+48.55
Donley	80.68	77.3	-4.18	+10.35
Gray	166.06	160.62	-3.28	+6.02
Hansford	138.14	110.84	-19.76	+36.70
Hartley	131.46	101.67	-22.66	+51.40
Hemphill	69.57	68.78	-1.13	+2.26
Hutchinson	160.96	152.14	-5.49	+8.38
Lipscomb	203.1	198.49	-2.37	+10.28
Moore	30.78	23.84	-22.56	+35.37
Ochiltree	34.81	24.88	-28.61	+33.06
Oldham	104.33	103.75	-0.56	+1.42
Parmer	34.87	24.96	-28.43	+34.64
Potter	125	124.92	-0.16	+0.44
Randall	45.99	43.52	-5.38	+10.27
Roberts	22.7	21.90	-3.6	+10.17
Sherman	57.96	33.81	-41.67	+36.91
Swisher	60.02	50.96	-15.09	+41.47
Wheeler	310.5	309.89	-0.29	+0.92
Avg change			-12.12	+21.66

Swisher move from the group with higher water level change to the lower group as compared to the baseline. The policy (2) seems to be even more effective in conserving water for those counties due to their higher cotton and wheat production.

Even though we have seen the severe impact of a 3 percent water restriction policy, we still want to take a look at the 5 percent water restriction policy as a way to investigate how much more of net revenue we need sacrifice in order to conserve even more water. In other words, we want to analyze the sensitivity of the change in saturated thickness with respect to the change in net revenues. As compared to policy (1), while policy (2) sacrifice 12 percent of the net revenues, it can conserve 5 more percent of saturated thickness. Here, the tradeoff between net revenues and saturated thickness is around 2.5 to 1.

Table 10: Farmers' net revenues for Texas Panhandle counties in scenario 3 with a 1 percent conversion to more water-efficient irrigation technology

County	**Year 2021**	**Year 2080**	**Percentage change**	**Baselinecompare**
Andrews	336.89	291.56	-13.46	+16.22
Armstrong	324.97	304.39	-6.33	+23.19
Briscoe	347.88	315.22	-9.39	+18.14
Carson	433.55	406.86	-6.16	+17.79
Castro	422.33	367.92	-12.88	+35.02
Dallam	376.13	300.36	-20.15	+31.81
Deaf Smith	433.79	380.67	-12.25	+34
Donley	439.49	440.05	+0.13	+22.78
Gray	358.74	315.37	-12.09	+16.51
Hansford	435.84	359.56	-17.5	+30.85
Hartley	485.46	423.78	-12.71	+33.57
Hemphill	353.03	329.2	-6.75	+21.34
Hutchinson	352.09	337.24	-4.22	+23.9
Lipscomb	366.21	326.73	-10.78	+15.08
Moore	427.85	358.49	-16.21	+31.22
Ochiltree	399.23	338.13	-15.3	+33.52
Oldham	383.37	340.63	-11.15	+14.42
Parmer	370.43	301.5	-18.61	+32.14
Potter	393.53	391.29	-0.57	+23.26
Randall	479.52	454.53	-5.21	+17.64
Roberts	433.79	424.16	-2.22	+19.94
Sherman	395.58	314.84	-20.41	+21.27
Swisher	479.52	401.6	-16.25	+31.09
Wheeler	347.56	342.54	-1.45	+23.88
Avg change			-10.5	+24.53

Policy (3) requires a 1 percent conversion to more water-efficient irrigation technology. In more details, it is a 1 percent conversion from furrow to sprinkler irrigation for corn, wheat and sorghum.

Referring to Table 10 and 11, policy (3) with conversion to water-efficient irrigation technology is very good at sustaining net revenues for farmers. Net revenues increase by 24 percent as

Table 11: Saturated Thickness for Texas Panhandle counties in scenario 3 with a 1 percent conversion to more water-efficient irirgation technology

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Andrews	50.24	43.83	-12.77	+0.92
Armstrong	40.04	37.86	-5.45	+1.10
Briscoe	26.6	19.82	-25.48	+0.36
Carson	116.51	83.27	-28.53	+1.15
Castro	70.09	18.35	-73.82	-1.56
Dallam	185.11	66.22	-64.23	-6.17
Deaf Smith	76.64	15.02	-80.4	-11.35
Donley	80.68	70.76	-12.29	+2.24
Gray	166.06	151.32	-8.88	+0.4
Hansford	138.14	62.54	-54.69	+1.78
Hartley	131.33	26.01	-80.22	-6.16
Hemphill	69.57	67.28	-3.29	+0.11
Hutchinson	160.97	140.07	-12.98	+0.88
Lipscomb	203.3	185.46	-8.78	+3.87
Moore	30.78	11.19	-63.65	-5.72
Ochiltree	34.84	15.61	-55.2	+6.47
Oldham	104.33	102.89	-1.96	+0.02
Parmer	34.87	11.25	-67.73	-4.67
Potter	125.12	124.45	-0.54	+0.06
Randall	46	38.98	-15.24	+0.4
Roberts	22.72	19.97	-12.11	+1.68
Sherman	57.96	11.73	-79.76	-1.18
Swisher	60.02	21.07	-64.9	-8.34
Wheeler	310.81	307.36	-1.11	+0.1
Avg change			-34.75	-0.98

compared to the baseline, on average. However, the increase varies across counties with some counties take advantages of the policy better than others.

However, from water conservation perspectives, the policy is not quite effective for most of the counties as compared to the two water restriction policies and even the baseline for some counties. The sprinkler irrigation technology, even though is more water-efficient in the sense that they provide higher yields for the similar pump, might still incentivize farmers to increase pumpage more to increase net revenues even higher. Some counties have saturated thickness reducing more severely than the sustainable threshold of 60-percent reduction such as Castro, Dallam, Deaf Smith, Hansford, Hartley, Ochiltree, Parmer, Sherman and Swisher. Other counties have both net revenues and saturated thickness falling within the sustainable benchmark. Therefore, policy (3) might not be ideal for the these 9 counties from the saturated thickness perspective.

The decreasing variable cost of production might be the main reason why the more efficient irrigation technology might induce farmers to use more water. Indeed, the more efficient irrigation technology can reduce the variable cost of production by reducing the amount of water that consumed but not applied to the crops.[7] Even though the pumping cost is increasing as the production using more water, the saving in variable production cost per acre still outweigh that increasing pumping cost and encourage the farmers to increase production. Moreover, the crop yield would increase the revenue so that it can outweigh the increase in pumping cost and yield higher net revenues for farmers. The higher marginal yield would further encourage farmers to increase production and in turn increase water consumption. This paradox has also been investigated by Pfeiffer and Lin (2014) and Grafton et al. (2018). This paradoxical increase in water extraction when converted to more efficient irrigation technology may be observed clearer in counties with major agricultural production since they are the ones able to see greatest change in net revenues.

The simulation allows for using more water through the changing water pumping rate. Even though there is a lower bound and an upper bound regarding crop production but the change in water usage under this policy is still within the threshold. More specifically, the crop production are allowed to vary within plus-or-minus 10 percent of previous year as followed Almas et al. (2006).

Depending on the region, the change in saturated thickness may vary. More specifically, the central region including counties like Castro, Dallam, Deaf Smith, Hartley, Moore, Parmer, Sherman, and Swisher may see more reduction in saturated thickness than others. The changing in irrigation technology may not save much water and instead end up using more water for some counties toward the end of the time horizon due to the way the saved water is reused in the following periods. Moreover, according to Ward and Pulido-Velazquez (2008), while more efficient irrigation technology can increase the crop water application rate, it may also increase the evaportranspiration rate, which might end up increasing the consumptive use of water over time.

We would also use the same group classification as in the baseline of the lower 50th percentile

7. Casterline (1992).

and upper 50th percentile under policy (3). According to this classification, group (1) includes Andrews, Armstrong, Briscoe, Carson, Donley, Gray, Hemphill, Hutchinson, Lipscomb, Moore, Oldham, Potter, Randall, Roberts, and Wheeler counties. Group (2) will include Castro, Dallam, Deaf Smith, Hansford, Hartley, Ochiltree, Parmer, Sherman and Swisher counties. Even though the group classification under policy (3) is the same as the baseline, we see that Moore county shifts from group with higher saturated thickness reduction to the one with lower reduction. This change is due to the fact that Moore county having crop combination, higher production of wheat and cotton, which better adapt to the change in irrigation technology.

Table 12: Farmers' net revenues for Texas Panhandle counties in scenario 4 with a 2 percent conversion to dryland

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Andrews	336.89	239.40	-28.94	+0.74
Armstrong	324.97	233.21	-28.24	+1.29
Briscoe	347.88	273.40	-21.41	+6.12
Carson	399.23	322.63	-19.19	+4.77
Castro	422.33	312.11	-26.1	+21.8
Dallam	376.13	234.3	-37.71	+14.25
Deaf Smith	433.79	319.87	-26.26	+19.99
Donley	439.49	367.17	-16.46	+6.19
Gray	358.74	243.66	-32.08	-3.48
Hansford	435.84	283.23	-35.02	+13.34
Hartley	485.46	352.53	-27.38	+18.9
Hemphill	353.03	256.11	-27.45	+0.64
Hutchinson	352.09	262.62	-25.41	+2.71
Lipscomb	403.60	261.32	-35.25	-9.4
Moore	427.85	282.91	-33.88	+13.56
Ochiltree	399.23	276.21	-30.82	+19.56
Oldham	383.37	290.54	-24.21	+1.35
Parmer	370.43	240.55	-35.06	+15.69
Potter	393.53	325.56	-17.27	+6.56
Randall	479.52	375.3	-21.74	+1.12
Roberts	433.79	366.63	-15.48	+6.67
Sherman	395.58	242.61	-35.24	+6.44
Swisher	433.79	319.86	-26.26	+21.08
Wheeler	347.56	281.24	-19.08	+6.24
Avg change			-42.66	-8.81

Policy (4) requires a 2 percent conversion from irrigated to dryland crop production. More specifically, the applicable crops for this policy include wheat, cotton, and sorghum. The policy, as the other ones, also aims at conserving water while not reducing the revenues too significantly.

Referring to Table 12 and 13, all counties experience some reduction in net revenues, but the reduction is not high as compared to the two water restriction policies.The change in net revenues varies across the counties depending on their crop combination as collected from the NASS data. The counties' net revenues decrease by 43 percent on average, which is only 9 percent different from

Table 13: Saturated Thickness for Texas Panhandle counties in scenario 4 with a 2 percent conversion to dryland

County	**Year 2021**	**Year 2080**	**Percentage change**	**Baselinecompare**
Andrews	50.24	44.85	-10.72	+2.96
Armstrong	40.04	38.14	-4.75	+1.80
Briscoe	26.6	20.77	-21.89	+3.95
Carson	116.51	89.58	-23.12	+0.92
Castro	70.09	32.89	-53.07	+19.19
Dallam	185.11	106.74	-42.34	+15.72
Deaf Smith	76.64	40.05	-47.74	+21.32
Donley	80.68	72.04	-10.71	+3.82
Gray	166.06	154.79	-6.79	+2.51
Hansford	138.14	79.06	-42.77	+13.70
Hartley	131.45	58.86	-55.23	+18.84
Hemphill	69.57	67.69	-2.7	+0.70
Hutchinson	160.97	145.53	-9.59	+4.27
Lipscomb	203.1	188.44	-7.31	+0.77
Moore	30.78	17.70	-42.51	+15.42
Ochiltree	34.84	20.51	-41.14	+20.53
Oldham	104.33	103.6	-0.7	+1.27
Parmer	34.87	18.92	-45.75	+17.31
Potter	125.12	124.57	-0.44	+0.16
Randall	46	40.64	-11.65	+4.00
Roberts	22.72	20.42	-10.11	+3.67
Sherman	57.96	24.81	-57.19	+21.39
Swisher	60.02	34.66	-42.25	+14.30
Wheeler	310.81	308.1	-0.87	+0.34
Avg change			-24.64	+9.13

the baseline. Moreover, all counties have net revenues falling within the sustainable threshold.

