ESSAYS ON THE ECONOMIC EFFECTS OF PRODUCER RESPONSES TO DECLINING WATER AVAILABILITY FROM THE OGALLALA AQUIFER

by

Sydney Reynolds

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Approved:

Dr. Bridget Guerrero — Date
Chairman, Thesis Committee

Dr. Bill Golden — Date
Member, Thesis Committee

Dr. Lal K. Almas — Date
Member, Thesis Committee

Dr. Lance Keith — Date
Department Head, Agricultural Sciences

Dr. Kevin Pond — Date
Dean, Paul Engler College of Agriculture and Natural Sciences

Dr. Angela Spalding — Date
Dean, Graduate School

ABSTRACT

With withdrawals from the Ogallala Aquifer continuing to exceed the recharge rate, water conservation is of great importance in the Texas High Plains. In this area, producers must continuously reexamine their production decisions as groundwater availability diminishes. Two studies were conducted which evaluate the economic effects of producer responses to declining water availability from the Ogallala Aquifer.

Study one provides the dynamically iterative results from a MATLAB-based economic intertemporal allocation model that combines the economic decisions faced by producers, influenced by groundwater availability, and the changes in the available resources which affect future decision-making regarding groundwater use in the Palo Duro and Double Mountain Fork Watersheds. The temporal allocation results reflect how the conditions that producers face will change over the planning horizon under six scenarios including the status quo, a 10 and 25 percent acreage reduction, an increase of energy prices, and an increase and decrease in precipitation.

In both watersheds, an increase in precipitation results in an increase in both producer profit and value added. In Hartley County within the Palo Duro Watershed, a 10 percent acreage reduction results in the lowest decline in the sum of projected producer profit ($1,812 million) with a 3.3 percent decrease from the status quo. As the availability of water declines, so does the yield, revenue, and overall profitability for each crop.

However, the policies that conserve the greatest amount of water may not be the most ideal situation for producers. Focusing on value added, a 25 percent reduction in irrigated acres provides the second highest increase in value added for the rural economy. This scenario also projects a 6.4 percent decrease in total water use and a 25.9 increase in ending saturated thickness. In Lynn County and the Double Mountain Fork Watershed, the considerably lower starting well capacity and saturated thickness result in the acreage reduction scenarios being the only scenarios in which there is any change in total water use or ending saturated thickness.

As groundwater levels continue to decline in the Ogallala Aquifer, stakeholders, policymakers, and producers encourage the adoption of new irrigation technology in an effort to conserve groundwater, extend the economic life of the aquifer, and enhance profitability. Study two evaluates the economic feasibility of one such technology currently receiving attention in the Central Ogallala region, the mobile drip irrigation (MDI) application system. This study compares MDI to low elevation spray application irrigation by evaluating the changes in variable cost per hectare to calculate the payback period for a MDI system under three levels of investment cost for grain and fiber crops representing three levels of water use while holding yield constant. Using a 3% discount rate, under the medium level of investment cost ($371 per hectare), a discounted payback period of 4.9, 9.0, and 6.3 years is required for corn, cotton, and sorghum/wheat, respectively. As the cost per hectare to convert an existing center pivot drops to $185 per hectare, the payback period also drops to 2.3, 4.2, and 3.0 years, respectively. Thus, producers growing higher water use crops are able to recover the costs of the conversion to MDI through increased water use efficiency quicker than producers growing medium and lower water use crops.

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And of course, I must thank my committee, Drs. Bridget Guerrero, Bill Golden, and Lal Almas for helping me through this process. Thank you for your support, guidance, and assistance throughout the many twists and turns this project has taken. This research would not have been possible without the support and funding from the Ogallala Water Coordinated Agriculture Project, a multi-disciplinary collaborative effort funded by USDA-NIFA, and the Ogallala Aquifer Program. They have an outstanding group of people working in each of their respective areas and, without a doubt, provided key information, support, and were always willing to lend a hand with my research and I would not have been able to complete these projects without their help. I feel very fortunate to have been involved with such a great group of people and a particular thank you to the OWCAP Texas group and the Objective 3 team for all the hydrology information and model help they provided.

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CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

The Ogallala Aquifer underlies portions of eight states and approximately 174,000 square miles in the Great Plains of the United States and serves thousands of farmers and ranchers who produce irrigated crops which support a significant portion of the region's economy, Figure 1-1. Once locations with seemingly unlimited water available for irrigation, many parts of the United States are facing drastically reduced water availability. This is unquestionably true for many areas within the Ogallala Region where water use is exceeding recharge rates due to increasing demand for crop production. This area produces several key agricultural products such as corn, cotton, sorghum, and wheat that have traditionally been part of the landscape. These crops utilize water from the Ogallala Aquifer and are an important facet in the regional economy. In the coming years, the area will face the challenge of maintaining agricultural production with an increasing rate of decline in aquifer levels. Many governmental agencies within the region have considered, have implemented, or are debating over mandates limiting pumping in attempt to reduce the rapid decline in saturated thickness (McGuire, 2017).

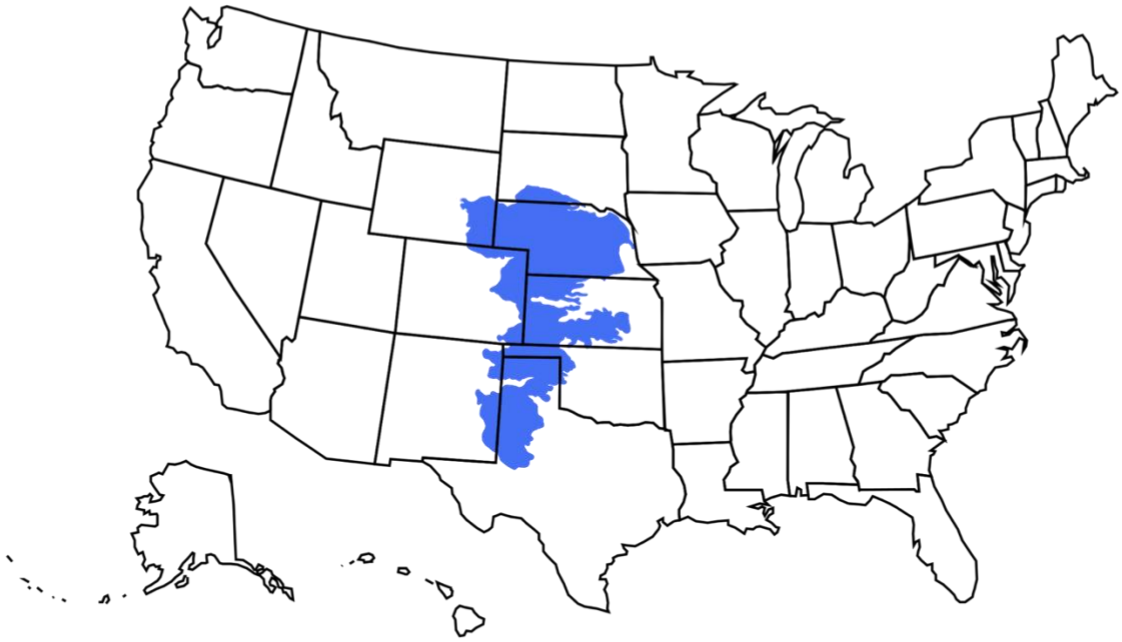

Figure 1-1. The location of the Ogallala Aquifer within the United States.

Water resources are facing stress from over usage as well as quality concerns. Focusing on the agricultural industry, there are significant implications for farmers and ranchers, which will have economy-wide consequences particularly in a region where agriculture is the dominant use of land, and the production of crops and livestock are the principal drivers of the region’s economy. Water pumped from the aquifer supports the production of nearly 30 percent of the irrigated crops produced in the United States as well as a significant number of hogs and both beef and dairy cattle. Irrigated agriculture from groundwater moved into widespread use in the area during the 1930s and 1940s and has only continued to increase. From 1949 to 2015, the number of irrigated acres served by the aquifer has increased more than sevenfold, from 2.1 million to 15 million acres, as estimated by the U.S. Geological Survey (McGuire, 2017).

On a global scale, less than one percent of water is available for human and animal consumption, and within many semi-arid regions, this is further compounded by the lack and variability of annual rainfall to adequately provide the water necessary to maximize crop yields during the growing season (McGuire, 2017). The availability of irrigation has allowed for the expansion of crops grown as well as the ability of producers to continue production during times of little or no rainfall. The ability to irrigate provides opportunity for economic growth; however, increasing irrigation also causes a decline in the availability of natural resources (Burt, 1966).

For thousands of years, irrigation has been a key piece of production agriculture. Water used for agricultural irrigation comes from either surface water or groundwater. Adding the ability to use groundwater allows for a larger area to be irrigated as compared to what would be possible on surface water alone. Depending on location, groundwater is used as a supplement to surface water during periods of low flow, or as the primary source of irrigation water. The advantages to groundwater include the ability to store with very little loss to evaporation, alleviation of pollution levels when water percolates through the ground during recharge, and the ability to withdraw water near the application site for immediate use. However, the agricultural sector is often criticized for high wastage and inefficient use of water at the farm level, potentially the result of the low cost of irrigation at a value which fails to signal the scarcity of the resource to farmers (Turner et al., 2004).

Developing countries are especially dependent on water for irrigation, illustrated by the fact that in all regions of the world, except North America and Europe, the most abundant use of water is for agriculture (United States Geological Survey, 2020). A 2016 study by Chebil and Frijia focused on the cereal grain sector in Tunisia, which is the primary source of food for most households. Despite this, productivity has remained very low compared to its potential, and imports have been typically needed to meet domestic demand. The efficiency of allocating water was determined by comparing the marginal value of product for water with the market price for producers. If the price of water was less than the marginal value of product, water was determined to be underused, and farm profits could potentially be raised by increasing the use of water. If the opposite was true, water was determined to be overused, and a reduction in use could raise farm profits. The point of maximum efficiency, and thus maximum profit, is reached when the marginal value product of water is equal to the market price of water (Chebil and Frjia, 2016).

While there are several options in terms of increasing sustainability of water resources, irrigation water use efficiency in agricultural production, which is defined as total yield per unit of land divided by irrigation water applied, is of particular importance. A more recent paper by Fan et al. (2018) looked at how farmers decide on land allocation to each crop and levels of irrigation water applied within a multi-crop system. More specifically, their study analyzed economic irrigation water use efficiency (EIWUE) within a system of two irrigated crops (corn and soybeans). While many irrigation and water efficiency studies are conducted at a local field level, Fan et al. evaluated a broader spectrum of how water was being used in soybean and corn production and how decisions were made. More specifically, the following factors were evaluated: efficiency rates of enhanced irrigation systems as compared to traditional systems, climate variability effects on production decisions, the major influential factors on irrigation choices, and how the production decisions were affected by the previously mentioned factors (Fan et al., 2018).

Using irrigation water from both multiple sources and on-farm surface water only had a negative effect on EIWUE when compared to groundwater. The EIWUE for corn was decreased as water prices increased and was decreased for both crops as energy costs increase. This suggests that increasing water prices will not increase the efficiency of water usage. However, they did find that the use of irrigation increased the efficiency of both crops and, interestingly, fewer wells on the farm may increase the efficiency of irrigation water. Additionally, higher temperatures during the growing season promote more efficient use of water. This is also similar to droughts—when droughts are due to either low levels of precipitation or higher temperature levels, farmers are more aware of potential production problems not only during the current drought but also in the following years (Fan et al., 2018).

Focusing on the Texas High Plains, Burt (1966) authored much of the early work on the economics of water use in the area. There are two factors that typically keep withdrawals from exceeding average recharge: as the water table lowers, the pumping costs increase, and the value of the water is a contingency against uncertain levels recharge. In the Ogallala Aquifer, the rate of use exceeding recharge levels is the result of water used for production being of greater economic value at present than in the future (Burt, 1966).

Singh (2014) reviewed previous literature on allocation optimization models focused on irrigation water implemented under linear programming, nonlinear programming, dynamic programming, and genetic algorithms. The objective function for the optimization of irrigation models generally was maximizing net farm income or profit per acre. Greater efficiency of irrigation water application through effective water management strategies and reallocation of water resources to higher-value products can be a key piece in balancing utilization to extend the life of the aquifer (Singh, 2014).