Regarding saturated thickness, most counties see smaller reduction as compared to the baseline and policy (3). Indeed, as compared to the baseline, the saturated thickness levels increase by close to 9 percent, on average.

To consider the policy against our threshold, the policy may be sustainable for all the counties regarding both from net revenues and saturated thickness perspective.

Under policy (4), we would also use the same group classification of group (1) as the lower 50th percentile in saturated thickness reduction and group (2) as the upper 50th percentile in saturated thickness reduction. According to this classification, group (1) includes Andrews, Armstrong, Briscoe, Carson, Donley, Gray, Hemphill, Hutchinson, Lipscomb, Moore, Oldham, Potter, Randall, Roberts, and Wheeler counties. Group (2) will include Castro, Dallam, Deaf Smith, Hansford, Hartley, Moore, Ochiltree, Parmer, Sherman and Swisher counties. Under policy (4), the members in each group regarding changes in saturated thickness are the same as compared to the baseline.

Table 14: Farmers net revenues for Texas Panhandle counties in scenario 5 with a combination of 3 percent water use reduction and 1 percent conversion to water-efficient irrigation technology

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Andrews	336.89	108.53	-67.79	-38.11
Armstrong	324.97	111.77	-65.61	-36.08
Briscoe	347.88	114.82	-66.99	-39.47
Carson	433.55	139.42	-67.84	-43.89
Castro	422.33	106.55	-74.77	-26.87
Dallam	376.13	91.50	-75.67	-23.72
Deaf Smith	433.79	109.91	-74.66	-28.42
Donley	439.49	144.93	-67.02	-44.38
Gray	358.74	116.64	-67.49	-38.89
Hansford	435.84	109.85	-74.8	-26.44
Hartley	485.46	121.57	-74.96	-28.68
Hemphill	353.03	119.35	-66.19	-38.1
Hutchinson	352.09	113.5	-67.76	-39.64
Lipscomb	366.21	114.07	-68.85	-42.99
Moore	427.85	106	-75.23	-27.79
Ochiltree	399.23	101.35	-74.62	-25.79
Oldham	383.37	119.02	-68.95	-43.39
Parmer	370.43	91.24	-75.37	-24.62
Potter	393.53	131.19	-66.66	-42.83
Randall	479.52	152.85	-68.13	-45.27
Roberts	433.79	140.22	-67.68	-45.52
Sherman	395.58	98.7	-75.05	-33.37
Swisher	433.79	117.66	-75.46	-28.12
Wheeler	347.56	117.45	-66.21	-40.88
Avg change			-70.57	-35.55

Policy (5) is a combination of policy (1) and (3), as it requires a combination of 3 percent reduction in irrigation water use and 1 percent conversion to more water-efficient irrigation technology.

Table 15: Saturated Thickness for Texas Panhandle counties in scenario 5 with a combination of 3 percent water use reduction and 1 percent conversion to water-efficient irrigation technology

County	**Year 2021**	**Year 2080**	**Percentage change**	**Baselinecompare**
Andrews	50.24	46.88	-6.69	+6.99
Armstrong	40.04	38.81	-3.07	+3.47
Briscoe	26.6	23.15	-12.97	+12.88
Carson	116.51	97.16	-16.61	+13.07
Castro	70.09	48.76	-30.44	+41.82
Dallam	185.11	134.73	-27.22	+30.84
Deaf Smith	76.64	51.23	-33.15	+35.90
Donley	80.68	75.47	-6.46	+8.07
Gray	166.06	158.26	-4.7	+4.6
Hansford	138.14	98.18	-28.93	+27.54
Hartley	131.46	86.21	-34.42	+39.64
Hemphill	69.57	68.41	-1.66	+1.73
Hutchinson	160.97	148.23	-7.91	+5.95
Lipscomb	203.3	196.11	-3.54	+9.11
Moore	30.78	20.20	-34.37	+23.56
Ochiltree	34.84	19.59	-43.78	+17.89
Oldham	104.33	103.49	-0.81	+1.17
Parmer	34.87	19.85	-43.10	+19.97
Potter	125	124.8	-0.26	+0.35
Randall	46	42.37	-7.87	+7.78
Roberts	22.72	21.41	-5.79	+7.99
Sherman	57.96	23.71	-59.09	+19.49
Swisher	60.02	38.16	-36.43	+20.13
Wheeler	310.5	309.31	-0.48	+0.43
Avg change			-18.74	+15.03

Referring to Table 14 and 15, policy (5) also does a good job in conserving water, increase the saturated thickness considerably as compared to the baseline scenario, by 15 percent on average. For policy (5), the impact of water restriction might be larger than the impact of a conversion between the irrigation technology on net revenues and saturated thickness. This is may be because there is 3 percent decrease in water use while there is only 1 percent conversion to water-efficient irrigation technology. However, the more efficient irrigation technology can still help reduce the negative change in net revenues by 7 percent, making the reduction at 35 percent as compared to the baseline. Policy (5) still proves to be better than policy (1) since the net revenues reduction is less severe (with 7 percent difference) while the conservation of saturated thickness is not much less (1 percent difference).

Regarding our benchmark, all counties have the changes in saturated thickness falling within the sustainable threshold. Nevertheless, regarding net revenues, counties including Castro, Dallam, Deaf Smith, Gray, Hansford, Hartley, Hutchinson, Lipscomb, Moore, Ochiltree, Oldham, Parmer, Sherman and Swisher have net revenues reduction exceeding 75 percent threshold by a small amount. These counties are also the ones with higher percentage of agriculture production and more serious reduction in saturated thickness.

Through considering the overall impact of policy (5), the policy would be worse for counties like Castro, Dallam, Deaf Smith, Gray, Hansford, Hartley, Hutchinson, Lipscomb, Moore, Ochiltree, Oldham, Parmer, Sherman and Swisher as compared to others. From water conservation perspectives, no county sees saturated thickness reduction exceeding the threshold. For those counties, the better policies are policy (4) since the decrease in net revenues are smaller with not much larger reduction in saturated thickness as compared to the baseline.

Utilizing the same group classification as in the baseline, under policy (5), group (1) will also include the counties being in the lower 50th percentile reduction of saturated thickness and group (2) will include the counties in the upper 50th percentile of saturated thickness reduction. According to this criteria, group (1) will include Andrews, Armstrong, Briscoe, Carson, Donley, Gray, Hemphill, Hutchinson, Lipscomb, Oldham, Potter, Randall, Roberts, and Wheeler counties. On the other hand, group (2) will include Castro, Dallam, Deaf Smith, Hansford, Hartley, Moore, Ochiltree, Parmer, Sherman and Swisher counties. Under policy (5), the group compositions are the same as compared the baseline.

Moreover, we also want to look at some alternative water restriction policies since the two policies we consider proved to be harsh on net revenues. More specifically, we want to consider a policy with 1 percent reduction in water use annually.

Policy (6) refers to a 1 percent decrease in irrigation water use. This policy aims at improving the saturated thickness status from the baseline while not decrease the net revenues too significantly. Referring to Table 16 and 17, as opposed to the baseline scenario, policy (6) decreases net revenues by a small amount of 1.56 percent, on average. However, the change in net revenues varies across the counties, with some counties seeing higher reduction than others. The net revenues even increase for counties like Andrews, Armstrong, Dallam, Hemphill, Parmer, Potter and Wheeler. Based on our threshold, the net revenues for all counties are falling within the

Table 16: Farmers' net revenues for Texas Panhandle counties scenario 6 with 1 percent decrease in water irrigation use

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Andrews	336.89	281.14	-16.55	+13.13
Armstrong	324.97	268.11	-17.5	+12.03
Briscoe	347.88	237.43	-31.75	-4.22
Carson	433.55	292.99	-32.42	-8.47
Castro	422.33	234.46	-44.49	+3.41
Dallam	376.13	203.14	-45.99	+5.97
Deaf Smith	433.79	241.75	-44.27	+1.98
Donley	439.49	334.91	-23.80	-1.15
Gray	358.74	245.17	-31.66	-3.06
Hansford	435.84	237.37	-45.54	+2.82
Hartley	485.46	269.68	-44.45	+1.83
Hemphill	353.03	288.34	-18.33	+9.77
Hutchinson	352.09	240.43	-31.72	-3.60
Lipscomb	366.21	249.03	-32	-6.14
Moore	427.85	235.05	-45.06	+2.37
Ochiltree	399.23	218.8	-45.2	+3.63
Oldham	383.37	260.50	-32.05	-6.48
Parmer	370.43	201.48	-45.61	+5.14
Potter	393.53	301.74	-23.33	+0.5
Randall	479.52	322.95	-32.65	-9.8
Roberts	433.79	291.94	-32.70	-10.54
Sherman	395.58	212.76	-46.22	-4.54
Swisher	433.79	262.98	-45.16	+2.18
Wheeler	347.56	268.57	-22.73	+2.60
Avg change			-34.63	+0.39

Table 17: Saturated Thickness for Texas Panhandle counties scenario 6 with 1 percent decrease in water irrigation use

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Andrews	50.24	44.09	-12.23	+1.45
Armstrong	40.04	37.75	-5.71	+0.83
Briscoe	26.6	20.17	-24.17	+1.67
Carson	116.51	85.75	-26.40	+3.28
Castro	70.09	28.95	-58.69	+13.57
Dallam	185.11	133.22	-28.03	+30.02
Deaf Smith	76.64	33.61	-56.15	+12.91
Donley	80.68	70.85	-12.19	+2.34
Gray	166.06	151.97	-8.49	+0.81
Hansford	138.14	68.44	-50.46	+6.01
Hartley	131.45	48.04	-63.46	+10.61
Hemphill	69.57	67.45	-3.04	+0.35
Hutchinson	160.96	140.95	-12.43	+1.43
Lipscomb	203.1	189.51	-6.79	+5.86
Moore	30.78	15.27	-50.41	+7.52
Ochiltree	34.84	16.82	-51.74	+9.93
Oldham	104.33	102.75	-1.52	+0.46
Parmer	34.87	16.18	-53.61	+9.45
Potter	125.12	124.5	-0.49	+0.11
Randall	45.95	39.50	-14.13	+1.52
Roberts	22.7	20.18	-11.21	+2.58
Sherman	57.97	19.57	-66.24	+12.34
Swisher	60.02	29.37	-51.06	+5.50
Wheeler	310.81	307.81	-0.97	+0.25
Avg change			-28.84	+4.93

sustainable benchmark of 75 percent.

On the other hand, the reduction in saturated thickness falls as compared to the baseline, with most of the counties experience much less than 60 percent decrease in saturated thickness except Hartley and Sherman counties. Moreover, as compared to the baseline, the saturated thickness levels increase by around 5 percent, on average. Regarding the water conservation perspective, the saturated thickness levels of most counties are all falling within the sustainable benchmark except for Hartley and Sherman counties.

Policy (6) seems to be better than the other water restriction policies for most counties since it is not too harsh on net revenues, with more than 50 percent improvement compared to policy (2) and more than 40 percent improvement compared to policy (1). Nevertheless, as we can see from the results of policy (6)'s simulation, this policy might be not be good for Hartley and Sherman counties in terms of saturated thickness. Indeed, policy (6) can only conserve around 5 percent compared to the baseline, while policy (1) can conserve 16 percent and policy (2) can conserve around 21 percent. Between policy (6) and policy (1) and (2), the tradeoff between net revenues and saturated thickness is around 2.5 to 1.

Applying the same group identification as in the baseline, under policy (6), group (1) will also include counties having saturated thickness reduction in the lower 50th percentile and group (2) will include the counties with saturated thickness reduction in the upper 50th percentile. According to this criteria, group (1) will include Andrews, Armstrong, Briscoe, Carson, Donley, Gray, Hemphill, Hutchinson, Lipscomb, Oldham, Potter, Randall, Roberts, and Wheeler counties. On the other hand, group (2) will include Castro, Dallam, Deaf Smith, Hansford, Hartley, Moore, Ochiltree, Parmer, Sherman and Swisher. Here we can see that, even though the threshold for group classification changes, the members of the groups stay the same as compared to the baseline.

After looking at each scenario in details, it is important to derive a comprehensive analysis of all the policies across different counties to better construct the most appropriate policy implementation for each county. The policy impact results are reported below in average percentage changes across all the counties. Moreover, we also provide the confidence interval for net revenue and saturated thickness result for each scenario for the sake of providing clearer insight into how the results vary across all counties.

Table 18: Policy impacts in terms of average percentage change in net revenues and saturated thickness

Policy	**NR**	**ST**	**NRCI**	**STCI**	**NR-Bline**	**ST-Bline**
Baseline	-35.02	-31.82	(-38.81, -31.24)	(-43.2, -24.33)		
Policy 1	-77.33	-17.42	(-78.78, -75.87)	(-22.8, -12.04)	-42.31	+16.35
Policy 2	-89.34	-12.12	(-90.15, -88.53)	(-15.93, -8.3)	-54.32	+21.66
Policy 3	-10.5	-34.75	(-12.6, -8.39)	(-44.99, -24.51)	+24.53	-0.98
Policy 4	-42.66	-24.64	(-29.14, -24.69)	(-31.5, -17.78)	-8.81	+9.13
Policy 5	-70.57	-18.74	(-71.9, -69.24)	(-24.56, -12.92)	-35.55	+15.03
Policy 6	-34.63	-28.84	(-38.1, -31.16)	(-38.63, -21.54)	+0.39	+4.93

Among the policy scenarios, the changing into more water-efficient irrigation technologies is more effective considering the balance between sustaining farmers' net revenue and groundwater conservation since the policy can sustain the net revenues as compared to the baseline while still conserving certain water level through the saturated thickness. Water restriction, even though does a better job in conserving water, however, it decrease farmers' net revenue more severely. As a result, we also consider the mixture between different policies. Policy (5) does a good job at conserving water, but the reduction in revenues might be harsh for some counties. This leads us to the importance of considering the county-specific policy impact from both revenue and saturated thickness perspectives.

Regarding the net revenue perspective, the best policy would be policy (3) however at the cost of unsustainable reduction in saturated thickness for Castro, Dallam, Deaf Smith, Hansford, Hartley, Moore, Ochiltree, Parmer, Sherman and Swisher counties. Nevertheless, policy (3) would still be worth pursuing for counties with significant increase in net revenues but insignificant change in saturated thickness.

Regarding the saturated thickness, the best policy would be policy (2) despite the unsustainable reduction in net revenues for all counties. Unfortunately, from the water conservation perspective, Sherman county might seems problematic since it sees saturated thickness level falling below the sustainable threshold across all the policies.

At first, the policy that is good at balancing between sustaining net revenues and sustaining saturated thickness would be policy (4) since the saturated thickness does not decrease too significantly from the baseline while the increase in saturated thickness is undeniable. Nevertheless, this policy might not be the best for all counties.

Policy (6), which requires the 1 percent decrease in irrigation water use, might be better than policy (4) for some counties. The reason is because overall it increases the net revenues by 0.5 percent as compared to the baseline - better than policy (4), while increase the saturated thickness by close to 5 percent, which is not much lower than policy (4).

Due to the changing impact of different policies on the counties, we can see that a uniform policy might not be ideal for all the counties. We may need to customize the policy according certain county-specific characteristics. Thus, we are aiming at matching the county characteristics with the appropriate policy.

The next task is to looking more into the possible crop combination or the mixture of policies to help balance between net revenues and saturated thickness. Moreover, for such consideration, we also account for the variability in counties' economies. We need to consider whether there are county-specific characteristics that shape the net revenues and saturated thickness like this. Indeed, we want to also look at the geographical characteristic of those counties within the aquifer. Moreover, it is also important to consider the agricultural production characteristics in each county.

We have to see whether there is some connection between population level and agricultural level and in turn water depreciation problem. Indeed, across different scenarios, we have classified the counties into two groups depending on their saturated thickness reduction. It is, therefore, important to differentiate among counties of the two groups regarding the factors leading to various saturated thickness level. Across the scenarios, the composition of the two groups is as

Table 19: Texas Panhandle population level and growth

Variable	Year 2011	Year 2019	Population growth (in percent)
Andrews	15,386	18,705	+21.57
Armstrong	1,936	1,887	-2.53
Briscoe	1,718	1,457	-15.19
Carson	6,238	5,926	-5
Castro	7,919	7,673	-3.11
Dallam	6,605	7,304	+10.58
Deaf Smith	19,522	18,546	-5
Donley	3,624	3,342	-7.78
Gray	22,661	21,886	-3.42
Hansford	5,524	5,520	-0.07
Hartley	5,974	5,669	-5.11
Hemphill	3,758	3,994	+6.28
Hutchinson	22,024	20,938	-4.93
Lipscomb	3,260	3,398	+4.23
Moore	22,070	20,940	-5.12
Ochiltree	10,147	10,131	-0.16
Oldham	2,072	2,112	+19.31
Parmer	10,157	9,718	-4.32
Potter	122,305	117,415	-4
Randall	123,424	137,713	+11.58
Roberts	926	854	-7.78
Sherman	3,019	3,059	+1.32
Swisher	7,808	7,432	-4.82
Wheeler	5,316	5,338	+0.41

below despite in one or two of policies.

Table 20: Different groups of counties based on saturated thickness depletion

Lowerdepletion	**Agpercentage**	**Higherdepletion**	**Agpercentage**
Andrews	66.72	Deaf Smith	87.13
Armstrong	6.39	Hartley	89.2
Briscoe	40.53	Ochiltree	72.61
Carson	35.53	Parmer	60.38
Donley	54.4	Sherman	81.85
Gray	24.86	Dallam	80.65
Hemphill	14.5	Castro	96.92
Hutchinson	54.26	Hansford	61.83
Lipscomb	47.14	Moore	82.97
Oldham	8.97	Swisher	64.28
Potter	2.06		
Randall	22.32		
Roberts	44.81		
Wheeler	27.12		

Across different policy scenarios and also the baseline, there are counties that consistently seeing smaller reduction in saturated thickness such as Andrews, Armstrong, Briscoe, Carson, Donley, Gray, Hemphill, Hutchinson, Lipscomb, Oldham, Potter, Randall, Roberts, and Wheeler counties. On the other hand, there are counties that consistently seeing larger reduction in saturated thickness including Deaf Smith, Hartley, Ochiltree, Parmer, and Sherman. Some other counties like Dallam, Castro, Hansford, Moore and Swisher also see larger reduction in saturated thickness across most of the policy scenarios but might switch under some specific policies. Indeed, Dallam, Castro, Hansford and Swisher counties moves from the group with higher water level change to the lower group under policy (2). On the other hand, Moore county shifts from group with higher saturated thickness reduction to the one with lower reduction under policy (3). The counties that see large reduction in saturated thickness are the more problematic ones that we need to pay more attention when evaluating the policy impacts in terms of conserving groundwater. All the counties with larger reduction in saturated thickness are also the ones with higher agricultural production percentage, with all having agricultural percentage greater than 60 percent. However, not all counties with higher agricultural percentage are having depletion problem. Andrews county has agricultural percentage of 66.72 percent but does not see much change in saturated thickness. As a result, we can see that agricultural percentage may have an impact on the counties' saturated thickness under different policy but it is not the only significant factor as crop combination and the location along the aquifer may also play a role.

Throughout the baseline and different policy scenarios, we can see some correlations between the changes in net revenues and the changes in saturated thickness. More specifically, the correlation between saturated thickness and net revenues is positive. Indeed, throughout the different policy scenarios except policy (3), there are certain counties like Deaf Smith, Hartley, Ochiltree, Parmer, and Sherman that are seeing at the same time their saturated thickness and net revenues declining relative more significantly than others. On the other hand, there are other counties like Andrews, Armstrong, Briscoe, Carson, Donley, Gray, Hemphill, Hutchinson, Lipscomb, Oldham, Potter, Randall, Roberts, and Wheeler that seeing their net revenues not declining much because their saturated thickness changing by small percentage. Through these different groups, we can see that not only do net revenues and saturated thickness have a positive correlation but also group (2) would have stronger positive correlation than group (1). More sepcifically, group (2) - the one that has the worse reduction in saturated thickness - also has the worse reduction in net revenues across different scenarios.

Counties with higher agricultural percentage include Andrews, Armstrong, Briscoe, Castro, Dallam, Deaf Smith, Hansford, Hartley, Moore, Ochiltree, Parmer, Sherman and Swisher. Among these counties, Armstrong, Briscoe, Castro, Dallam, Hansford, Hartley, Parmer, Sherman, and Swisher are the one with relatively low population level (less than 10,000 people). Oldham and Wheeler, the counties with less than 10,000 population, are also partially dependent on agriculture, with the percentage being 42.52 and 48.45 respectively. Even though, most of the less populous counties depending considerably on agriculture, the water usage and the water depletion problem varies among those counties. Some counties are more dependent on crop farming while others are depending more on ranching and livestock raising. For the agricultural percentage in the context of our paper, we focus only on the crop farming side. On the other hand, the counties with the highest population (more than 100,000 people) like Potter and Randall do not have high agricultural percentage.

Texas Panhandle is a semi-arid region with a great deal of year-to-year variation in precipitation. This leads to a great deal of variation in the year-to-year production of agricultural products under natural precipitation. Therefore the Texas Panhandle relies on irrigation to both increase and stabilize production (Almas et al. 2004). The irrigation water demand shift will include not only changing in the amount of irrigated land but also conversion between different crop grows within the existing irrigated area. In the Texas Panhandle, the amount of irrigated land is increasing in Andrews, Armstrong, Carson, Donley, Gray, Hansford, Lipscomb, Ochiltree, Oldham, Potter, Randall, Robert, Sherman and Wheeler counties while decreasing in Briscoe, Castro, Dallam, Deaf Smith, Hartley, Hemphill, Hutchinson, Moore, Parmer, and Swisher counties.

Some counties are seeing larger water-level changes since the pre-development of the Ogallala Aquifer of around 1950 until 2005 includes Dallam, Sherman, Hansford, Ochiltree, Lipscomb, Hartley, Moore, Hutchinson, Carson, Deaf Smith, Castro and Swisher (USGS 2017). Among those counties, the ones where we see more adversely effects from policy (4), which is deemed as the optimal policy in balancing between net revenues and saturated thickness, are Hutchinson, Lipscomb and Sherman counties.