Focusing on the Southern sub-region of the Ogallala, which includes the Southern High Plains, a 2008 study evaluated conservation policies over a 60-year planning horizon in a 24-county area in Texas, New Mexico, and Kansas. The General Algebraic Modeling System (GAMS) was used to solve the optimization models (Wheeler-Cook et al., 2008). The optimization model aimed to maximize net present value (NPV) of net returns to land, management, groundwater, and irrigation systems for each county as a whole. While maximizing net present value, the following factors were included in the model: saturated thickness and pumping lift requirements, annual recharge rate, water application, pumping capacities, total irrigation acreage less than 100 percent, no greater than a 33 percent shift in acreage allotment from the previous year, and a non-negativity requirement (Wheeler-Cook et al., 2008).

Using the nonlinear dynamic optimization model in GAMS, four potential policies, including a baseline scenario of no change, were evaluated. These policies were further evaluated for 19 of the 24 counties that showed a reduction in the saturated thickness over the planning horizon. There were five counties that demonstrated an increase in saturated thickness based on the baseline scenario as the likely result of minimal levels of irrigated acres within the counties. For those counties showing decreases in the saturated thickness of the aquifer, three levels of drawdown policies were considered—0, 50, and 75 percent (Wheeler-Cook et al., 2008).

While the authors indicate that wide-spread, blanket water conservation policies are likely to be inefficient due to significant differences of hydrologic characteristics and current irrigation levels and practices within the study region, the 0 percent drawdown policy is not necessary for most counties in the region. While this policy would certainly conserve significant amounts of water from the aquifer, it would also significantly decrease NPV and economic activity across the region. This highly restrictive policy would best be implemented only in counties, or even portions of counties, that currently exhibit extensive annual drawdown, and the authors suggest it would only be implemented for a portion of the acres in that area. Similar results were also noted with the 50 and 75 percent policies as there were multiple counties in which this policy was a nonbinding constraint due to the baseline scenario not resulting in a significant enough annual level of drawdown to require a restriction of drawdown. Particularly in counties with considerable irrigated acres, a policy restricting drawdown to the levels evaluated in this study results in discontinuation of irrigated practices on a significant number of acres and thus reduces NPV (Wheeler-Cook et al., 2008). As a result, further work in evaluating policies requiring a smaller reduction in drawdown for this area may prove useful.

Given the significance of agricultural water use globally, several relevant studies have been conducted internationally. The Murray-Darling Basin, located in northern New South Wales, Australia, has been the source of irrigation water for the area for decades. Increased levels of irrigation usage from the basin has resulted in significant environmental degradation, which encouraged discussion regarding the efficiency of irrigated commodities, particularly cotton. In this location, the cost of water is rather low, resulting in the cost being just the cost of supply rather than the true cost to society in terms of scarcity. This has led to inefficient levels of water extraction and overuse of irrigation (Lee et al., 2006).

The authors set up the framework to reflect rational producer behavior with resource constraints using the theory that producers make their production decisions such that profit is maximized while using scarce resources. Their objective was to optimize the level of profit based on the distribution of water from the Mooki Basin with a set level of water supply and options in crop choice, source of water, irrigation rate, and irrigation systems. When setting up the model, there were two options for irrigation water, either from surface water or pumped from groundwater. Groundwater resulted in higher fixed and variable costs due to the requirement of pumping; however, it was a more reliable source than surface water and therefore was used whenever surface water was in short supply. This model also distinguished between water consumed by the plant and application due to the loss of water from application to plant (Lee et al., 2006).

A matrix of net profit, level of irrigation water used, land area, and drainage incurred was then set up to optimize returns. Within the model, deep drainage constraints were set up to prevent excessive water runoff and over-usage. Overall, these drainage constraints were able to be imposed at a relatively low cost with any level of water availability. However, if the level of water available was extremely low, imposing these deep drainage constraints would have no significant consequence on profit. Between the seven possible activities in the 53 units, irrigated cotton was the only profitable entity using either surface or groundwater. Additionally, while dryland cotton was only a third as profitable as the irrigated variety, it was still the most profitable dryland alternative (Lee et al., 2006).

Aljanabi et al.'s 2008 study covered an optimization model that aimed to maximize the predicted net benefit for each farm from the cultivation of different types of crops using reclaimed water near the Euphrates River. The mixed-integer nonlinear programming framework ANTIGONE in GAMS was used to solve the optimization model with up to four potential crops grown in each farm. The potential changes that may occur within the optimization results due to increased efficiency in irrigation systems and the adoption of new technology were also addressed. This was particularly applicable to the study region as flood irrigation is the primary method with reported water use efficiency rates of 45-55 percent. Even a small increase in irrigation efficiency, from 45 to 55 percent, resulted in a net benefit increase of 30.7 percent. These benefits continued until an irrigation efficiency of greater than 75 percent was used. As the efficiency of irrigation increased, crops with a lower economic value began to be cultivated as the water availability rose. Whereas with systems holding lower irrigation efficiency rates, only the highest economic value crops are selected for production (Aljanabi et al., 2008).

Earlier work conducted in Iran compared linear and non-linear programming (Ghahraman and Sepaskhah, 2004). A simple non-linear programming model was compared with an updated non-linear programming optimization model that added soil water balance. The model was run for both single crop (corn) and multiple cropping systems (wheat, barley, corn, and sugar beet), which allowed for various cropping patterns to be tested using a stochastic dynamic programming water allocation optimization model. The key differences between the models were enlarged as irrigation water was reduced, and the shortage increased as the result of assumptions that were oversimplified in the first model (Ghahraman and Sepaskhah, 2004).

Previous studies on the management of groundwater in various aquifer regions have shown varying results in terms of efficient administration (Johnson et al., 2011). On an individual producer level, the effectiveness of conservation policies can be hard to measure. When all users pump from the same aquifer without clear knowledge of other's practices, there is less of an incentive to participate in conservation policies. It is not guaranteed that by individually reducing the use of water from the Ogallala Aquifer, there will be additional water available in the future. As a result, many farmers will simply continue to pump water every year in an effort to make a short run profit with little or no thought regarding future pumping endeavors (Gisser and Sanchez, 1980). It should be noted that attitudes have changed in more recent years, and producers are putting more consideration is into future conservation (Shelper et al., 2019).

As the conditions of declining water availability and concerns about the future use of water continue to be of key importance around the world, it is certainly also true of areas served by the Ogallala Aquifer. Producers and stakeholders in the region are continuing to find ways to sustain farm profitability while maintaining water availability. Water-conserving production techniques and technologies, reducing irrigation amounts, and considering alternative crops or production methods are all methods in use and under consideration in the region. Building from previous work, the use of a model integrating baseline hydrogeological data with agronomic and economic models will allow for the estimation of the economic effects of producer decisions and the resulting effects on aquifer levels allowing for the evaluation of management strategies or policy approaches under consideration. An integrated model plays a crucial role in estimating the range of services associated with conservation practices and the risks and rewards associated with them (Secchi, 2013). This serves to allow for better understanding of the economic tradeoffs and the long-term impact on the aquifer of proposed strategies or policies. Alongside other strategies from the groundwater conservation districts and local policymakers, producers are also considering the implementation of more efficient irrigation systems and technologies as they continue to irrigate. While these application systems have increased water use efficiency for many producers, they must be economically feasible for widespread adoption.

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CHAPTER II: EVALUATION OF WATER CONSERVATION SCENARIOS UTILIZING A MATLAB-BASED INTERTEMPORAL GROUDWATER MODEL IN THE TEXAS HIGH PLAINS

Introduction

As the largest underground water reservoir in the county, the Ogallala Aquifer provides much of the water used for irrigating crops in portions of eight states, including the Texas High Plains. The wide-spread use of irrigation moved into the area after World War II, and the use of irrigation has risen considerably throughout the twentieth century and has continued into the new millennium. Looking back to the early 1950s, parts of Texas had already documented declines in the water-level of more than 50 feet compared to 1938; these declines continued and reached more than 100 feet of water-level reduction in 1980 (McGuire, 2017). Still, in the 1990s, there were nearly three billion acre-feet of groundwater contained within the Ogallala Aquifer, but as withdrawal rates have continued to exceed the level of recharge, the amount of water available has continued to drastically decrease (Carlson, 2019).

Given water use is exceeding recharge rates and the increasing demands of production, water conservation is of great importance in the Texas High Plains. This area produces several key agricultural products such as corn, cotton, sorghum, and wheat that have traditionally been part of the landscape. These crops, along with livestock production, utilize water from the Ogallala Aquifer and are an important facet in the regional economy.

As water has continued to be pumped from the Ogallala Aquifer at unsustainable rates in the region, producers must continuously reexamine their production decisions as groundwater availability diminishes (Terrell and Johnson, 1999). This study provides the dynamically iterative results from a Matrix Laboratory (MATLAB)-based economic intertemporal allocation model that combines the economic decisions faced by producers, influenced by groundwater availability, and the changes in the available resources which affect future decision-making regarding groundwater use (The MathWorks Inc., 2018). The temporal allocation results will provide an assessment of groundwater policies or strategies under consideration and reflect how the conditions that producers face will change over the planning horizon.

The overall objective of this study is to evaluate possible strategies to help overcome the challenge of maintaining producer profitability while conserving water. Specifically, integrating baseline hydrogeological data with agronomic and economic models will allow for the estimation of the economic effects of producer decisions and the resulting effects on aquifer levels of different policy approaches and management strategies.

This analysis will help to more accurately estimate changes in crop mix, crop profit per acre, crop water use per acre, saturated thickness, total water use, total profit, and total value added over a 50-year planning horizon for six scenarios:

- Status quo, where irrigation continues without regulation;
- Acreage reduction of 10 and 25 percent of irrigated acres;
- Increase of energy prices, where the price of energy used for pump operation rises; and
- Variability of precipitation, including include less (75 percent of baseline) and additional (125 percent of baseline) precipitation.

The results allow for an understanding of the economic tradeoffs for producers under a range of water conservation policies and management strategies proposed or otherwise under consideration, in addition to the impact of changes in precipitation.

Data and Methods

General Approach

Producer decision making was projected over the 50-year study horizon utilizing a MATLAB-based economic intertemporal allocation model (The MathWorks Inc., 2018). The framework in the model assumed that producers behave rationally in making production decisions in order to maximize profit given defined model constraints of scarce resources, most importantly, water. Baseline economic input data of prices and variable costs were obtained from the Texas A&M AgriLife Extension Service crop enterprise budgets for Districts 1 and 2. This information, along with production functions developed from DSSAT model results, seasonal precipitation, and hydrogeologic data was incorporated into the model. Coupling cost and production functions allowed for the prediction of the profit-maximizing planting and irrigation decisions as a function of the spatially explicit aquifer, agronomic, and economic characteristics across five crops. The county-level models evaluate the profits and the level of water withdrawn from the Ogallala for each year over the 50-year planning horizon. The optimization model allows the profit, water use, and resulting hydrologic changes to be evaluated between various strategies and policies. The fundamental approach taken in this model is based on the previous framework used in Vestal, et al. (2017) and Amosson et al. (2009) as well as earlier work done in GAMS by Wheeler-Cook et al. (2008).

This model will be applied to five counties representing varying hydrologic conditions within the Palo Duro and Double Mountain Fork Watersheds in Texas. It assumes that land used for production under irrigated conditions at the beginning of the planning horizon will be allocated to one of four irrigated crops or transitioned into dryland production. The five crops analyzed in the model were irrigated corn, irrigated grain sorghum, irrigated cotton, irrigated wheat, and an aggregate dryland crop to take into account dryland crop production and subsequent revenues. The aggregate dryland crop represents the average values of dryland sorghum, dryland cotton, and dryland wheat.

Study Region

The study region focuses on two watersheds in Texas, Palo Duro and Double Mountain Fork, both of which heavily rely on the Ogallala Aquifer for irrigated agriculture. More specifically, five counties within these watersheds were chosen to be evaluated. Within the Palo Duro Watershed located in the northwest corner of the Texas

Panhandle, Hartley, Hansford, and Moore Counties were analyzed, Figure 2-1. While the Double Mountain Fork Watershed is defined differently within various programs, the counties of Lynn and Hockley represented the Double Mountain Fork Watershed in this study, Figure 2-2 (Uddameri and Ghaseminejad, 2020).