Also, it is crucial to look at the county-specific geographical location along the Ogallala Aquifer in order to explain the different movements of saturated thickness. The Texas part of the Ogallala Aquifer is within the artesian zone with relatively lower saturated thickness level with some counties seeing relatively significant changes in water levels. Relatively, Texas Panhandle has relatively higher saturated thickness level than the Texas South Plains. Within the Texas Panhandle,

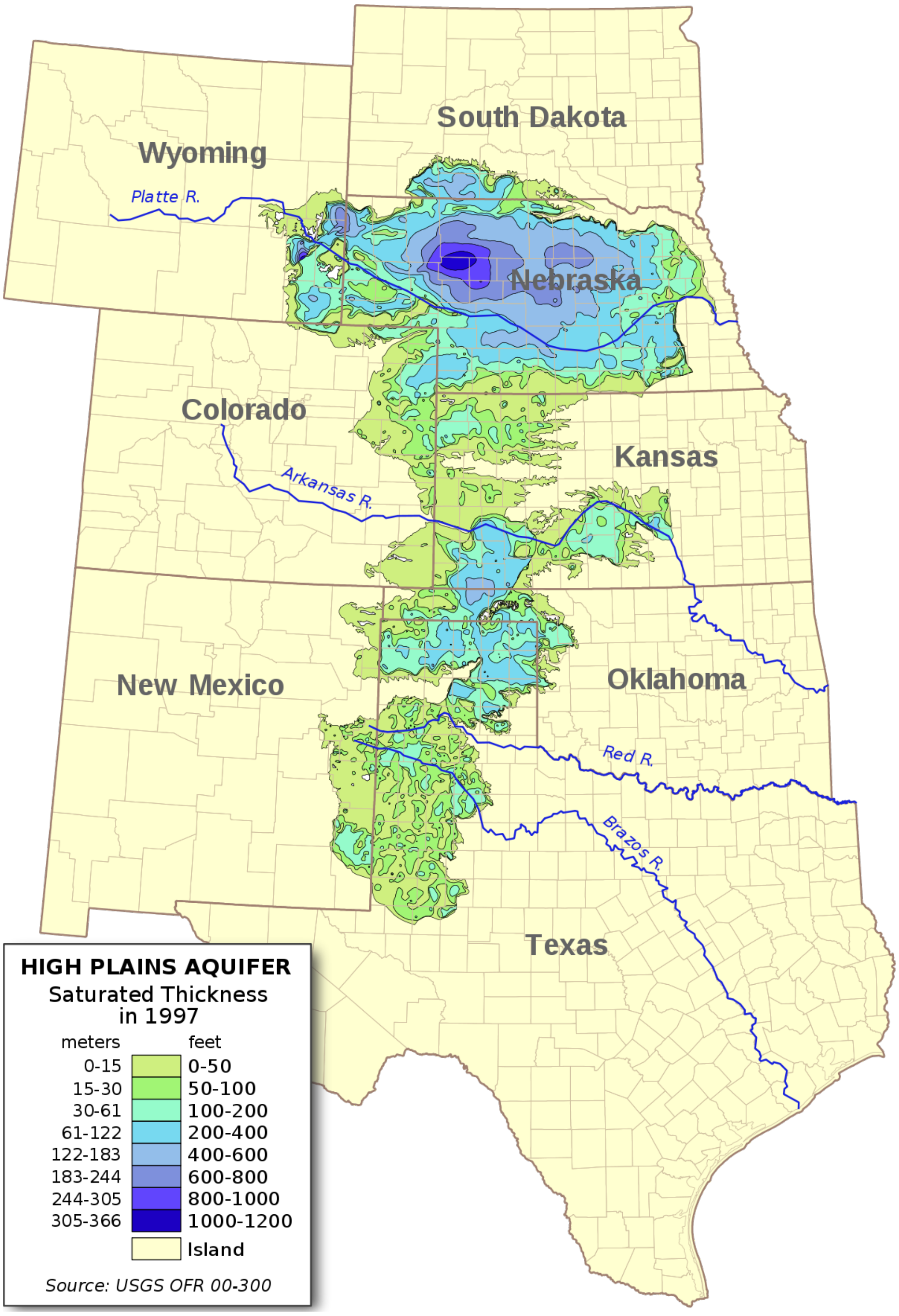
South Dakota
Wyoming
Platte R.
Nebraska
Colorado
Kansas
Arkansas R.
New Mexico
Oklahoma
Red R.
Brazos R.
Texas
HIGH PLAINS AQUIFER
Saturated Thickness
in 1997
meters
feet
0-15
0-50
15-30
50-100
30-61
100-200
61-122
200-400
122-183
400-600
183-244
600-800
244-305
800-1000
305-366
1000-1200
Island
Source: USGS OFR 00-300

Figure 3

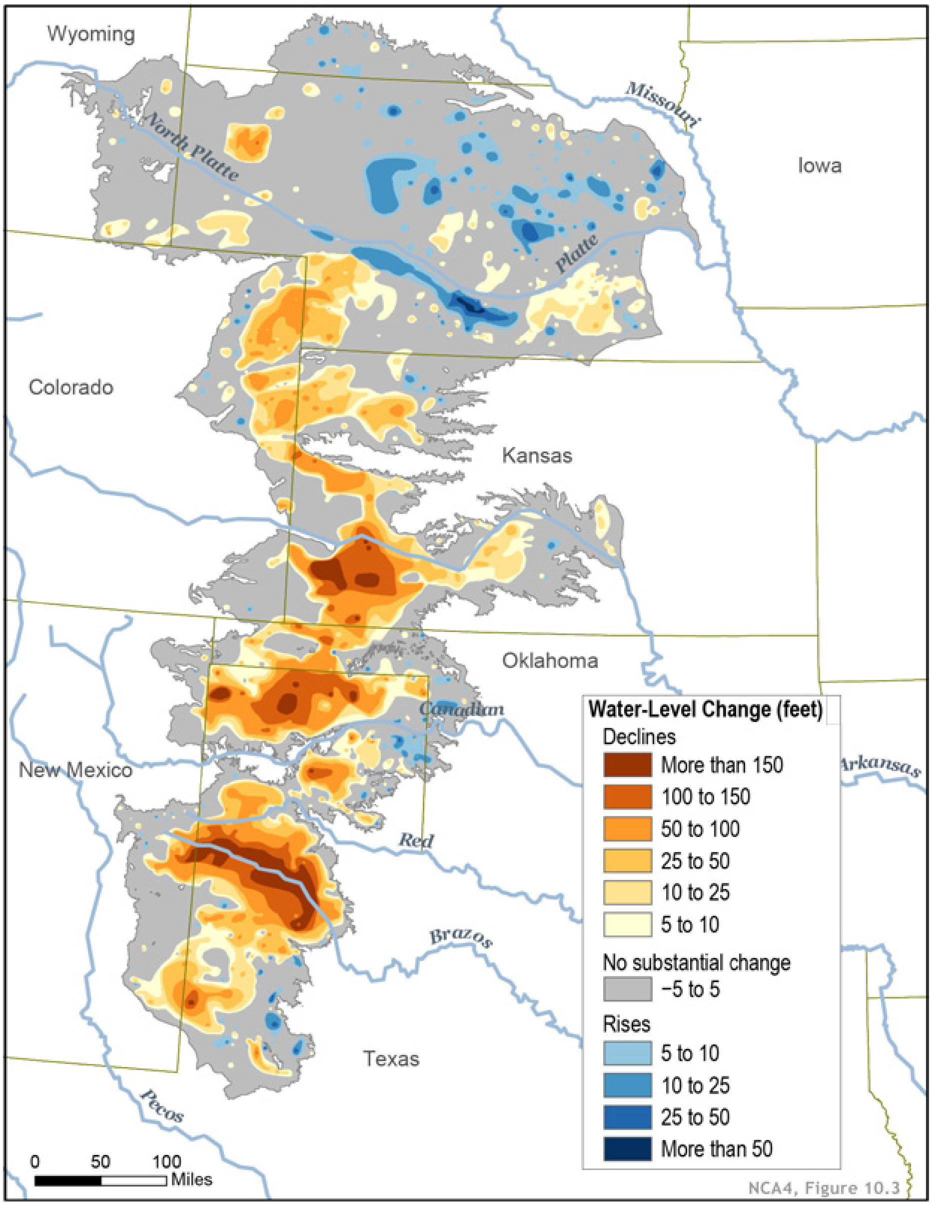
Wyoming
North Platte
Missouri
Iowa
Platte
Colorado
Kansas
Oklahoma
Canadian
New Mexico
Arkansas
Red
Brazos
Texas
Pecos
0
50
100
Miles
Water-Level Change (feet)
Declines
More than 150
100 to 150
50 to 100
25 to 50
10 to 25
5 to 10
No substantial change
−5 to 5
Rises
5 to 10
10 to 25
25 to 50
More than 50
NCA4, Figure 10.3

Figure 4

counties are the ones with higher saturated thickness level due to their locations are Armstrong, Donley, Hansford, Hutchinson, Roberts, Carson, Gray, Ochiltree, Oldham and Potter. Sherman is also in the area with higher saturated thickness level but over time, the high water level reduction leads its initial saturated thickness level in our paper to be relatively lower than the other counties.

The demographics of the counties might also have an impact on the agricultural production in the region. There are counties associated with the Amarillo metropolitan statistical areas like Armstrong, Carson, Oldham, Potter and Randall. The region's counties not associated with an MSA include Briscoe, Castro, Dallam, Deaf Smith, Donley, Gray, Hansford, Hartley, Hemphill, Hutchinson, Lipscomb, Moore, Ochiltree, Parmer, Roberts, Sherman, Swisher, and Wheeler counties. Randall County's population growth outpaced all others, rising by 14.1 percent, about on par with the state. Among the counties who see more adverse effects, the ones that seeing increasing population are Dallam, Lipscomb and Sherman while others are seeing decreasing population.

The eight counties (Deaf Smith, Hartley, Castro, Parmer, Sherman, Hansford, Dallam and Swisher) with the highest average agricultural cash receipts over the last five years, 2013-2017, are in this region. Seven of the top 10 counties (Sherman, Hartley, Dallam, Deaf Smith, Castro, Hansford and Parmer) with the highest value of wheat, sorghum, hay and corn production are in the High Plains Trade Area. Swisher and Carson counties ranking the top 15 percent for value of cotton and cottonseed produced. Hansford, Sherman, Ochiltree and Moore counties have all seen explosive growth in cotton receipts more recently. Average annual cash receipts derived from corn, wheat, sorghum each declined, while average annual receipts of cotton grew.

Across the different policies, Hartley and Sherman consistently see the largest changes in saturated thickness. The reasons for this consistent problem might be due to different characteristics of Hartley and Sherman county. More specifically, Hartley and Sherman counties are among the counties with the largest change in water level over time based on the map of water level change in Figure 3. Moreover, the agricultural production of these two counties are on the top highest, only after Castro and Deaf Smith, with major corn production. The annual groundwater pumpage of those two are also consistently the highest over the years leading to the simulation period, with Hartley being around 400,000 gallons per year and Sherman around 300,000 gallons per year.

On the other hand, Andrews, Briscoe and Hutchinson are the best counties in terms of sustaining net revenues while conserving saturated thickness even with not so small agricultural production thanks to several characteristics. Firstly, these counties see smaller changes in water level over time based on the map of water level change in Figure 3. Moreover, their crop combination also helps. These counties have relatively smaller water intensive production like corn while focusing more on water saving production like cotton. Another reason is there low groundwater pumping amount, ranging from low 1000s to low 10,000s gallons annually.