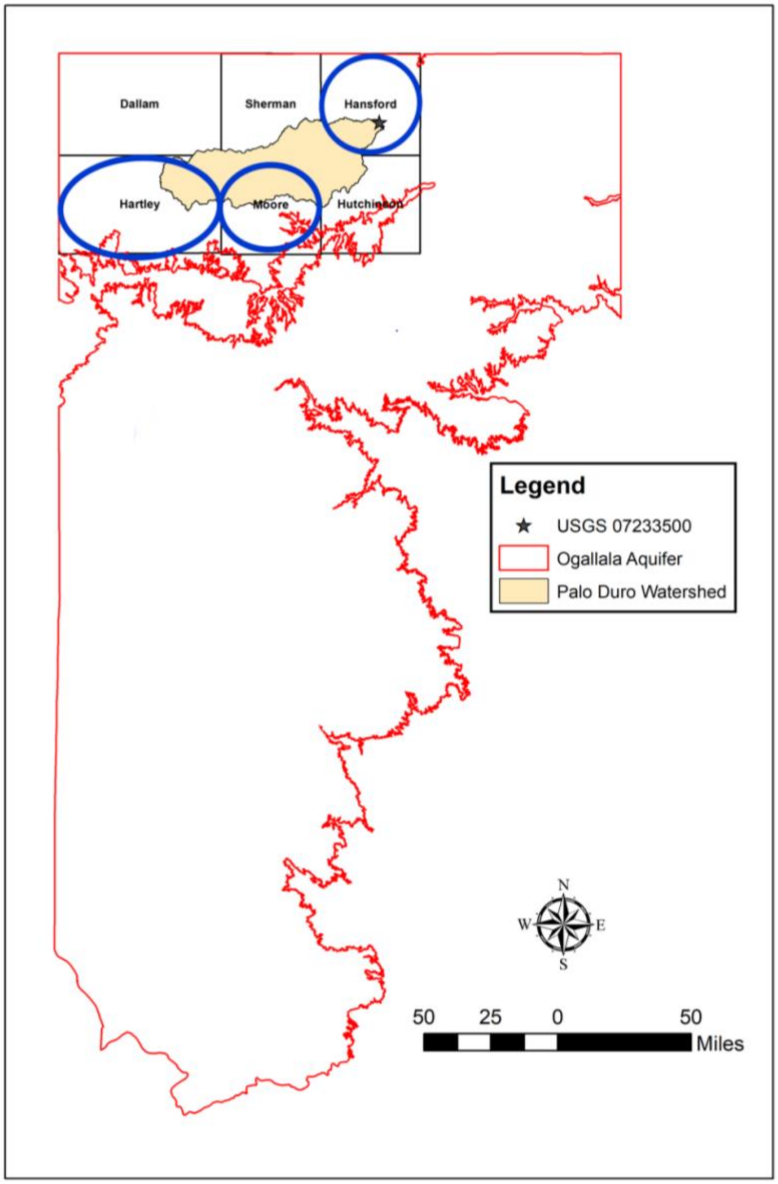

Figure 2-1. Location of counties evaluated within the Palo Duro Watershed.

Source: Uddameri and Ghaseminejad, 2020

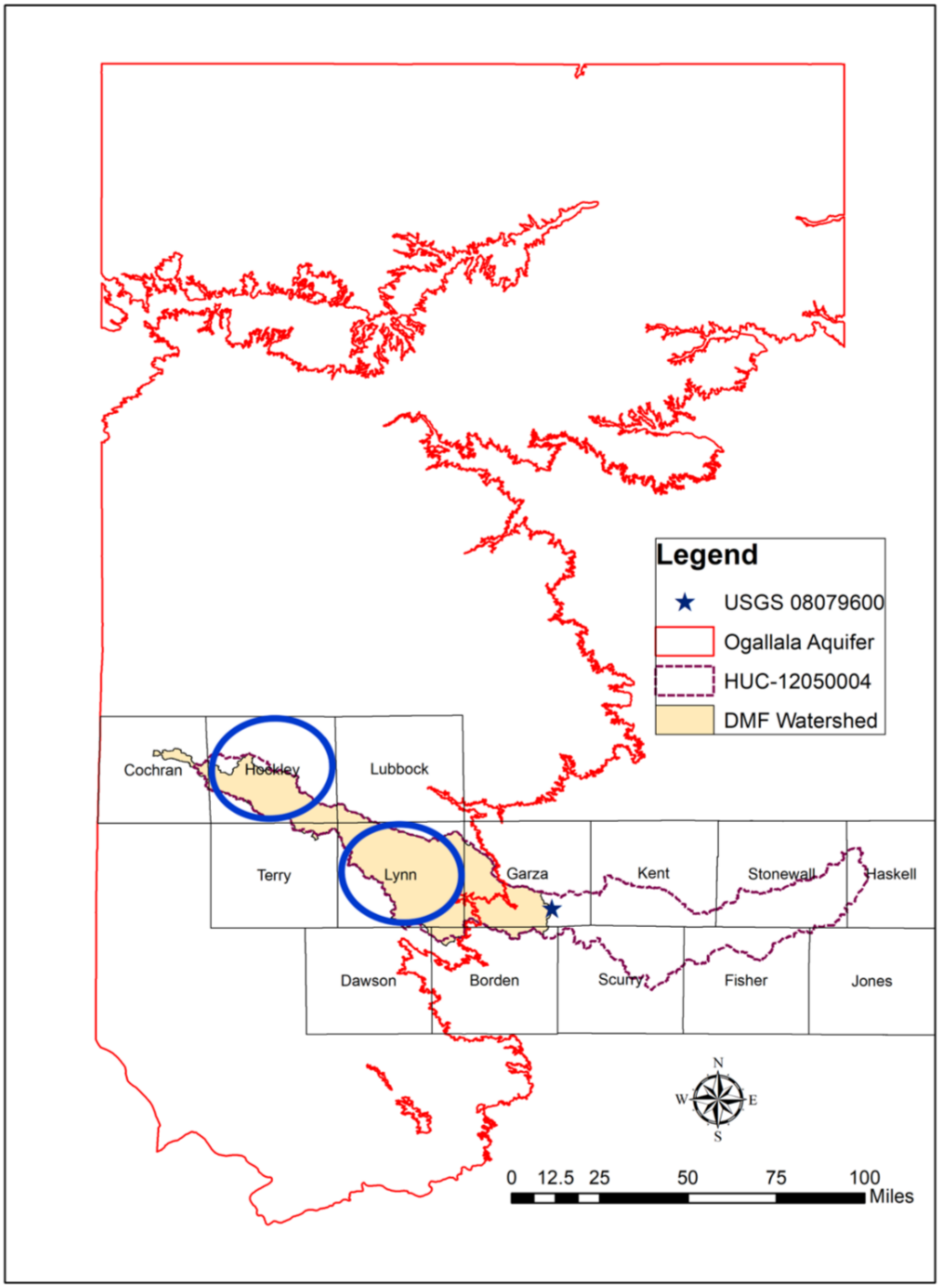

Figure 2-2. Location of counties evaluated within the Double Mountain Fork Watershed.

Source: Uddameri and Ghaseminejad, 2020

Production Functions

The foundation of the model was the crop-water production functions that were based on the calibrated Decision Support System for Agrotechnology Transfer (DSSAT) model runs, which represented soil, weather, and climate data from weather stations within each study region from 1981 to 2017 (Hoogenboom et al., 2019). The variability in yield is primarily a function of crop water use, which is accounted for by irrigation and precipitation. The estimated relationships between yield and water during the growing season for each crop in this study are represented in Equations 2-1 through 2-8. In these equations, yield is in bushels per acre for corn, sorghum, and wheat and pounds of cotton lint for cotton; IRR is irrigation applied in acre-inches per acre; IRR_2 is the squared term of IRR; PRCP is precipitation in acre-inches per acre from the planting date to harvest; and $PRCP_2$ is the squared term of PRCP. These production functions serve as a critical step in integrating the agronomic factors within the model to predict economic changes based on producer behavior and the resulting crop profit and production functions.

PALO DURO WATERSHED PRODUCTION FUNCTIONS

(2-1) $Corn\ Yield = 15.0 * IRR - 0.3 * IRR^2 + 15.0 * PRCP - 0.3 * PRCP^2 - 135.0$

(2-2) $Cotton\ Yield = 69.8 * IRR - 1.3 * IRR^2 + 38.9 * PRCP + 41.8$

(2-3) $Sorghum\ Yield = 10.3 * IRR - 0.2 * IRR^2 + 10.3 * PRCP - 0.3 * PRCP^2 - 56.8$

(2-4) $Wheat\ Yield = 6.2 * IRR - 0.2 * IRR^2 + 13.8 * PRCP - 0.6 * PRCP^2 - 38.7$

DOUBLE MOUNTAIN FORK WATERSHED PRODUCTION FUNCTIONS

(2-5) $Corn\ Yield = 15.0 * IRR - 0.3 * IRR^2 + 15.0 * PRCP - 0.3 * PRCP^2 - 135.0$

(2-6) $Cotton\ Yield = 60.0 * IRR - .7 * IRR^2 + 31.4 * PRCP - 0.3 * PRCP^2 + 25.0$

(2-7) $Sorghum\ Yield = 12.5 * IRR - .3 * IRR^2 + 11.6 * PRCP -$

$$-0.3 * PRCP^2 - 57.3$$

(2-8) $Wheat\ Yield = 6.2 * IRR - 0.2 * IRR^2 + 13.8 * PRCP -$

$$0.6 * PRCP^2 - 38.7$$

These production functions are the mathematical functions that best mimic the data generated from the DSSAT results for corn, cotton, and sorghum within both of the watersheds. The regressions from the DSSAT runs were based on a subset of the data using the most prominent soil types which were Sherm silty clay loam and Amarillo fine sandy loam for the Palo Duro and Double Mountain Fork Watersheds, respectively. As a result of a small number of acres of irrigated corn grown in the Double Mountain Fork Watershed and the lack of availability of local calibration data, the production functions for both watersheds are the same for corn. The production function for wheat was based on previous work by Stone et al. (2006) due to the lack of consistency within the DSSAT results to expected outcomes and previous work in the area. These functions make a reasonable prediction of grain yield given a level of inputs, irrigation water, and seasonal precipitation, and are consistent with economic, agronomic, and engineering principles. The production functions were calibrated based on long-term field trial data from the USDA-ARS Conservation and Production Research Laboratory in Bushland, TX and generate yield-water use observations and mimic reduced well capacity by varying irrigation frequency and amounts (Uddameri and Ghaseminejad, 2020). The functions generated indicate that the yield-water use relationships are quadratic and exhibit diminishing marginal returns, Figures 2-3 and 2-4.