Corn maintained its position as the highest total value crop produced in the region and averaged 551.12 million (US dollars) in cash receipts annually from 2013-2017. The annual average value of cotton in the region during the same period was 335.5 million (US dollars), which represented 21.2 percent of total crop receipts. This percentage is higher than cotton's 2009-2012 value of 18.9 percent.

The less water intensive crop, like cotton, can help address the dependence on irrigation water from Ogallala Aquifer. On the other hand, wheat irrigation demand is less than that of corn since it is usually planted in the fall and harvested in the spring, avoiding the dry summer (Cotterman 2018). As a result, converting to wheat and especially cotton production can help address the aquifer depletion problem especially for those counties that suffering more water level depletion. However, the net revenues might suffer since the cost of production might be higher for wheat and cotton. Among the counties that suffering from more adverse effects, Hutchinson and Lipscomb produced only cotton and wheat while Sherman county produced also corn and grain sorghum. As a result, in order to balance between net revenues and saturated thickness, especially counties like Hutchinson, Lipscomb and Sherman, there might need to be a mixture of conversion between different crop production and the uses of better irrigation technology like in policy (5). However, from the impacts of policy (5), we may need to adjust the magnitude of the percentage change in the policy otherwise there may be counties like Andrews, Briscoe, Gray, Hemphill, Hutchinson, Lipscomb, Oldham and Parmer seeing adverse effects on net revenues. Indeed, we might need to decrease the water restriction percentage while increase the conversion to water-efficient irrigation technology percentage. We can see that with lower percentage of water restriction in policy (6), the impact on net revenues is not as harsh while the water conserving effect does not decrease by a lot.

We want to customize the policy according to the county crop combination, agricultural production percentage and other water level-related characteristics while also considering our objectives of responding to the increasing depletion of the Ogallala Aquifer and sustaining the net revenues for farmers in the long run.

Overall, the counties that work better with the conversion dryland policy like Carson, Hartley, Deaf Smith, Hansford, Hartley, Ochiltree, Parmer, Sherman and Swisher are the ones with crop combination including a majority of wheat and cotton production that be converted to dryland production. Indeed, these counties have corn and cotton production adding up to be greater than 50 percent of the agricultural production. Moreover, Hartley and Sherman counties are on the top of agricultural production percentage. These counties are the ones either starting with low saturated thickness initially or seeing huge change in water level over time. The counties that work better with the 1 percent water restriction policy are Castro and Dallam. These counties are the ones with large agricultural production and major corn production. They are also the ones already seeing huge changes in water level over the years. Even though policy (6) is better overall in terms of net revenues, policy (4) are still better for quite a few counties since its 2 percent conservation of water use help reduce the pumping cost and as a result improve the net revenues for counties that use a lot of water for agriculture.

The counties that work better with the changing irrigation technology includes Andrews, Armstrong, Briscoe, Donley, Gray, Hemphill, Hutchinson, Moore, Lipscomb, Oldham, Potter, Randall, Roberts, and Wheeler. Most counties that work better with this changing irrigation technology policy are the ones with relatively higher saturated thickness initially. Those that do not start out with high saturated thickness can take advantage of this policy through their agricultural production mechanism. Most of the counties work better with the changing irrigation technology are the ones with not very huge agricultural production, being less than 50 percent. The two counties that have large agricultural production are the ones with more cotton and wheat production that can better take advantage of the changing irrigation technology.

For counties with more serious groundwater depletion problem, the changing irrigation technology or the conversion to dryland alone are not sufficient, there needs to be some form of water restriction in order to conserve the saturated thickness level.

Furthermore, it is crucial to sum up the characteristics that might set these counties in the Texas Panhandle into two groups of saturated thickness reduction, especially the counties that see higher saturated thickness reduction from others. Doing this would help us showing what factor might be improved in order to conserve saturated thickness level. First of all, the agricultural production percentage tends to exceed 50 percent. Secondly, most counties in group (2) see much larger change in saturated thickness in the years leading to the simulation, specifically from 50 to 150 ft since the early 1990s. Crop combination is the third factor, corn proves to be a more water intensive and may worsen the saturated thickness reduction. Indeed, most of the counties seeing huge saturated thickness changes have corn production of at least 25 percent and above, with most counties having corn production for more than 30 percent. However, it is the combination of these factors that set these counties apart from the others in terms of saturated thickness reduction. There are counties that either have relatively high corn production or may have not very high saturated thickness initially but still manage to conserve saturated thickness over time due to not very high agricultural production percentage.

The different information regarding the county-specific agricultural production shapes the initial crop combination for each county. These initial crop combination would affect both the net revenues and saturated thickness throughout the simulation period. More specifically, regarding the net revenues, the crop combination would affect the revenues and cost of production for each county since revenues and cost of production would change differently over time across the variety of crops. Moreover, the different agricultural production, the climate-related characteristic and the location across the aquifer would affect the pumping cost, which would be accounted for in the cost of production. Indeed, the cost of production would account for the changing harvest cost and irrigation cost for the different crop combination and water level condition over time.

Regarding the saturated thickness, the different agricultural production, the climate-related characteristic and the location across the aquifer would affect the simulation through the water pumping and recharge rate parameters in the equation. The changing population may also affect the changing water pumping rate over time as reflected through the simulation results. The changes in population level may impact farmers' net revenues and saturated thickness level indirectly through the pumping rate. Indeed, the trends in population guide the development pattern for the counties we consider. The population factor would also affects the initial saturated thickness of the counties.

The irrigated land information reflects the size of farmer on local level, which may create a spillover effect across the whole county level. Moreover, the declining irrigated land as shown from the dataset shows a pattern of increasing conversion to dryland production.

Overall, the factors that play a role in the built up to the simulation include the climate-related characteristics, the population level and the location along the aquifer. On the other hand, the factors that play a role throughout the simulation include the agricultural production percentage, the trends in crop combination and water pumping rate.

We also need to look at the counties in the Texas South Plains. In this region, we would also divide different counties into two groups regarding their saturated thickness reduction: group (1) being the lower 50th percentile and group (2) being the upper 50th percentile.

Table 21: Farmers' baseline net revenue for Texas South Plains counties

County	Year 2021	Year 2080	Percentage change
Bailey	256.98	143.3	-44.24
Borden	256.86	190.55	-25.81
Cochran	263.2	186.39	-29.18
Crosby	256.86	138.46	-46.09
Dawson	296.06	175.15	-40.84
Dickens	276.52	212.89	-23.01
Floyd	311.91	193.57	-37.94
Gaines	230.46	114.43	-50.35
Garza	249.88	170.41	-31.8
Glasscock	283.5	213.33	-24.75
Hale	276.88	197.71	-28.59
Hockley	224.24	115.36	-48.55
Howard	249.88	179.06	-28.34
Lamb	277.27	173.09	-37.57
Lubbock	256.98	143.3	-44.24
Lynn	243.66	126.45	-48.1
Martin	249.88	125.52	-49.77
Midland	249.88	170.41	-31.8
Terry	263.95	156.24	-40.81
Yoakum	218.77	130.15	-40.51
Avg change			-37.62

In the baseline, without any policy intervention, we can have a closer look into how the net revenues and saturated thickness vary across the two regions of interest. Indeed, when we look at the saturated thickness, there are some counties with even more serious water depletion than those of the Texas Panhandle.

In the baseline scenario, even though there is no change to the production regarding water restriction, or irrigation methods, the revenues still decrease over time due to the reduction of saturated thickness and the increasing pumping cost. From Table 19, the net revenues decrease by 38 percent on average, with all the counties having sustainable net revenues.

From Table 20 for counties in the Texas South Plains, we can see that some counties do not see their saturated thickness changing so much while others see much more considerably decrease in saturated thickness. This may be due to the difference in the initial saturated thickness, their

Table 22: Saturated Thickness baseline for Texas South Plains counties

County	Agriculturepercentage	Year 2021	Year 2080	Percentage change
Bailey	67.87	90.99	22.94	-74.78
Borden	9.36	127.72	123.99	-2.92
Cochran	56.72	35.06	15.87	-54.74
Crosby	71.67	99.58	18.08	-81.85
Dawson	80.56	70.24	14.99	-78.66
Dickens	24.67	155.52	153.93	-1.03
Floyd	76.75	35.69	16.7	-78.07
Gaines	69.39	80.13	25.67	-67.97
Garza	25.54	64.28	48.09	-25.19
Glasscock	33.59	33.23	24.25	-27.02
Hale	70.04	72	17.58	-75.58
Hockley	77.69	40.25	9.90	-75.39
Howard	10.84	30.33	26.04	-14.13
Lamb	61.14	66.11	18.22	-72.44
Lubbock	57.4	57.09	11.28	-80.24
Lynn	82.2	54.97	9.13	-83.4
Martin	75.91	51.8	7.74	-85.06
Midland	21.93	23.46	15.08	-35.74
Terry	69.73	84.01	24.58	-70.74
Yoakum	64.83	54.35	18.82	-65.38
Avg change				-56.98

minimal groundwater pumpage and also their agricultural production composition. Some counties starts out with higher saturated thickness but they sustain high groundwater pumping rates to facilitate the production of all the crops. These counties therefore see a much larger decrease in saturated thickness. On the other hand, some other counties, even though they do not have high initial saturated thickness, manage to sustain low groundwater pumpage through the use of more water-efficient crops like wheat and cotton. These counties, as a result, see insignificant decrease in saturated thickness. From the water conserving perspective, in the baseline, there are significant decreases in saturated thickness for all the counties, with the decrease being 57 percent on average. Indeed, the baseline would not be sustainable specifically for Bailey, Crosby, Dawson, Floyd, Gaines, Hale, Hockley, Lamb, Lubbock, Lynn, Martin, Terry and Yoakum.

Regarding the group classification in terms of saturated thickness reduction, we would still keep grouping the lower 50th percentile counties into group (1) and the upper 50th percentile counties into group (2). As a result, in the baseline, group (1) consists of Borden, Cochrans, Dickens, Garza, Glasscock, Howard, Midland counties. Group (2) consists of Bailey, Crosby, Dawson, Floyd, Gaines, Hale, Hockley, Lamb, Lubbock, Lynn, Martin, Terry and Yoakum counties.