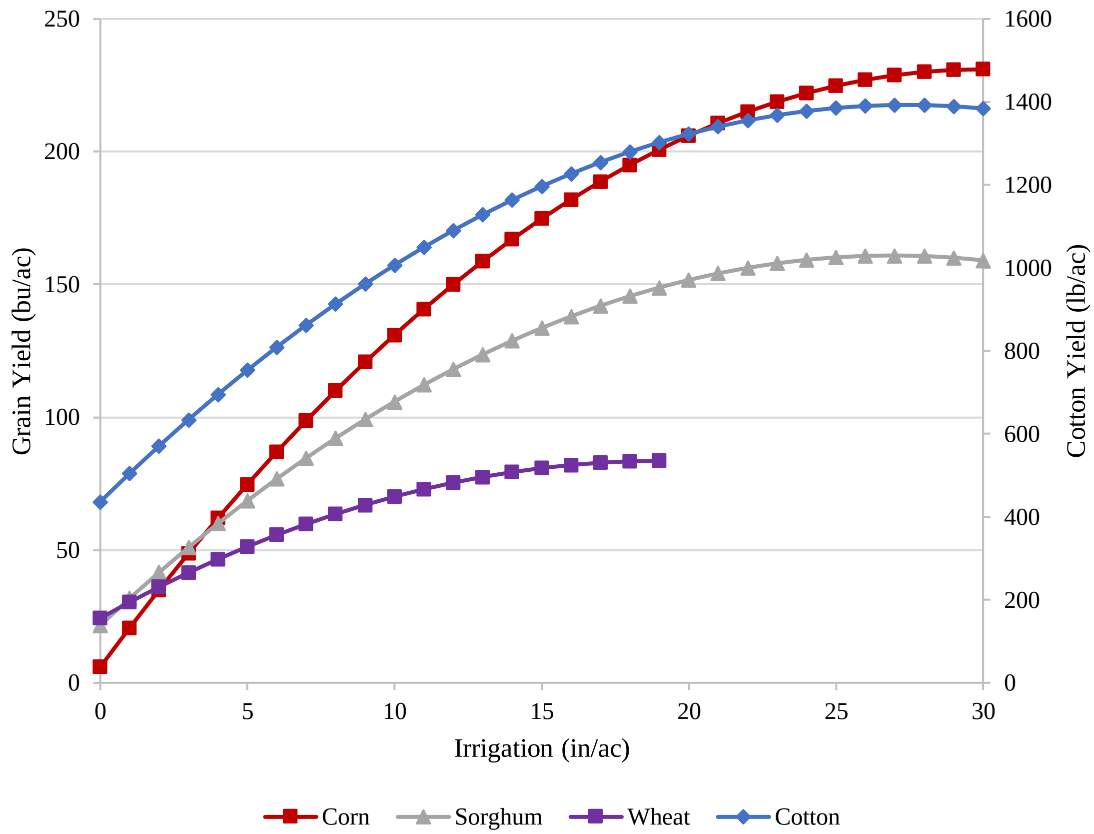

Figure 2-3. Production functions for corn, cotton, sorghum, and wheat in the Palo Duro Watershed graphed at average seasonal precipitation for varying levels of irrigation applied.

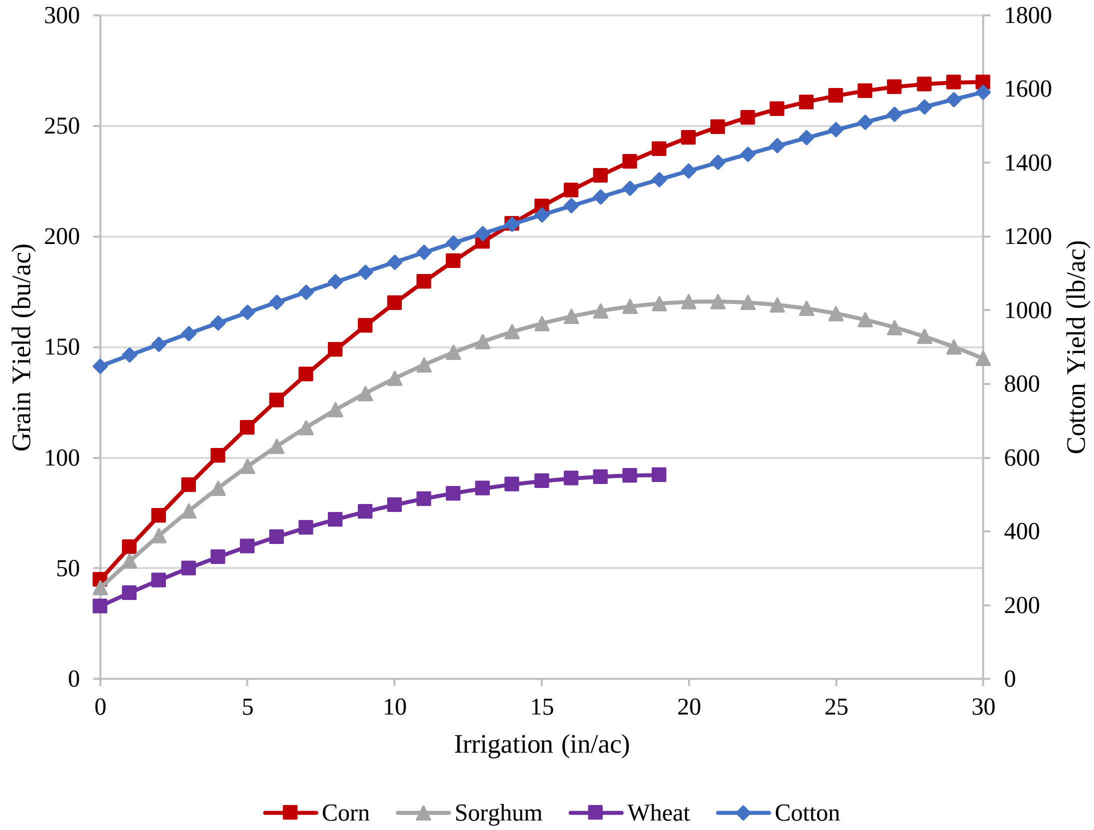

Figure 2-4. Production functions for corn, cotton, sorghum, and wheat in the Double Mountain Fork Watershed graphed at average seasonal precipitation for varying levels of irrigation applied.

<u>Production Inputs</u>

Four irrigated crops were analyzed in this model: irrigated corn (C1), irrigated cotton (C2), irrigated grain sorghum (C3), and irrigated wheat (C4). Additionally, a dryland crop (C5) was included as a choice for producers to allocate acreage. This dryland crop represented the average production and revenue from dryland cotton, sorghum, and wheat. While there is a variety of other irrigated crops grown in the five counties evaluated, these four irrigated crops represent the majority of acres cultivated under irrigated production methods. County-level crop acreage data were collected and a three-year average (2016-2018) was calculated (Farm Service Agency, 2019). In order to have the four crop choices represented in the total number of irrigated acres for each county, the data were scaled using percentages, Table 2-1. The percentage of acres planted to each crop was calculated using the total number of irrigated acres for the four crops analyzed only. This percentage was then applied to the total irrigated acres for all crops. This provided a reasonable assumption of how the acres would be allocated if corn, cotton, grain sorghum, and wheat were the only crops grown with the use of irrigation.

Table 2-1. Scaled acres for each irrigated crop by county.

County	Corn	Cotton	Grain Sorghum	Wheat	Total
Hansford	70,448	46,894	4,518	64,232	186,092
Hartley	154,247	25,345	21,291	70,169	271,052
Hockley	6,035	127,026	7,711	3,411	144,183
Lynn	3,857	80,868	2,465	4,299	91,489
Moore	70,142	33,687	2,188	28,710	154,426

Corn was the most prominent crop grown within the Palo Duro Watershed, followed by cotton. Cotton represented nearly all of the irrigated acres in the Double Mountain Fork Watershed. On average (2016-2018), there was nearly 850,000 acres cultivated under irrigated production in total over the five counties. This included 304,729 acres of corn, 313,820 acres of cotton, 38,173 acres of sorghum, and 170,821 acres of wheat, Table 2-1.

It was assumed that producers will choose the crop allocation and water application that will maximize profit based on available inputs. The use of an optimization objective function based on maximizing producer profits is consistent with past work in the field, including Vestal et al. (2017) and Amosson et al. (2009). This assumes that the outcomes of groundwater management will be based on the returns for producers. The use of an objective function based on producer profits implicitly assumed that the only relevant consideration in aquifer management is the profit impact to the producer. Golden and Guerrero (2017) suggest that there are other relevant objective functions, such as the value added regional impact on the rural economy. Within the dynamically iterative output, it was assumed that all acres initially cultivated will remain in agricultural production, and as well capacity diminishes, the crop mix may shift to include additional dryland acres.

Crop prices and costs of production were obtained (Amosson et al., 2015; Amosson et al, 2016; Amosson et al, 2017; Smith et al., 2015, 2016, 2017) and a three-year average (2016-2018) was calculated and modified in some cases as outlined below. This served as the main economic input for the MATLAB model, Tables 2-2 and 2-3. The price for wheat was adjusted to include income from grazing and cotton was also adjusted to reflect the additional income received for cottonseed. Variable costs per acre included all direct expenses included in the Texas A&M AgriLife Extension Service Budgets excluding seed, fertilizer, and harvesting costs. This included herbicide, fertilizer, and insecticide application, crop insurance, operator labor, fuel for tractors and pickup trucks, and repair and maintenance for implements, tractors, and general use equipment. Seed, fertilizer, and harvesting costs were included in the model as expenses that vary per unit of yield. When producers use less water or expect less water to be available for irrigation, the amount of seed and fertilizer will also be lower. Likewise, harvesting costs will change based on yield in terms of harvesting, hauling, and processing costs, where applicable. Additionally, the overall cost of custom harvesting was reduced from budgeted levels to reflect the majority of producers who do not hire an outside entity to harvest their crop.

Table 2-2. Crop and input prices for Hartley, Hockley, and Moore Counties.

	Corn	**Cotton**	**Grain Sorghum**	**Wheat**
Harvest Unit	Bushel	Pound (Lint)	Bushel	Bushel
Price/Unit[1]	$ 3.92	$ 0.78	$ 3.40	$ 4.99
Variable Costs	$ 185.28	$ 188.99	$ 143.46	$ 112.95
Per Unit Variable Costs[2]	$ 1.15	$ 0.28	$ 0.88	$ 1.66

[1] Wheat price adjusted to include grazing income and cotton price adjusted to include cotton seed income

[2] Per unit variable costs include seed, fertilizer, and hauling/processing

Source: Amosson et al., 2015; Amosson et al, 2016; Amosson et al, 2017

Table 2-3. Crop and input prices for Hockley and Lynn Counties.

	Corn	**Cotton**	**Grain Sorghum**	**Wheat**
Harvest Unit	Bushel	Pound (Lint)	Bushel	Bushel
Price/Unit[1]	$ 4.07	$ 0.77	$ 3.83	$ 6.16
Variable Costs	$ 163.32	$ 335.89	$ 148.13	$ 102.13
Per Unit Variable Costs[2]	$ 1.51	$ 0.27	$ 0.99	$ 2.35

[1] Wheat price adjusted to include grazing income and cotton price adjusted to include cotton seed income

[2] Per unit variable costs include seed, fertilizer, and hauling/processing

Source: Smith et al., 2015, 2016, 2017

A dryland crop was also a producer choice included in the model and was represented by a combination of dryland cotton, sorghum, and wheat. Realistically, yields, revenue, and costs vary considerably between producers, farms, and production practices. However, these were held constant in this study to allow more focus on the changes occurring due to changing water availability. Thus, an average profit per acre of $21.79 and $12.79 was used for the Palo Duro and Double Mountain Fork Watersheds, respectively (Amosson et al., 2015; Amosson et al, 2016; Amosson et al, 2017; Smith et al., 2015, 2016, 2017). The same price and cost adjustments were made as noted for the irrigated crops.

These crop prices were also used to calculate crop revenue in order to estimate the impacts to the rural economy under each scenario. As in Deines et al. (2020) and Thorvaldson and Pritchett (2006) 'value added' was used to estimate the impacts to rural communities in the study region, beyond direct crop revenue. Value added was calculated by multiplying the revenue for each crop acre by a regional impact factor specific to crop production inputs, including dryland production. The value added multiplier was generated using a regional economic input-output model, IMpact analysis for PLANning (IMPLAN) (IMPLAN Group, LLC, 2013) along with modifications performed through the analysis-by-parts method which utilized region-specific crop enterprise budgets. The value added figure consists of four components: employment compensation, proprietor income, other property income (such as rent), and indirect business taxes (IMPLAN Group, LLC, 2013).

Additionally, the precipitation from weather stations within each of the watersheds from 1981 to 2017 was incorporated into the model. The DSSAT runs provided the precipitation that occurred during the crop's growing season and these values were averaged to provide growing season precipitation for each watershed, Table 2-4 (Uddameri and Ghaseminejad, 2020). The Double Mountain Fork Watershed had a nearly 30 percent higher average precipitation and, in both watersheds, sorghum had the highest growing season precipitation.

Table 2-4. Average annual growing season precipitation for the Palo Duro and Double Mountain Fork Watersheds.

Precipitation (inches)	Corn	Cotton	Grain Sorghum	Wheat
Double Mountain Fork	15.14	13.17	16.23	8.44
Palo Duro	11.67	10.15	12.51	6.51

Source: Uddameri and Ghaseminejad, 2020

Hydrogeologic Inputs

The decline in saturated thickness is a primary concern within the study region, and MODFLOW was used to estimate the relationships within groundwater flows. MODFLOW is the United States Geological Survey model that uses finite numerical difference equation procedure with water budgets that account for recharge, withdrawals, and net lateral inflows to monitor the saturated thickness and water table elevation over time (Harbaugh, 2005). The pumping rate was calculated based on crop water requirements extracted from the DSSAT model. Each year there were two stress periods on the aquifer: the growing season where groundwater was being pumped, which occurred from April 15 through September 15, and the recovery period during the remainder of the year where no water was pumped.

The pumping requirements from DSSAT and groundwater levels from a regional MODFLOW model was used to develop autoregressive models for saturated thickness which allowed for the estimation of a linear drawdown relationship between total water use and the saturated thickness of the aquifer in each study region. Including the spatially-explicit groundwater flow processes within MODFLOW provided the relations between the land surface and subsurface hydrology (Bailey et al., 2016). Autoregressive models allow the memory of the aquifer to prior pumping to be captured within the model and serve to include water table dynamics in unconfined aquifers, such as the Ogallala. The linear relationship between acre-feet pumped and saturated thickness at the beginning of the growing season for a section of land with 500 irrigated acres for Hansford, Hartley, Hockley, Lynn, and Moore Counties was defined and then scaled to the number of irrigated acres within each of the counties in order to obtain an average county-level drawdown of saturated thickness, Equations 2-9 through 2-13, respectively (Uddameri and Ghaseminejad, 2020). In the following equations, CST is change in saturated thickness in feet and is the product of the constant representing the drawdown per acre and total water use in acre-feet (TWU).

(2-9) $CST = 0.00000605 * TWU$

(2-10) $CST = 0.00000784 * TWU$

(2-11) $CST = 0.00001156 * TWU$

(2-12) $CST = 0.00000605 * TWU$

(2-13) $CST = 0.00001006 * TWU$

Moreover, hydrogeologic information including hydraulic conductivity, specific yield, depth to water, initial head, saturated thickness, and well capacity was provided and incorporated into the model, Table 2-5 (Uddameri and Ghaseminejad, 2020).

Table 2-5. Hydrogeologic information for the counties evaluated.

County	Hydraulic Conductivity K (ft/d)	Specific Yield	Depth to Water (ft)	Initial Head (ft amsl)	Saturated Thickness (ft)	Well Capacity (gpm)
Hansford	46	0.21	302	3473	158	900
Hartley	19	0.17	364	2893	129	600
Hockley	33	0.20	128	3286	50	100
Lynn	10	0.16	79	3122	42	100
Moore	70	0.14	359	3263	115	600

Source: Uddameri and Ghaseminejad, 2020

Saturated thickness is directly related to depth to water (feet), maximum available water (ac-in), and well capacity (gallons per minute). The change in saturated thickness is equivalent to the change in depth to water and well capacity is adjusted using the same proportion that saturated thickness has moved relative to the initial value. The maximum available water for the growing season is based on the well capacity. As the maximum available water decreases it is a limiting factor in the amount of water that can be applied to a given crop. Maximum available water of in acre-inches available annually (MAWA) was calculated as a function of the well capacity in gallons per minute (GPM) multiplied by minutes per hour (60), hours per day (24), number of days water is pumped during the growing season (Days, set to 120), and number of inches per foot (12). This value was then divided by the product of gallons per cubic foot (7.48), square feet per acre (43560), and the number of irrigated acres under a center pivot (CP_Acres, set to 126), Equation 2-14. This provides the maximum available water for one well, assuming one well per center pivot.

(2-14) $$\text{MAWA} = (\text{GPM} * 60 * 24 * \text{Days} * 12)/(7.48 * 43560 * \text{CP\_Acres})$$

Particularly in Hockley and Lynn Counties, the hydrologic information for the county includes low capacity wells which limit the amount of irrigation that can be applied. While actual production practices in the area may include the operation of several wells in order to serve one center pivot, this study focuses on center pivots served by a single well.

Policy Analysis

Six scenarios were evaluated including status quo, acreage reduction of 10 and 25 percent, energy price increase, and a 25 percent increase and decrease in precipitation. The status-quo scenario assumed no change in policy or climate over the time horizon, where irrigation continued without regulation. In this scenario, water use is constrained so as to not rise above the initial use with the assumption that producers are already irrigating at the maximum rate for the region. This was compared to alternative scenarios to calculate economic tradeoffs from different policies and rainfall variability. Two scenarios reduced initial irrigated acreage in each county by 10 and 25 percent, respectively. This reduction was reflected in the model by reducing initial total water use by these same percentages and including this number as a maximum for the remainder of the study period. The energy price scenario reflects a price increase to $10 per thousand cubic feet for the Palo Duro Watershed where natural gas is the most common energy source for irrigation pumping (US Energy Information Administration, 2019). In the Double Mountain Fork Watershed where electricity is commonly used, an increased price of $14 per acre-inch was used (Smith et al., 2016). Finally, two scenarios that included less (75 percent of baseline) and additional (125 percent of baseline) precipitation were included to determine the difference in results based on precipitation changes within the region.

Results

The MATLAB model was run for each scenario (six) and each county (five) and results are presented below for Hartley County within the Palo Duro Watershed and Lynn County for the Double Mountain Fork Watershed. Results for Hansford, Hockley, and Moore Counties can be found in Appendices A, B, and C, respectively. Results include crop mix, crop profit per acre, and crop water use per acre for the status quo scenario. Additionally, saturated thickness, total water use, total profit, and total value added are presented for each scenario.

A few factors regarding the results that generally apply to all counties should be noted. First, while it was expected that the increased precipitation scenario would result in greater ending saturated thickness as compared to the status quo scenario, this is not the case. The greater amount of water available to the crop during the growing season results in higher yields, allowing irrigated crops to continue to be profitable. On the other hand, reduced rainfall reduces yield and dryland production becomes more profitable sooner relative to continuing irrigation. As a result, total water use is lower, and correspondingly, a greater amount of saturated thickness remains at the end of the 50-year planning horizon. Second, the marginal cost of groundwater used for irrigation increases when the price of energy used for center pivot operation is raised, and thus, the profitability of all irrigated crops drops.

It should be noted that the change in crop mix was limited to a one percent increase per year for corn and cotton and five percent increase for grain sorghum and wheat. Acres allocated to each of the irrigated crops did not have a lower bound on the rate of change nor were there any constraints on the rate of change for dryland acres. These limits were put in place to avoid corner solutions and more closely mimic historic crop mix changes.

Hartley County

Representing the Palo Duro Watershed, Hartley County is the western most county and represents the largest county in the study area as well as the county with the greatest total water use. The majority of irrigated acres are allocated to corn, and results indicate that the number of acres in this commodity continues to increase until the profitability of corn drops below irrigated wheat and then dryland, Figures 2-5 and 2-6. Irrigated sorghum acres quickly switch to any of the other three more profitable irrigated crops and do not come back into production as it is the least profitable of the irrigated crops. Cotton remains the most profitable crop over the entire study period and is the only crop where acres continue to rise every year, Figure 2-5.

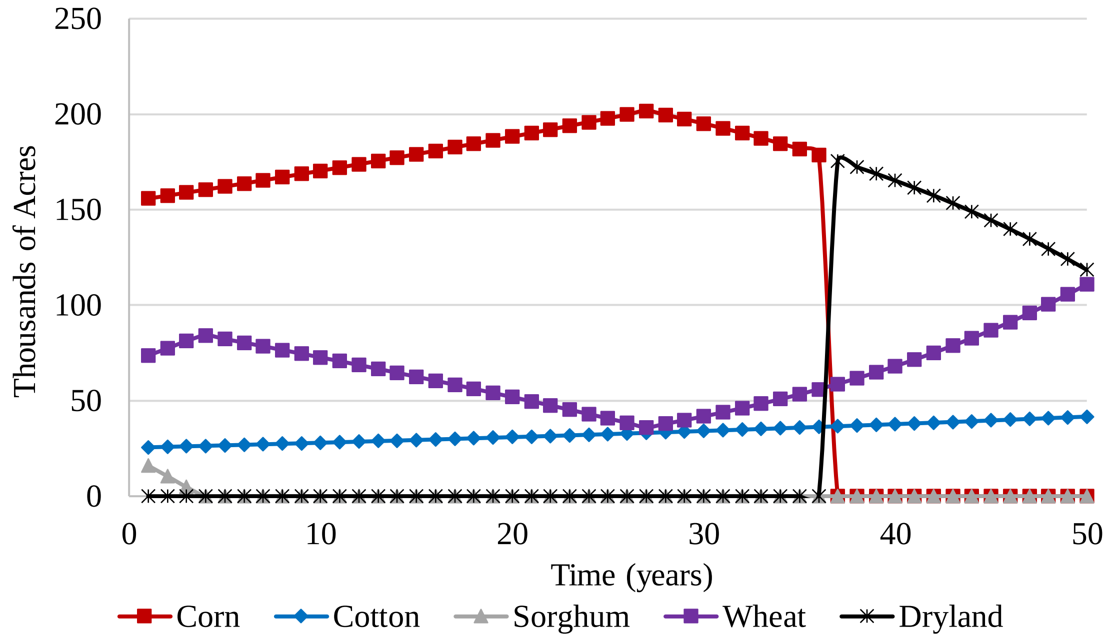

Figure 2-5. Number of acres planted to each crop in Hartley County under the status quo scenario over the 50 year study period.

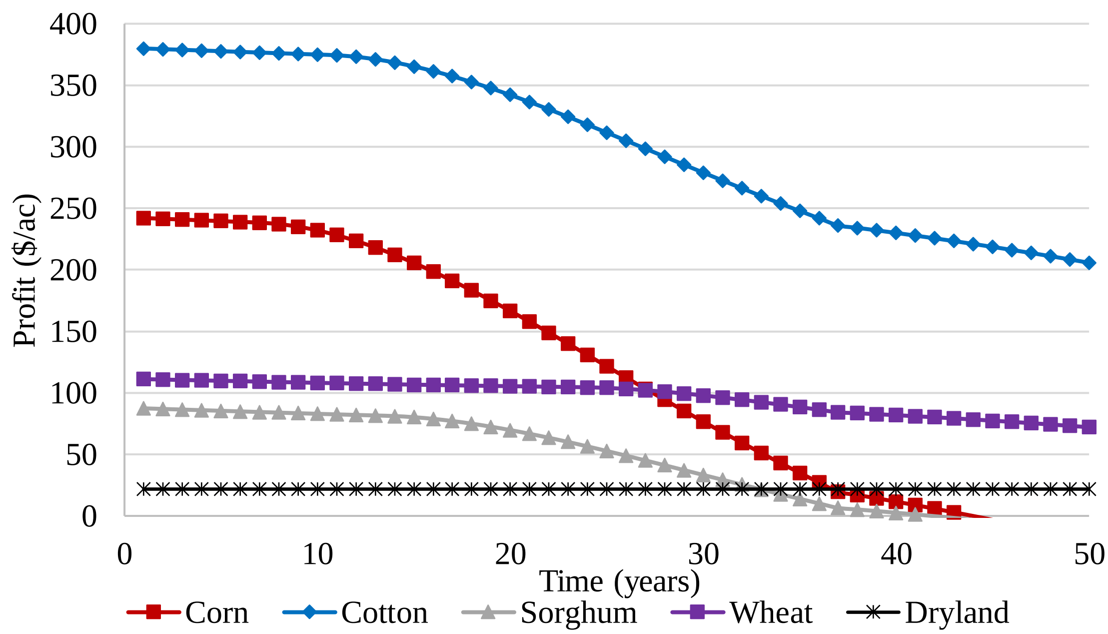

Figure 2-6. Profit per acre for each crop in Hartley County under the status quo scenario over the 50 year study period.

Profit per acre for each of the crops remains steady for approximately ten years of the planning horizon while the profit maximizing level of irrigation is available. As the availability of water declines, so does the yield, revenue, and overall profitability for each crop. Cost of pumping also increases as the saturated thickness decreases and the distance the water must be pumped increases, further contributing to lower profit, Figure 2-6.