Policy (1) refers to the 3 percent decrease in irrigation water use. This policy aims at improving the saturated thickness status from the baseline, however, may be at the cost of revenue reduction. Indeed, referring to Table 21 and 22, policy (1) decreases the net revenues significantly, by 76 percent on average. Additionally, the net revenues might not be sustainable for most of the

Table 23: Farmers' net revenue for Texas South Plains counties in scenario 1 with 3 percent decrease in water use for irrigation

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Bailey	256.98	52.15	-79.71	-35.47
Borden	256.86	86.75	-66.22	-40.41
Cochran	263.2	70.88	-73.07	-43.89
Crosby	256.86	51.4	-79.99	-33.9
Dawson	296.06	60.54	-79.55	-38.71
Dickens	276.52	92.11	-66.69	-43.68
Floyd	311.91	64.62	-79.28	-41.34
Gaines	230.46	45.89	-80.09	-29.74
Garza	249.88	67.45	-73.01	-41.21
Glasscock	283.5	75.83	-73.25	-48.5
Hale	276.88	60.43	-78.17	-49.58
Hockley	224.24	45.21	-79.84	-31.28
Howard	249.88	86.09	-65.55	-37.20
Lamb	277.27	57.72	-79.18	-41.61
Lubbock	256.98	52.15	-79.71	-35.47
Lynn	243.66	48.65	-80.04	-31.93
Martin	249.88	49.33	-80.26	-30.49
Midland	249.88	67.45	-73.01	-41.21
Terry	263.95	54.22	-79.46	-38.65
Yoakum	218.77	45.91	-79.02	-38.51
Avg change			-76.25	-38.64

Table 24: Saturated Thickness for Texas South Plains counties in scenario 1 with 3 percent decrease in water use for irrigation

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Bailey	90.99	59.72	-34.37	+40.42
Borden	127.72	126.01	-1.34	+1.58
Cochran	35.06	26.25	-25.13	+29.61
Crosby	99.58	62.29	-37.45	+44.4
Dawson	70.24	44.9	-36.07	+42.58
Dickens	155.37	154.79	-0.47	+0.56
Floyd	76.12	48.03	-36.91	+41.16
Gaines	80.13	57.09	-28.76	+36.81
Garza	64.22	56.85	-11.56	+13.63
Glasscock	33.2	29.12	-12.37	+14.66
Hale	72	46.74	-35.09	+40.49
Hockley	40.25	26.23	-34.82	+40.58
Howard	30.3	28.36	-6.49	+7.65
Lamb	66.11	44.17	-33.19	+39.25
Lubbock	57.09	31.92	-44.09	+36.16
Lynn	54.97	33.90	-38.32	+45.08
Martin	51.8	31.58	-39.04	+46.02
Midland	23.46	19.61	-16.42	+19.32
Terry	84.01	56.78	-32.41	+38.33
Yoakum	54.35	37.95	-30.17	+35.21
Avg change			-26.72	+30.67

counties except for Borden, Cochran, Dickens, Garza, Glasscock and Howard based on the defined threshold.

From the water conservation perspective, policy (1) increase the saturated thickness by 30 percent compared to the baseline. Moreover, all counties satisfy the threshold for sustainable saturated thickness.

Regarding the group classification in terms of saturated thickness reduction, we would still put the lower 50th percentile counties into group (1) and the upper 50th percentile counties into group (2). As a result, under policy (1), group (1) consists of Borden, Cochrans, Dickens, Gaines, Garza, Glasscock, Howard, Midland counties. Group (2) consists of Bailey, Crosby, Dawson, Floyd, Hale, Hockley, Lamb, Lubbock, Lynn, Martin, Terry and Yoakum counties. As compared to the baseline, Gaines county has moved from group (2) to group (1) thanks to the implementation of water restriction policy.

Table 25: Farmers' net revenue for Texas South Plains counties in scenario 2 with 5 percent decrease in irrigation water use

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Bailey	256.98	28.39	-88.95	-44.72
Borden	256.86	47.22	-81.62	-55.80
Cochran	263.2	38.58	-85.34	-56.16
Crosby	256.86	27.97	-89.11	-43.01
Dawson	296.06	32.95	-88.87	-48.03
Dickens	276.52	50.14	-81.87	-58.86
Floyd	311.91	35.17	-88.72	-50.78
Gaines	230.46	24.98	-89.16	-38.82
Garza	249.88	36.71	-85.31	-53.51
Glasscock	283.5	41.28	-85.44	-60.69
Hale	276.88	32.89	-88.12	-59.53
Hockley	224.24	24.61	-89.03	-40.47
Howard	249.88	46.86	-81.25	-52.91
Lamb	277.27	31.42	-88.67	-51.1
Lubbock	256.98	28.39	-88.95	-44.72
Lynn	243.66	26.48	-89.13	-41.03
Martin	249.88	26.85	-89.25	-39.49
Midland	249.88	36.71	-85.311	-53.51
Terry	263.95	29.51	-88.82	-48.017
Yoakum	218.77	24.99	-88.568	-48.07
Avg change			-86.95	-49.33

Policy (2) requires a 5 percent decrease in irrigation water use. The policy aims at conserving water level more considerably but also at the cost of higher revenue reduction.

Referring to Table 23, in terms of net revenues, we can see that policy (2) of 5 percent water use reduction is too severe for most of the counties. More specifically, policy (2) decreases net revenues by 87 percent, on average. Additionally, all of the counties cannot satisfy the sustainable threshold for net revenues.

Table 26: Saturated Thickness for Texas South Plains counties in scenario 2 with 5 percent decrease in irrigation water use

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Bailey	90.99	69.25	-23.9	+50.89
Borden	127.71	126.54	-0.92	+1.99
Cochran	35.06	28.93	-17.47	+37.27
Crosby	99.58	73.79	-25.9	+55.94
Dawson	70.24	53.37	-25.44	+53.22
Dickens	155.37	155.01	-0.33	+0.7
Floyd	76.12	56.34	-26	+52.07
Gaines	80.13	64.26	-19.81	+45.76
Garza	64.28	59.15	-7.98	+17.21
Glasscock	33.23	30.35	-8.68	+18.34
Hale	72	54.09	-24.87	+50.71
Hockley	40.25	30.59	-24	+51.4
Howard	30.33	28.97	-4.48	+9.66
Lamb	66.11	50.7	-23.31	+49.13
Lubbock	57.09	41.18	-27.87	+52.37
Lynn	54.97	40.43	-26.45	+56.94
Martin	51.8	37.85	-26.94	+58.12
Midland	23.44	20.82	-11.25	+24.49
Terry	84.01	65.03	-22.6	+48.15
Yoakum	54.35	43.02	-20.86	+44.52
Avg change			-18.45	+38.94

Regarding the saturated thickness, the policy conserves water even more effectively than the 3 percent reduction in irrigation water use. As compared to the baseline, the saturated thickness level increases by 39 percent, with all counties satisfying the sustainable threshold for saturated thickness. Even though it is more effective in conserving water this policy leads most of the revenues values to fall below the sustainable benchmark that make it infeasible to apply.

Regarding the group classification in terms of saturated thickness reduction, we would still keep grouping the lower 50th percentile counties into group (1) and the upper 50th percentile counties into group (2). As a result, under policy (2), group (1) consists of Borden, Cochrans, Dickens, Gaines, Garza, Glasscock, Howard, Midland counties. Group (2) consists of Bailey, Crosby, Dawson, Floyd, Hale, Hockley, Lamb, Lubbock, Lynn, Martin, Terry and Yoakum counties. As compared to the baseline, Gaines county has moved from group (2) to group (1) thanks to the implementation of water restriction policy.

Table 27: Farmers' net revenue for Texas South Plains counties in scenario 3 with 1 percent conversion to more water-efficient irrigation technology

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Bailey	256.98	162	-36.96	+7.28
Borden	256.86	214.19	-16.61	+9.2
Cochran	263.2	205.35	-21.98	+7.2
Crosby	256.86	154.04	-40.03	+6.07
Dawson	296.06	200.09	-32.42	+8.42
Dickens	276.52	241.55	-12.63	+10.38
Floyd	311.91	222.87	-28.55	+9.39
Gaines	230.46	130.02	-43.58	+6.76
Garza	249.88	186.22	-25.48	+6.32
Glasscock	283.5	235.45	-16.95	+7.8
Hale	276.88	229.14	-17.24	+11.352
Hockley	224.24	130.94	-41.6	+6.95
Howard	249.88	203.98	-18.37	+9.98
Lamb	277.27	194.91	-29.7	+7.87
Lubbock	256.98	162	-36.96	+7.28
Lynn	243.66	142.03	-41.71	+6.4
Martin	249.88	141.10	-43.53	+6.24
Midland	249.88	186.22	-25.48	+6.32
Terry	263.95	174.94	-33.72	+7.09
Yoakum	218.77	145.74	-33.38	+7.12
Avg change			-29.84	+7.77

Policy (3) requires a 1 percent conversion to more water-efficient irrigation technology. In more details, it is the 1 percent conversion from pivot to drip irrigation for cotton production.

Referring to Table 25 and 26, policy (3) decreases the net revenues by 29.84 percent on average, which is less than the reduction in the baseline. Indeed, for all counties, the net revenues are better than in the baseline scenario thanks to the more efficient irrigation technology. All counties are having net revenues falling within the sustainable threshold.

Table 28: Saturated Thickness for Texas South Plains counties in scenario 3 with 1 percent conversion to more water-efficient irrigation technology

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Bailey	90.99	22.31	-75.48	-0.7
Borden	127.72	124.18	-2.77	+0.15
Cochran	35.05	16.99	-51.53	+3.22
Crosby	99.58	15.55	-84.38	-2.54
Dawson	70.24	12.67	-81.96	-3.31
Dickens	155.52	154.04	-0.96	+0.07
Floyd	76.12	13.51	-82.25	-4.19
Gaines	80.13	25.39	-68.31	-2.74
Garza	64.28	48.89	-23.95	+1.24
Glasscock	33.2	24.88	-25.14	+1.88
Hale	72	17.31	-75.97	-0.38
Hockley	40.24	8.9	-77.88	-2.49
Howard	30.33	26.25	-15.35	-1.07
Lamb	66.11	17.05	-74.21	-1.77
Lubbock	57.09	11.01	-80.72	-0.48
Lynn	54.97	9.06	-83.51	-0.12
Martin	51.8	9.91	-80.86	+4.19
Midland	23.46	15.54	-33.78	+1.96
Terry	84.01	28.10	-66.55	+4.19
Yoakum	54.35	20.46	-62.36	+3.02
Avg change			-57.3	-0.32

Nevertheless, from water conservation perspectives, the policy would not be effective. On average, the saturated thickness level decreases by 57 percent. Moreover, the saturated thickness associated with this policy might not be sustainable for Bailey, Crosby, Dawson, Floyd, Gaines, Lamb, Lubbock, Martin Terry and Yoakum counties.

Regarding the group classification in terms of saturated thickness reduction, we would still put the lower 50th percentile counties into group (1) and the upper 50th percentile counties into group (2). As a result, under policy (3), group (1) consists of Borden, Cochrans, Dickens, Garza, Glasscock, Howard, Midland counties. Group (2) consists of Bailey, Crosby, Dawson, Floyd, Gaines, Hale, Hockley, Lamb, Lubbock, Lynn, Martin, Terry and Yoakum counties. The group composition under policy (3) is the same as in the baseline.

Table 29: Farmers' net revenue for Texas South Plains counties in scenario 4 with 2 percent conversion from irrigation to dryland for wheat, cotton and sorghum

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Bailey	256.98	138.823	-45.98	-1.75
Borden	256.86	177.24	-31	-5.18
Cochran	263.2	139.5	-47	-17.81
Crosby	256.86	144.46	-43.76	+2.34
Dawson	296.06	176.92	-40.24	+0.6
Dickens	276.52	214.85	-22.36	+0.71
Floyd	311.91	167.33	-46.35	-8.41
Gaines	230.46	111.4	-51.66	-1.32
Garza	249.88	193.9	-22.4	+9.4
Glasscock	283.5	206.62	-27.12	-2.37
Hale	276.88	152.98	-44.75	-16.16
Hockley	224.24	119.09	-46.89	+1.67
Howard	249.88	193.9	-22.4	+27.36
Lamb	277.27	141.78	-48.87	-11.29
Lubbock	256.98	202.35	-32.23	+12.01
Lynn	243.66	141.5	-41.93	+6.18
Martin	249.88	141.51	-43.37	+6.4
Midland	249.88	203.49	-18.56	+13.24
Terry	263.95	136.09	-48.44	-7.63
Yoakum	218.77	97.61	-55.38	-14.87
Avg change			-39.03	-1.41

Policy (4) requires a 2 percent conversion from irrigated to dryland crop production. More specifically, the applicable crops for this policy include wheat, cotton, and sorghum. The policy, as the other ones, also aims at conserving water while not reducing the revenues too significantly.