Additionally, water use per acre declines as water availability declines, Figures 2-7 and 2-8. The initial annual water use (ac-in/ac) is the profit maximizing level for each of the crops, given the constraints of the model. Water use per acre then begins to decline when water becomes limited in a pattern similar to saturated thickness over time. This occurs first with corn, which is highest water use crop. It should be noted that the profit maximizing levels of irrigation from this model under the status quo scenario are likely higher than actual irrigation application due to several factors including conservation programs, limits on pumping, permit requirements, and potentially lower than average well capacities. However, the irrigated crops are still more profitable than the dryland choice as evidenced by the increase in acres of the three most profitable crops, Figure 2-5. The limit on the rate of change for each of the crops continues to be a key factor in determining the annual crop mix. In year 37 of the study period, a shift to dryland acres occurs with continued shifts to the remaining profitable crops, cotton and wheat.

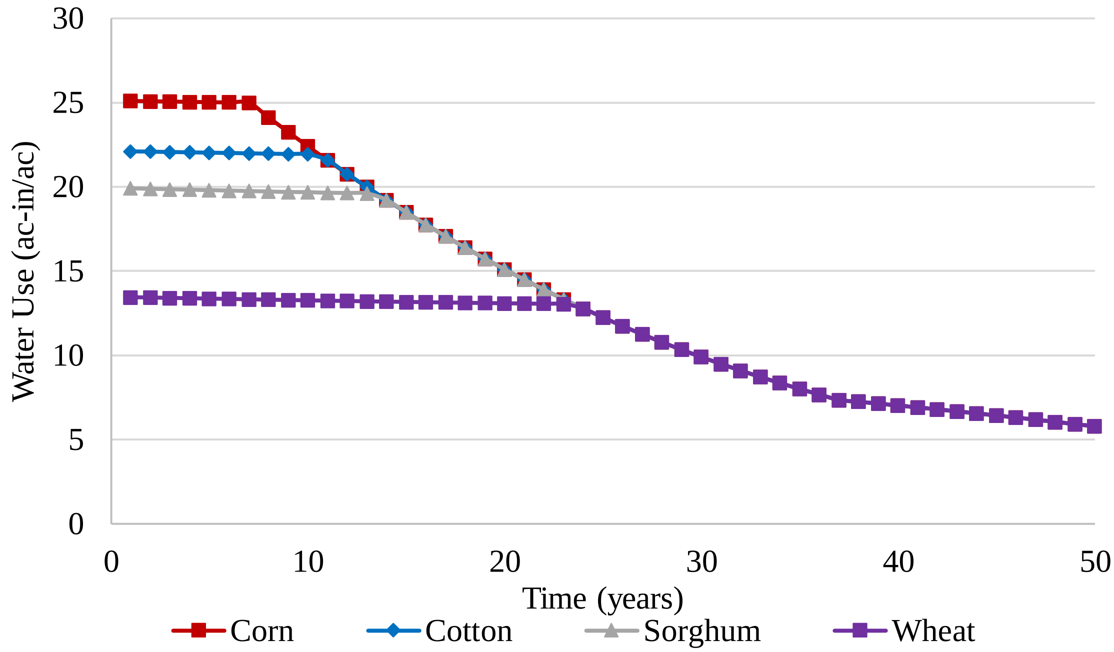

Figure 2-7. Annual water use (ac-in/ac) for each crop in Hartley County under the status quo scenario over the 50 year study period.

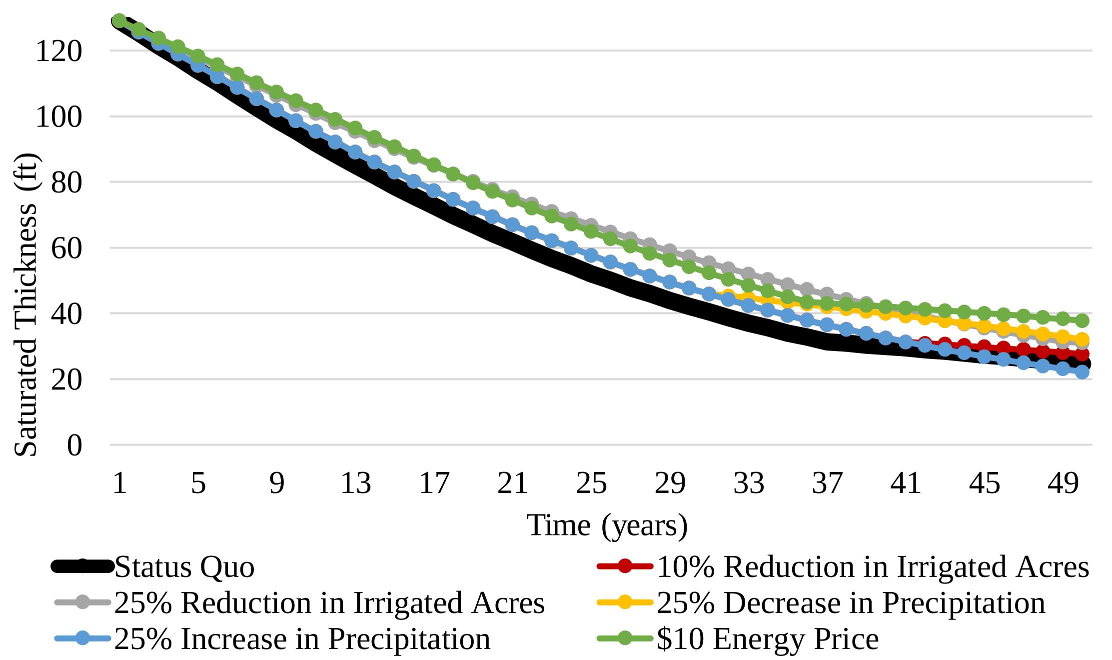

Figure 2-8. Saturated thickness (feet) under each scenario in Hartley County over the 50 year study period.

The rise of energy prices provides the greatest amount of ending saturated thickness (37.8 feet), a 53.5 percent increase over the status quo results, Figure 2-8 and Table 2-6. This increase comes with reduced total profit over the planning horizon as well as a decrease in total water use. On the other hand, the 25 percent increase in precipitation scenario results in the lowest ending saturated thickness (22.2 feet), a 9.8 percent decrease from the status quo scenario.

Table 2-6. Comparison of profit, value added, total water use, and ending saturated thickness for all scenarios in Hartley County over the 50 year study period.

Scenario	*Profit (mil $)*	*% Change in Profit*	*Value Added (mil $)*	*% Change in VA*	*TWU (1,000 ac-ft)*	*% Change in TWU*	*Ending ST (ft)*	*% Change in ST*
Status Quo	1,874	-	4,398	-	13,386	-	24.6	-
10% Acreage Reduction	1,812	-3.3%	4,473	1.7%	12,990	-3.0%	27.6	12.1%
25% Acreage Reduction	1,731	-7.6%	4,592	4.4%	12,533	-6.4%	31.0	25.9%
25% Decrease Precipitation	1,217	-35.1%	3,463	-21.3%	12,475	-6.8%	32.1	30.2%
25% Increase Precipitation	2,391	27.6%	5,038	14.5%	13,728	2.6%	22.2	-9.8%
$10 Fuel Price	1,012	-46.0%	4,136	-6.0%	11,692	-12.7%	37.8	53.5%

Sharp drops in annual water use occur in each scenario when the dryland crop becomes more profitable than one of the initially more profitable crops, Figure 2-9. The 10 and 25 percent acreage reduction scenarios both prolong the number of years before this occurs. Under the scenario with increased precipitation, this drop is never realized during the planning horizon. On the other hand, and as expected, a decrease in precipitation results in this drop off occurring seven years earlier as compared to the status quo scenario. While every scenario (except an increase in precipitation) decreases the sum of total water use over 50 years, all scenarios use a lower amount of water annually at the beginning of the planning horizon as compared to the status quo scenario, Table 2-6 and Figure 2-9.

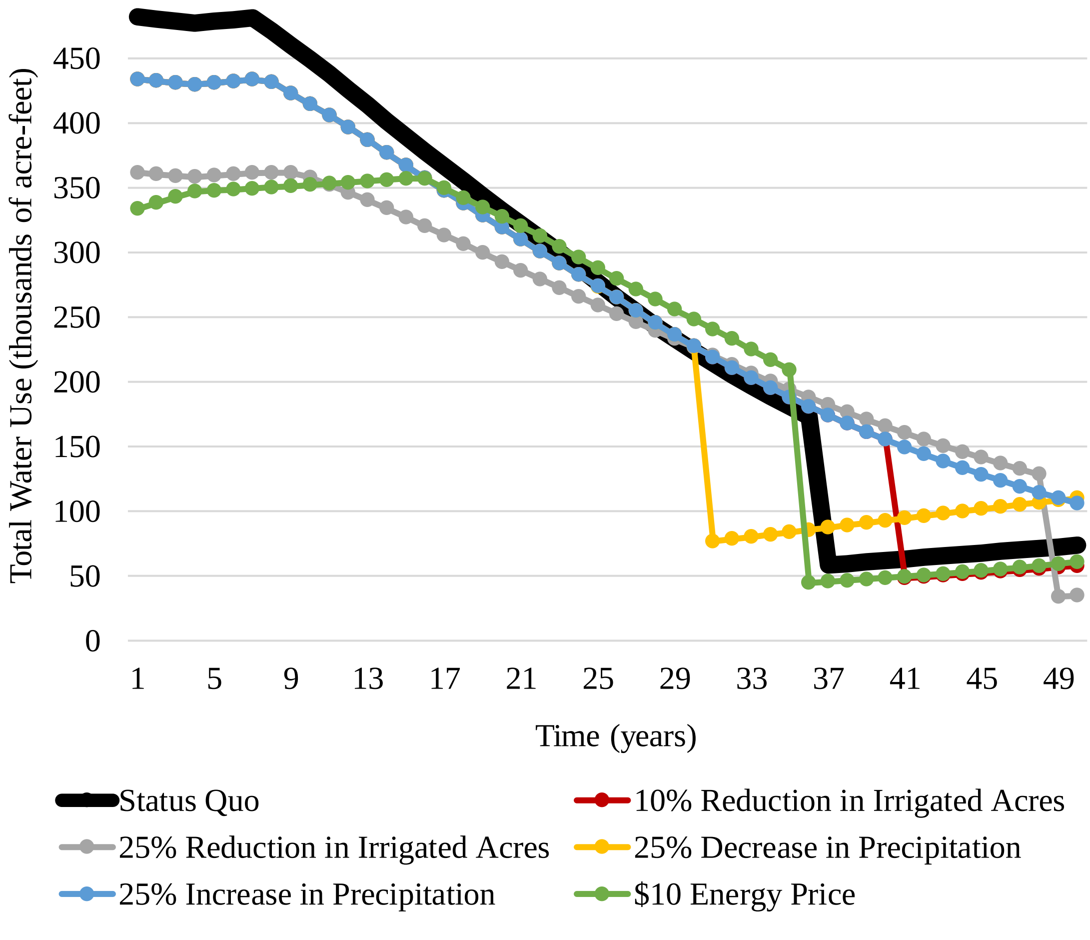

Figure 2-9. Total annual water use (acre-feet) under each scenario in Hartley County over the 50 year study period.

Results indicate a generally stable level of total profit for the county for varying amounts of time, depending on the scenario, followed by steady declines in annual profit as the water availability decreases, Figure 2-10. After the shift, a small increase occurs in water use and profit as the acres shift to other irrigated crops that are more profitable than dryland, based on the limits of increasing acres. Alternatively, sharp declines in value added occur at the same time as the switch to a substantial number of dryland acres. This is due to the fact that value added is calculated from revenue as opposed to profit. The switch to dryland results in more drastic changes in total revenue, whereas profit declines more steadily over time with an increasing marginal cost of pumping as water levels decline, Figure 2-11. In the acreage reduction scenarios, the decline in profit was projected to be 3.3 and 7.6 percent compared to the status quo scenario for the 10 and 25 percent acreage reduction scenarios, respectively, Table 2-6. A decline also occurs in total water use; however, it is a smaller percentage when compared to the status quo results.

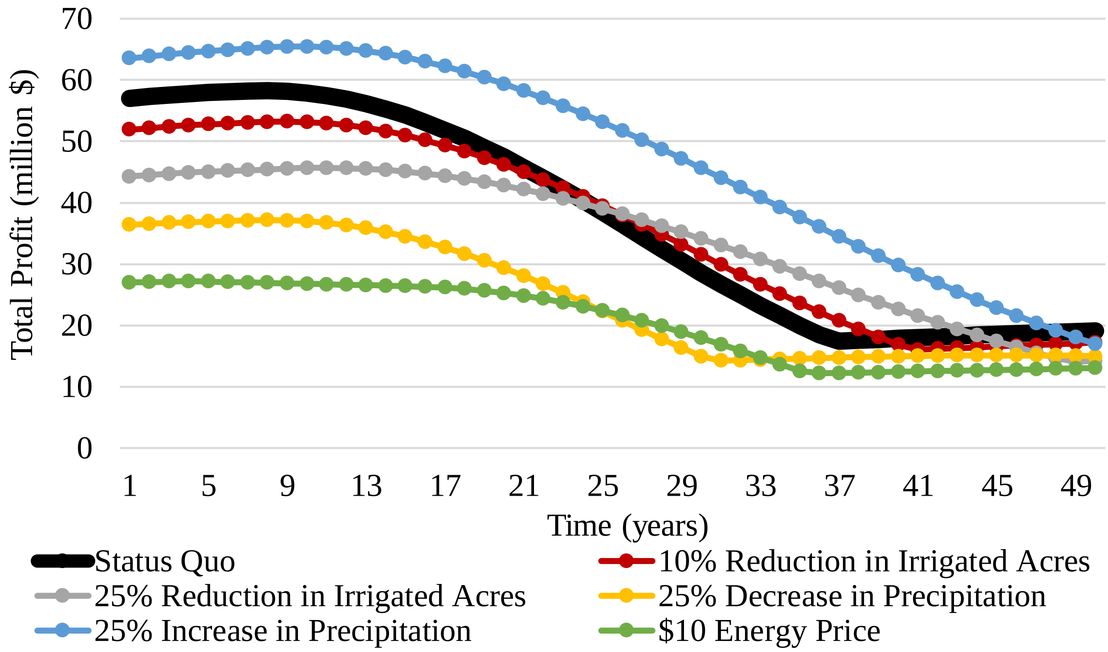

Figure 2-10. Total annual profit under each scenario in Hartley County over the 50 year study period.

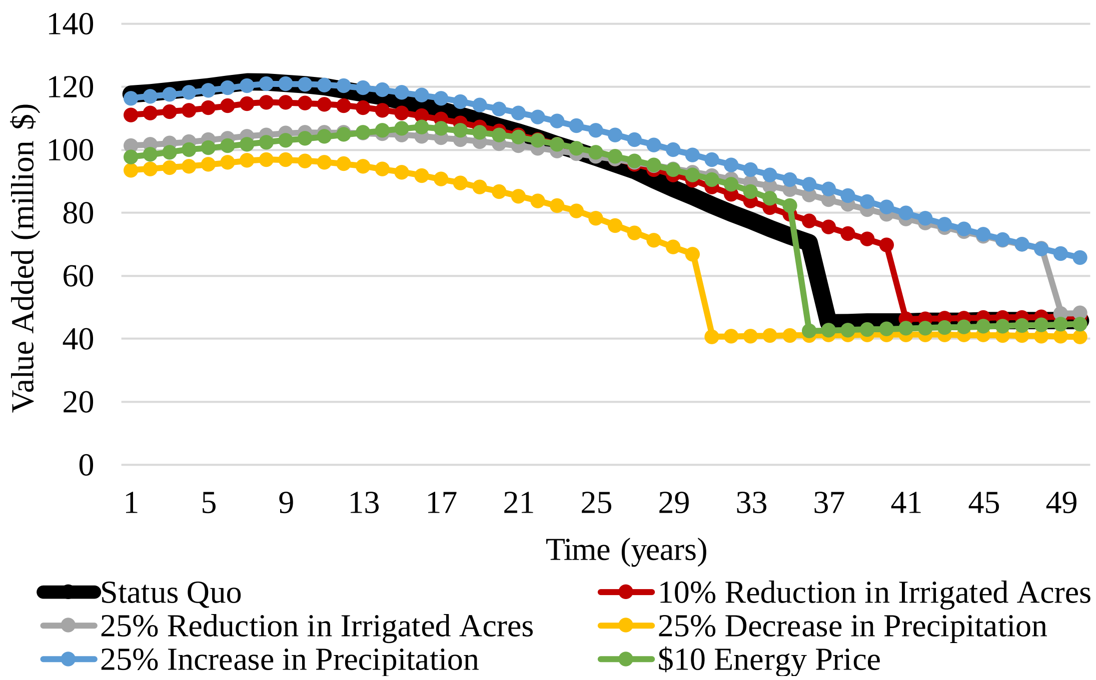

Figure 2-11. Total annual value added under each scenario in Hartley County over the 50 year study period.

Lynn County

In the Double Mountain Fork Watershed, Lynn County has considerable limits on irrigation based on the initial well capacity and saturated thickness. In addition, the starting acreage allocation is over 88 percent cotton, and as the most profitable crop, there is a slow switch to entirely cotton under every scenario, Figures 2-12 and 2-13. Additionally, as the irrigated crops remain profitable over the planning horizon, there is no switch to dryland acres.

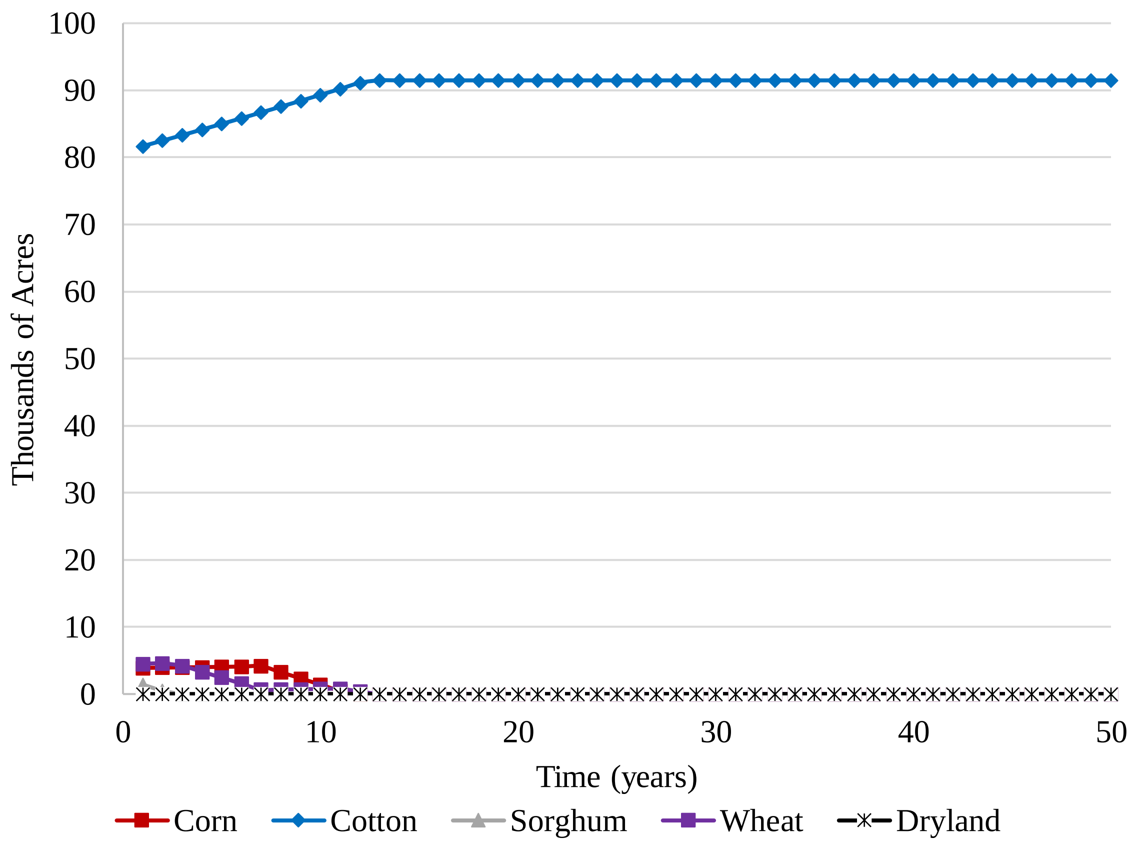

Figure 2-12. Number of acres planted to each crop in Lynn County under the status quo scenario over the 50 year study period.

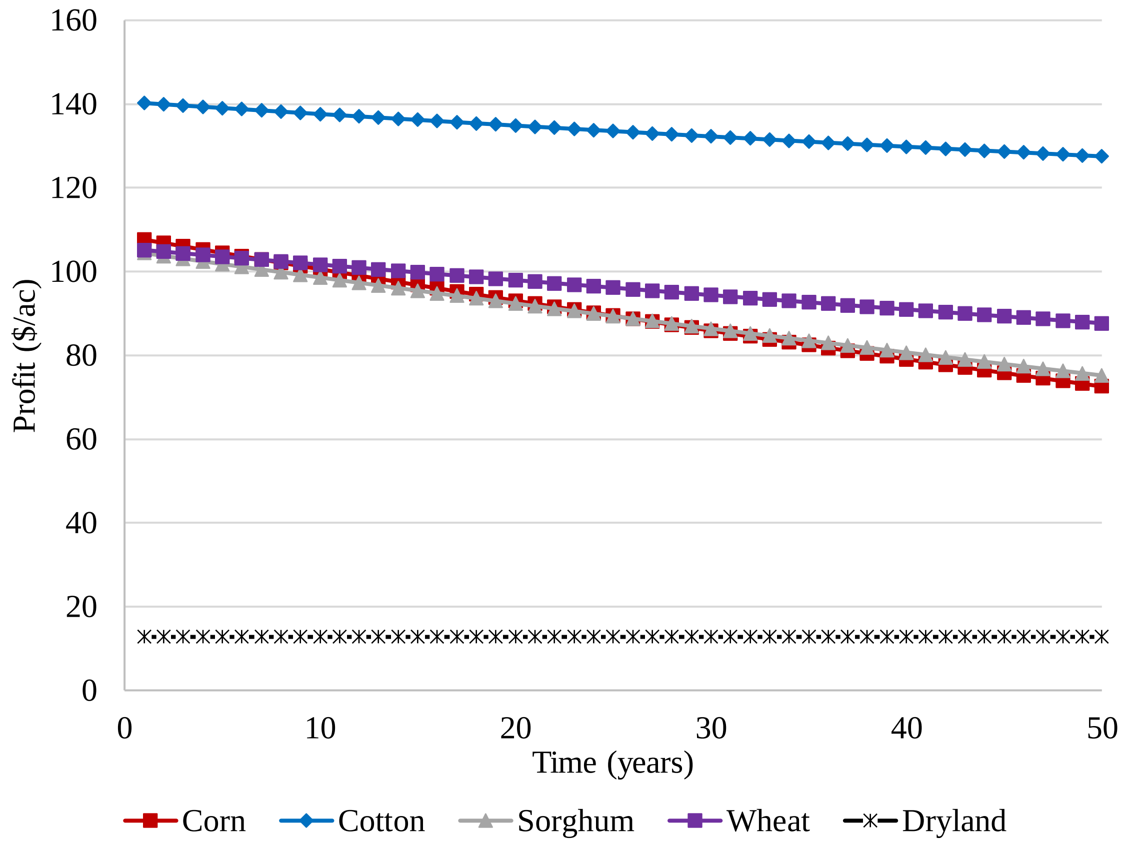

Figure 2-13. Profit per acre for each crop over 50 years in Lynn County under the status quo scenario over the 50 year study period.