Referring to Table 27 and 28, the changes in net revenue for this policy vary across counties, but the average reduction is around 39 percent. As compared to the baseline, some counties experience lower net revenues while others enjoy higher net revenues depending on their crop combination, as followed the NASS data. Indeed, cotton is the most efficient crops when converting to dryland so counties with higher proportion of cotton planting have more advantages. Policy (4) is more

Table 30: Saturated Thickness for Texas South Plains counties in scenario 4 with 2 percent conversion from irrigation to dryland for wheat, cotton and sorghum

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Bailey	90.99	43.02	-52.72	+22.06
Borden	127.72	125.02	-2.11	+0.81
Cochran	35.06	20.56	-41.34	+13.4
Crosby	99.58	39.85	-59.98	+21.86
Dawson	70.24	29.17	-58.47	+20.19
Dickens	155.52	154.36	-0.75	+0.27
Floyd	76.12	35.41	-53.48	+24.59
Gaines	80.13	44.51	-44.46	+21.11
Garza	64.28	52.26	-18.71	+6.49
Glasscock	33.23	26.78	-19.41	+7.62
Hale	72	35.62	-50.53	+25.05
Hockley	40.25	19.30	-52.04	+23.35
Howard	30.33	27.15	-10.49	+3.64
Lamb	66.11	33.92	-48.69	+23.75
Lubbock	57.09	22.97	-59.77	+20.47
Lynn	54.97	23.09	-58	+25.4
Martin	51.8	21.74	-58.03	+27.02
Midland	23.46	17.01	-27.51	+8.23
Terry	84.01	43.3	-48.46	+22.28
Yoakum	54.35	32.11	-40.93	+38.93
Avg change			-40.29	+17.10

effective in conserving water than policy (3) but not as effective as the two water restriction polices mentioned above. Indeed, policy (4) conserve around 17 percent of saturated thickness as compared to the baseline. With the 2 percent conversion to dryland, both net revenues and saturated thickness fall within the sustainable threshold for all counties.

Regarding the group classification in terms of saturated thickness reduction, we would still keep grouping the lower 50th percentile counties into group (1) and the upper 50th percentile counties into group (2). As a result, under policy (4), group (1) consists of Borden, Cochrans, Dickens, Gaines, Garza, Glasscock, Howard, Midland and Yoakum counties. Group (2) consists of Bailey, Crosby, Dawson, Floyd, Hale, Hockley, Lamb, Lubbock, Lynn, Terry and Martin counties. Under policy (4), Gaines has moved from group (2) to group (1) thanks to the conversion to dryland production.

Table 31: Farmers' net revenue for Texas South Plains counties in scenario 5 with 3 percent water use decrease and 1 percent conversion to water-efficient irrigation technology

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Bailey	256.98	66.64	-74.07	-29.83
Borden	256.86	101.13	-60.63	-34.82
Cochran	263.2	93.71	-64.39	-35.21
Crosby	256.86	64.28	-74.98	-28.88
Dawson	296.06	76.99	-74	-33.16
Dickens	276.52	106.07	-61.64	-38.63
Floyd	311.91	83.48	-73.24	-35.3
Gaines	230.46	58.74	-74.51	-24.16
Garza	249.88	90.98	-63.59	-31.79
Glasscock	283.5	96.84	-65.84	-41.09
Hale	276.88	79.15	-71.41	-42.82
Hockley	224.24	57.65	-74.29	-25.73
Howard	249.88	101.21	-59.5	-31.15
Lamb	277.27	72.05	-74.02	-36.44
Lubbock	256.98	66.6	-74.08	-29.85
Lynn	243.66	61.51	-74.76	-26.65
Martin	249.88	62.60	-74.95	-25.18
Midland	249.88	90.98	-63.59	-31.79
Terry	263.95	67.62	-74.38	-33.57
Yoakum	218.77	57.15	-73.88	-33.37
Avg change			-70.09	-32.47

Policy (5) refers to the combination of a 3 percent reduction in water use and a 1 percent conversion to more efficient irrigation technology. Referring to Table 29 and 30, policy (5) decreases the net revenue for most of the counties by around 70 percent on average. Moreover, the reduction in the revenue is around 32 percent from the baseline. Here, we can see that there is an improvement in net revenues between policy (5) and policy (1), with 6 percent improvement. Indeed, under policy (5), the net revenues for all counties are still within the sustainable threshold, unlike policy (1) where most of the counties having net revenues falling beyond the threshold.

Table 32: Saturated Thickness for Texas South Plains counties in scenario 5 with 3 percent water use decrease and 1 percent conversion to water-efficient irrigation technology

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Bailey	90.99	62.33	-31.5	+43.28
Borden	127.72	126.14	-0.12	+1.68
Cochran	35.06	27.02	-22.94	+31.8
Crosby	99.58	65.09	-34.64	+47.21
Dawson	70.24	47.84	-31.88	+46.77
Dickens	155.52	154.86	-0.42	+0.6
Floyd	76.12	51.55	-32.29	+45.78
Gaines	80.13	58.69	-26.76	+38.81
Garza	64.28	57.39	-10.72	+14.48
Glasscock	33.23	29.55	-11.09	+15.93
Hale	72	49.68	-31	+44.58
Hockley	40.25	27.19	-32.44	+42.96
Howard	30.33	28.51	-6.01	+8.12
Lamb	66.11	46.40	-29.81	+ 42.63
Lubbock	57.09	32.88	-42.42	+37.83
Lynn	54.97	35.43	-35.56	+47.84
Martin	51.8	33.06	-36.18	+48.87
Midland	23.46	19.92	-15.11	+20.62
Terry	84.01	59.18	-29.56	+41.19
Yoakum	54.35	39.07	-28.11	+37.27
Avg change			-24.48	+32.91

From the water conservation perspective, no county sees saturated thickness level falling below the sustainable threshold. As compared to the baseline, policy (5) conserves more than 32 percent of the saturated thickness level. Nevertheless, the policy might not work perfectly for most counties since it decrease the net revenues below its sustainable benchmark. Overall, the combination with more efficient irrigation technology in policy (5) helps improve the net revenues (6 percent improvement) while still conserve the saturated thickness quite good, improving 2 percent from policy (1).

Regarding the group classification in terms of saturated thickness reduction, we would still keep grouping the lower 50th percentile counties into group (1) and the upper 50th percentile counties into group (2). As a result, under policy (5), group (1) consists of Borden, Cochrans, Dickens, Gaines, Garza, Glasscock, Howard, Lamb, Midland, Terry and Yoakum counties. Group (2) consists of Bailey, Crosby, Dawson, Floyd, Hale, Hockley, Lubbock, Lynn, and Martin counties. Under policy (5), Gaines has moved from group (2) to group (1) thanks to the water restriction.

Once again for the Texas South Plains, with policy (5), the water restriction's impact might be too harsh and over-weighs the impact of the conversion between irrigation technologies, even though the net revenue situation is slightly improved. This is may be because there is 3 percent decrease in water use while there is only 1 percent conversion to water-efficient irrigation technology. This observation poses the question of whether another combination of percentage change in each aspect of the policy should be considered. Indeed, designing the percentage change in each policy is important.

Policy (6) refers to the 1 percent reduction on water use every year. Referring to Table 31, net revenues decrease by about 35 percent on average, which is actually increase by 3 percent compared to the baseline scenario. Indeed, the increase in net revenue even under the water restriction comes from the fact that net revenues for some of the counties increase since their pumping cost decreases. Moreover, no county exceeds the defined sustainable threshold for net revenues.

From the water conservation perspective, saturated thickness level increases by close to 13 percent as compared to the baseline. However, Crosby, Dawson, Floyd, Lubbock, Lynn, and Martin counties exceed the sustainable threshold for saturated thickness reduction.

Regarding the group classification in terms of saturated thickness reduction, we would still keep grouping the lower 50th percentile counties into group (1) and the upper 50th percentile counties into group (2). As a result, under policy (6), group (1) consists of Borden, Cochrans, Dickens, Gaines, Garza, Glasscock, Howard, Midland, Terry and Yoakum counties. Group (2) consists of Bailey, Crosby, Dawson, Floyd, Hale, Hockley, Lamb, Lubbock, Lynn, and Martin counties. Under policy (6), Gaines has moved from group (2) to group (1) thanks to the water restriction.

Once we have looked at the impact of each policy on the Texas South Plains counties, it is crucial to construct a comprehensive analysis of all the different scenarios to provide better policy recommendation for the region.

Among the scenarios, scenarios (1) and (2) with 3 and 5 percent reduction in water pumpage

Table 33: Farmers' net revenue for Texas South Plains counties in scenario 6 with 1 percent water use decrease

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Bailey	256.98	147.4	-42.64	+1.6
Borden	256.86	240.55	-6.35	+19.47
Cochran	263.2	196.54	-25.33	+3.86
Crosby	256.86	145.76	-43.25	+2.84
Dawson	296.06	170.54	-42.4	-1.56
Dickens	276.52	255.41	-7.64	+15.38
Floyd	311.91	181.38	-41.85	-3.91
Gaines	230.46	130.51	-43.37	+6.98
Garza	249.88	187.03	-25.15	+6.65
Glasscock	283.5	210.28	-25.83	-1.08
Hale	276.88	171.21	-38.16	-9.57
Hockley	224.24	128.21	-42.83	-5.73
Howard	249.88	238.72	-4.47	+23.87
Lamb	277.27	162	-41.57	-4
Lubbock	256.98	147.4	-42.64	+1.6
Lynn	243.66	138.14	-43.31	+4.8
Martin	249.88	140.44	-43.8	+5.97
Midland	249.88	187.03	-25.15	+6.65
Terry	263.95	152.73	-42.14	-1.33
Yoakum	218.77	128.94	-41.06	-0.56
Avg change			-33.45	+4.17

Table 34: Saturated Thickness for Texas South Plains counties in scenario 6 with 1 percent water use decrease

County	Year 2021	Year 2080	Percentage change	Baselinecompare
Bailey	90.99	38.54	-57.65	+17.14
Borden	127.72	124.85	-2.25	+0.67
Cochran	35.06	20.27	-42.18	+12.56
Crosby	99.58	36.83	-63.02	+18.83
Dawson	70.24	27.67	-60.6	+18.06
Dickens	155.52	154.29	-0.79	+0.24
Floyd	76.12	28.97	-61.95	+16.12
Gaines	80.13	41.59	-48.09	+17.48
Garza	64.28	51.80	-19.41	+5.78
Glasscock	33.23	26.32	-20.81	+6.21
Hale	72	29.95	-58.41	+17.17
Hockley	40.25	16.83	-58.19	+17.21
Howard	30.33	27.03	-10.89	+3.24
Lamb	66.11	29.22	-55.8	+16.64
Lubbock	57.09	15.91	-72.13	+8.11
Lynn	54.97	19.64	-64.28	+19.11
Martin	51.8	17.85	-65.54	+19.51
Midland	23.46	17.04	-27.38	+8.36
Terry	84.01	38.23	-54.49	+16.25
Yoakum	54.35	26.93	-50.45	+14.93
Avg change			-44.72	+12.68

Table 35: Policy impacts in terms of average percentage change in net revenues and saturated thickness

Pol	NR	ST	NRCI	STCI	NR-Bline	ST-Bline	ΔNRBPa	ΔSTBPa
Bline	-37.62	-56.98	(-41, -34.3)	(-67.9, -46.9)			-35.02	-31.82
Pol 1	-76.25	-26.72	(-78.1, -74.4)	(-31.7, -21.7)	-38.64	+30.67	-42.31	+16.35
Pol 2	-86.95	-18.45	(-87.9, -86)	(-21.9, -15.0)	-49.33	+38.94	-54.32	+21.66
Pol 3	-29.84	-57.3	(-33.6, -26.1)	(-68.1, -46.5)	+7.77	-0.32	+24.53	-0.98
Pol 4	-39.03	-40.29	(-43.2, -34.9)	(-47.6, -33)	-8.81	+17.10	-8.81	+9.13
Pol 5	-70.09	-24.48	(-72.2, -68)	(-29.1, -19.9)	-32.47	+32.91	-35.55	+15.03
Pol 6	-33.45	-44.72	(-38.5, -28.4)	(-53.0, -36.4)	+4.17	+12.68	+0.39	+4.93

are most effective in conserving water as reflected through the change in saturated thickness over the time horizon. The impact on farmers' net revenue, however, is quite severe. Policy (5) is also effective in conserving water while the impact on net revenues is not as severe when compared to the 3 percent reduction in water pumpage.

While the impacts of policy (1), (2) and (5) are similar due to their focuses on water restriction, the impacts of policy (3) and (4) are quite different from the others across the counties. The differences may stem from the variation of crop combination and their irrigation technology. More specifically, counties with larger cotton production can take advantage of policy (3) better while the counties with more wheat, cotton and sorghum production can take advantage of policy (4) better.

Regarding policy (3), even though it increases the net revenue over time as compared to the baseline, the conservation impact might not be as high compared to the water restriction policies since the more efficient irrigation technology might still decrease the water level. The policy, therefore, might not be beneficial for some counties due to this reason.

Policy (4) and policy (6) are the among the better policies that decrease net revenues by only small amount while still conserving water compared to the baseline. Between the two policies, policy (4) with the 2 percent conversion to dryland proves to be the better option, on average, since it does not decrease net revenues by much while still conserving water more effectively. Nevertheless, there are still counties that can take advantage of the 1 percent water restriction from policy (6).

In the baseline, the change in saturated thickness is worse in the case of Texas South Plains as compared to Texas Panhandle, which also reflects in the higher reduction in net revenues. Moreover, due to the more serious aquifer depletion problem, any policy that can improve water usage can improve the saturated thickness by higher percentage as compared to the baseline than in the case of Texas Panhandle. We can also see that the impacts of the policies vary in terms of net revenues across the two regions especially the conversion to more water-efficient irrigation technology and conversion to dryland. The conversion to more water-efficient irrigation technology seems to work better in the Texas Panhandle by increasing the net revenues higher than in the Texas South Plains by a small amount. On the contrary, the conversion to dryland policy seems to work better in the Texas South Plains as reflected through the smaller decrease in net revenues as compared to Texas Panhandle. These variations may be due to the geographical differences across the two regions that may change the saturated thickness conditions, crop combination and irrigation technologies being applied.

For the Texas South Plains, we also classify the counties into two groups based on the saturated thickness reduction. Even though there are some transfers between the groups for one or two policies, the composition of the two groups are as reported below across most scenarios.

The counties with higher agricultural percentage include Bailey, Cochran, Crosby, Dawson, Floyd, Gaines, Hale, Hockley, Lamb, Lubbock, Lynn, Martin, Terry, and Yoakum. Across the different scenarios, group (2) with counties that have higher saturated thickness reduction needs more attention from water conservation perspective. Even though the group composition may vary

Table 36: Different groups of counties based on saturated thickness depletion

Lowerdepletion	Agpercentage	Higherdepletion	Agpercentage
Borden	9.36	Bailey	67.87
Cochran	56.72	Crosby	71.67
Dickens	24.67	Dawson	80.56
Garza	25.54	Floyd	76.75
Glasscock	33.59	Gaines	69.39
Howard	10.84	Hale	70.04
Midland	21.93	Hockley	77.69
		Lamb	61.14
		Lubbock	57.4
		Lynn	82.2
		Martin	75.91
		Terry	69.73
		Yoakum	64.83

slightly across the different scenarios, the counties that are consistently seeing higher saturated thickness reduction include Bailey, Crosby, Dawson, Floyd, Hale, Hockley, Lamb, Lubbock, Lynn, and Martin. These counties are also the ones with high percentage of agriculture production. However, not all counties that have high agricultural production are having serious aquifer depletion problems. Gaines, Terry, and Yoakum can switch the group with lower saturated thickness reduction under the conversion to dryland production and the different water restriction policies. As a result, we can see that agricultural production is a factor but it is not the only determinant, crop combination also matters. Indeed, Gaines and Yoakum, thanks to their major wheat and cotton production, can take advantage of the conversion to dryland better so that the aquifer depletion problem is not as serious as other major agricultural counties.

From Figure 4 and 5, we can see that among the Texas South Plains counties, Bailey, Lamb, Hale, Floyd, Lubbock, and Crosby are the counties seeing the largest reduction in water level since the early 1990s.

The Lubbock MSA, includes Crosby, Lubbock and Lynn counties. The region's counties not associated with a metropolitan area include Bailey, Childress, Cochran, Dickens, Floyd, Garza, Hale, Hockley, Lamb, Motley, Terry, and Yoakum counties. The population level and change information below helps guide the initial aquifer conditions of each county and also the county-specific water pumping rate.

Similar to the analysis in the Texas Panhandle, for the Texas South Plains, we also need to customize the policy according to county-specific agricultural production percentage, crop combination and aquifer condition while also stick to our objectives of balancing between net revenues and saturated thickness.

The counties that work better with the conversion to dryland policy include Bailey, Crosby, Dawson, Floyd, Hockley, Lubbock, Lynn, Martin, and Yoakum. These counties are the ones with high agricultural production percentage and specifically with more major wheat and cotton production that can take advantage of the dryland production better.

Figure 5: Texas South Plains counties

Table 37: Texas South Plains population level and growth

Variable	Year 2011	Year 2021	Population growth
Bailey	7,079	7,100	+0.3
Borden	620	613	-1.13
Cochran	3,127	2,887	-7.68
Crosby	6,044	5,737	-5.08
Dawson	13,747	12,728	-7.41
Dickens	2,427	2,203	-9.23
Floyd	6,507	5,803	-10.82
Gaines	17,123	20,706	+20.93
Garza	6,319	6,070	-3.94
Glasscock	1,179	1,510	+28.07
Hale	36,381	33,046	-9.17
Hockley	22,931	23,021	+0.39
Howard	34,990	36,664	+4.78
Lamb	14,063	13,123	-6.68
Lubbock	283,408	310,569	+9.58
Lynn	5,886	5,951	+1.10
Martin	4,884	5,771	+18.16
Midland	140,224	176,832	+26.11
Terry	12,543	12,528	-0.12
Yoakum	7,825	8,631	+10.30

The counties that work better with the conversion to more efficient irrigation technology include Borden, Dickens, Garza, Glasscock, Howard, and Midland. These counties are the ones with relatively smaller water level change over time that can increase the net revenues through the more efficient irrigation technology without hurting the aquifer saturated thickness. Moreover, these counties have relatively smaller scale of agricultural production.

The counties that work better with the 1 percent water restriction policies include Gaines, Hale, Lamb, and Terry. These counties are the ones with high agricultural production percentage and relative large portion of corn production.

Across the different policies, Lubbock, Crosby, Floyd, Dawson, and Martin consistently see the largest changes in saturated thickness. The reasons for this consistent problem might be due to different characteristics of these counties. More specifically, Lubbock, Floyd and Crosby counties are among the counties with the largest change in water level over time based on the map of water level change in Figure 3. Moreover, the agricultural production of these counties are on the top highest, with most of these counties having major corn production. The annual groundwater pumpage of those counties are also consistently the highest over the years leading to the simulation period, ranging from 150,000 to 350,000 gallons per year.

On the other hand, Glasscock and Midland are the best counties in terms of sustaining net revenues while conserving saturated thickness even some considerable levels agricultural production thanks to several characteristics. Firstly, these counties see smaller changes in water level over time based on the map of water level change in Figure 3. Moreover, their crop combination also helps especially in the case of Glasscock where its production is focusing more on cotton and less on corn.

It is also crucial to sum up the characteristics that might set various counties in the Texas South Plains into the two groups of saturated thickness reduction, especially the counties that see higher saturated thickness reduction from others. The factors differentiating the group of higher saturated thickness reduction from the other in Texas South Plains are similar to those for Texas Panhandle, the only difference is that the change in saturated thickness over the years leading to the simulation for Texas South Plains is higher. More specifically, it is still the combination of high corn production, high agricultural production percentage and large saturated thickness level change over time that set these counties apart from the others in terms of saturated thickness reduction. There are counties that either have relatively high corn production or may have not very high saturated thickness initially but still manage to conserve saturated thickness over time due to relatively lower agricultural production percentage.

Overall, recharge from precipitation on agricultural land is higher while groundwater irrigation return (pumpage minus crop demand) is lower in Texas Panhandle than in Texas South Plains (USGS Survey). Moreover, the water-level change (in percentage) in Texas Panhandle is less than that of the Texas South PLains. These differences can be observed through figure 3 and 4. Due to these differences, the impact of the different policies and policy recommendation would vary between these regions.

6 Concluding remarks

Various counties across the Texas Panhandle and the Texas South Plains may find different optimal policy due to their varying crop-irrigation technology combination and saturated thickness conditions. Moreover, the aquifer condition also varies across the two regions so we may also need to tailor the policies accordingly.

Some form of long term water pump restriction (percentage per year or permanent conversion) is necessary in order to achieve any considerable water savings. Indeed, in terms of water conservation and extending the usable life of the Ogallala Aquifer for both regions, water restriction policy and conversion to dryland production are both better than conversion between irrigation technology. Nevertheless, there would not be a panacea policy for all counties. Different counties may need some customized policy depending on their agricultural production percentage, current aquifer depletion problem, and socio-economic conditions. Moreover, there are certain counties that having more serious aquifer depletion problem, which are also the ones need more attention to water conservation since agriculture is their major industry. The policy (6), which requires a combination of 1 percent reduction in groundwater use is the optimal policy for counties that have relatively high agricultural production percentage while at the same having huge corn production across the two regions. On the other hand, policy (3) proves to be efficient for counties that do not have huge water level change over the years leading to the simulation and do not have high agricultural production percentage either. Policy (4) also proves to be efficient for counties that have high agricultural production percentage and also massive wheat and cotton production.

For both Texas Panhandle and Texas South Plains, policies like conversion to dryland and the 1 percent water restriction would help improve both net revenues and saturated thickness for most of the counties in the regions thanks to their decreasing pumping cost from the aquifer, especially those with more major agricultural production. The number of counties that can implement either of the two policies in the Texas South Plains is higher than that of Texas Panhandle due to the South Plains' more serious aquifer depletion problem.

Once again, the observations and policy proposals from the paper have shed light on how the county-specific agricultural production and groundwater level condition along the aquifer can affect the policies impacts beside the county crop combination.

From this paper, we have estimated the impacts of different policies on the counties across the Texas Panhandle and Texas South Plains while also proposing some county-specific policies tailoring to different agricultural production and crop combination. Nevertheless, it is also crucial to analyze the trade-offs between conserving water level and sustaining net revenues in more details for future research. The policy recommendations can be further tailored to county-specific characteristics as they are subject to change in the future.

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