Due to the considerable limits on irrigation primarily from the 100 gpm well capacity, the water use for all four of the irrigated crops is the same and is the maximum amount that can be pumped. The same water limitations occur for every crop due to the level of maximum available water, Figure 2-14. In Lynn County, only the acreage reduction scenarios result in increased saturated thickness at the end of the planning horizon, Figure 2-14 and Table 2-7. As a result of the limited saturated thickness at the beginning of the planning horizon, the increase of saturated thickness from the reduction in irrigated acres is less than what is would be in a county with more saturated thickness.

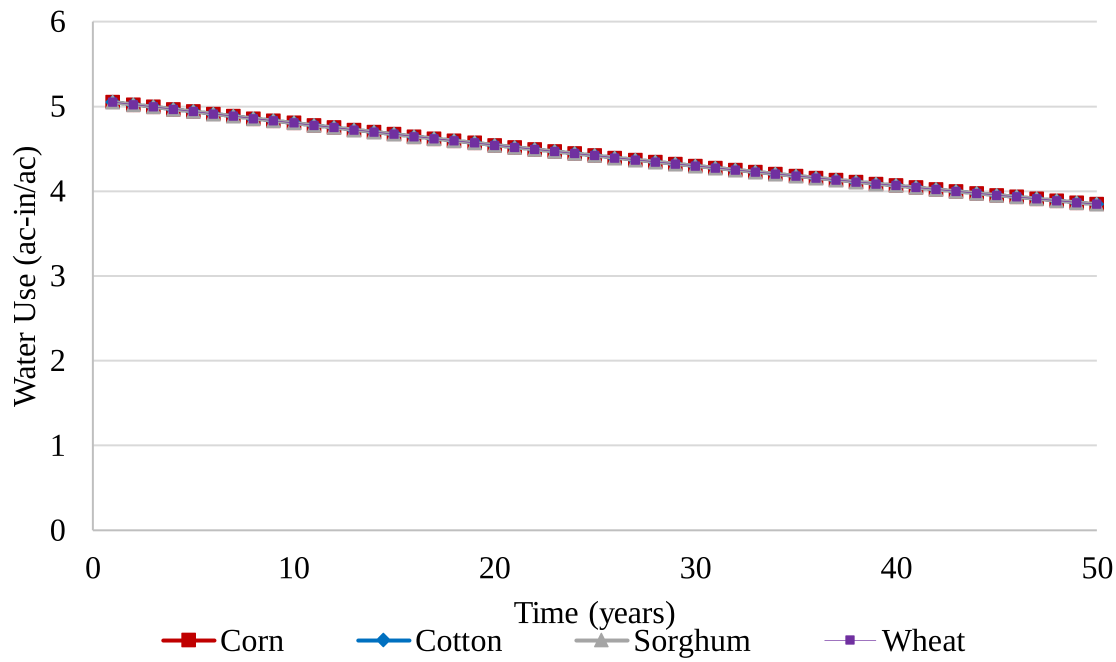

Figure 2-14. Annual water use (ac-in/ac) for each crop in Lynn County under the status quo scenario over the 50 year study period.

Table 2-7. Comparison of profit, value added, total water use, and ending saturated thickness for all scenarios in Lynn County over the 50 year study period.

Scenario	*Profit (mil $)*	*% Change in Profit*	*Value Added (mil $)*	*% Change in VA*	*TWU (1,000 ac-ft)*	*% Change in TWU*	*Ending ST (ft)*	*% Change in ST*
Status Quo	609	-	2,652	-	1,686	-	32.0	-
10% Acreage Reduction	556	-8.6%	2,519	-5.0%	1,537	-8.8%	32.9	2.8%
25% Acreage Reduction	477	-21.7%	2,203	-17.0%	1,306	-22.5%	34.2	7.1%
25% Decrease Precipitation	401	-34.2%	2,402	-9.4%	1,686	0.0%	32.0	0.0%
25% Increase Precipitation	805	32.2%	2,886	8.8%	1,686	0.0%	32.0	0.0%
$14 Fuel Price	588	-3.4%	2,652	0.0%	1,686	0.0%	32.0	0.0%

In counties with lower starting saturated thickness, such as Lynn, there is less variation between scenarios in ending saturated thickness, Figure 2-15 and Table 2-7. The increase and decrease in seasonal precipitation result in no change in the ending saturated thickness or total water use as a result of the already limited irrigation use, Figures 2-15 and 2-16. However, the precipitation changes significantly impact profit and value added as the changes in crop yield result from the varied rainfall amounts. Particularly as this watershed has higher levels of precipitation, the 25 percent increase and decrease scenarios have a larger total change in the amount of precipitation than in the Palo Duro Watershed. As total water use slowly declines over the planning horizon, the same thing occurs with total profit and value added, Figures 2-17 and 2-18. With the low amount of irrigation water applied, the increase and decrease in precipitation considerably impacts in the counties within the Double Mountain Fork Watershed. For example, a 25 percent increase in the seasonal precipitation results in a 32.2 percent increase in the sum of total profit over 50 years, Table 2-7.

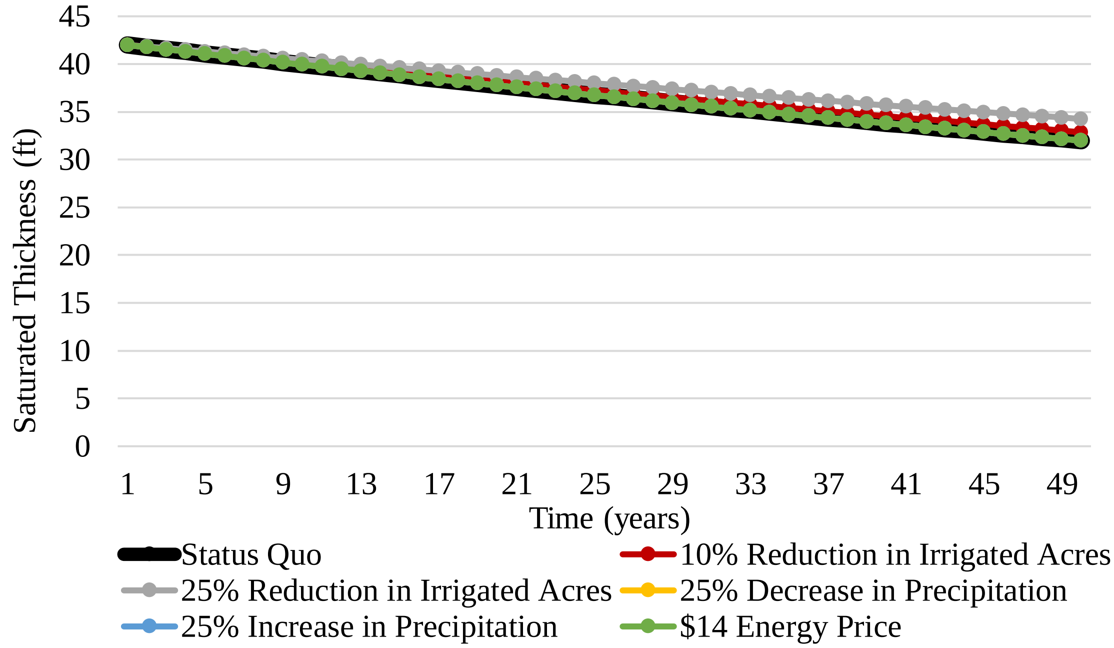

Figure 2-15. Saturated thickness (feet) under each scenario in Lynn County over the 50 year study period.

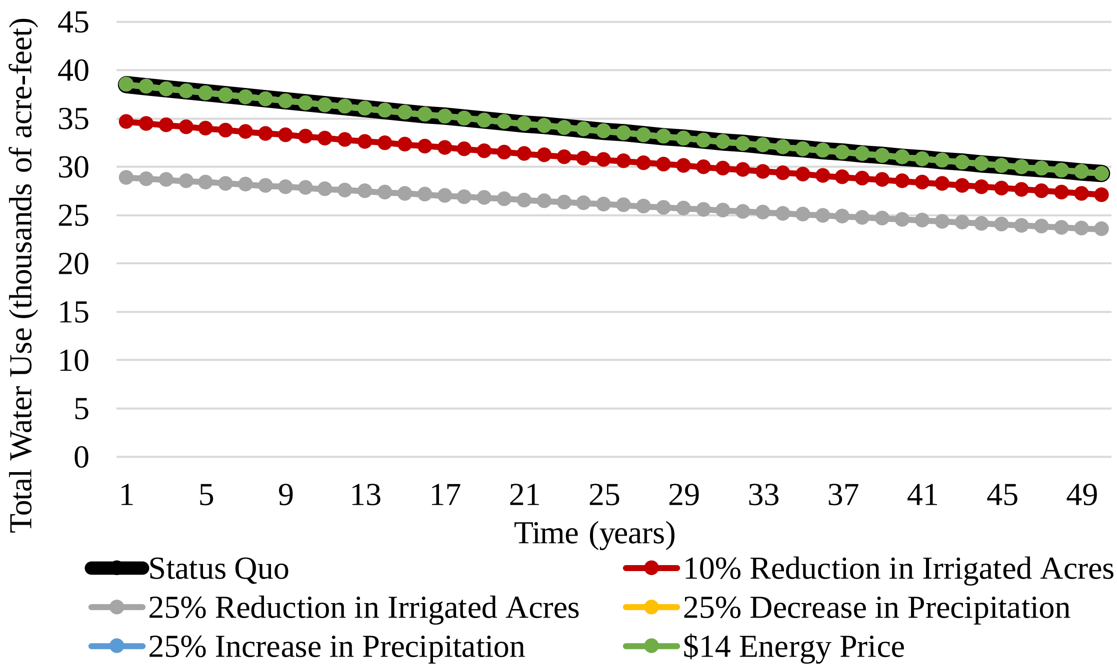

Figure 2-16. Total annual water use (acre-feet) under each scenario in Lynn County over the 50 year study period.

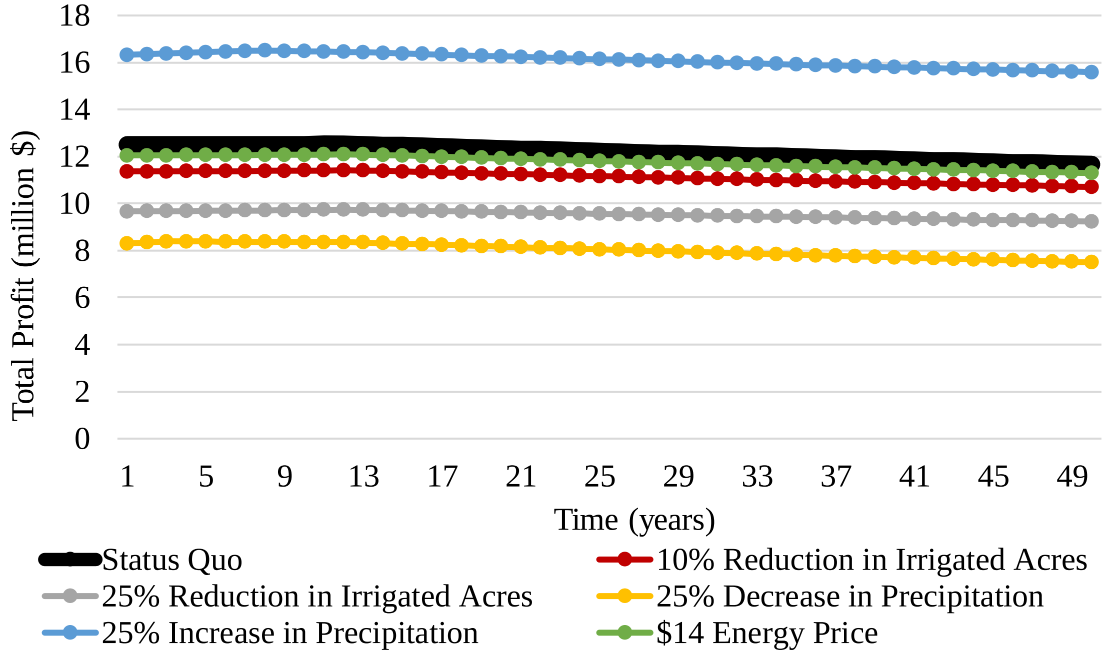

Figure 2-17. Total annual profit under each scenario in Lynn County over the 50 year study period.

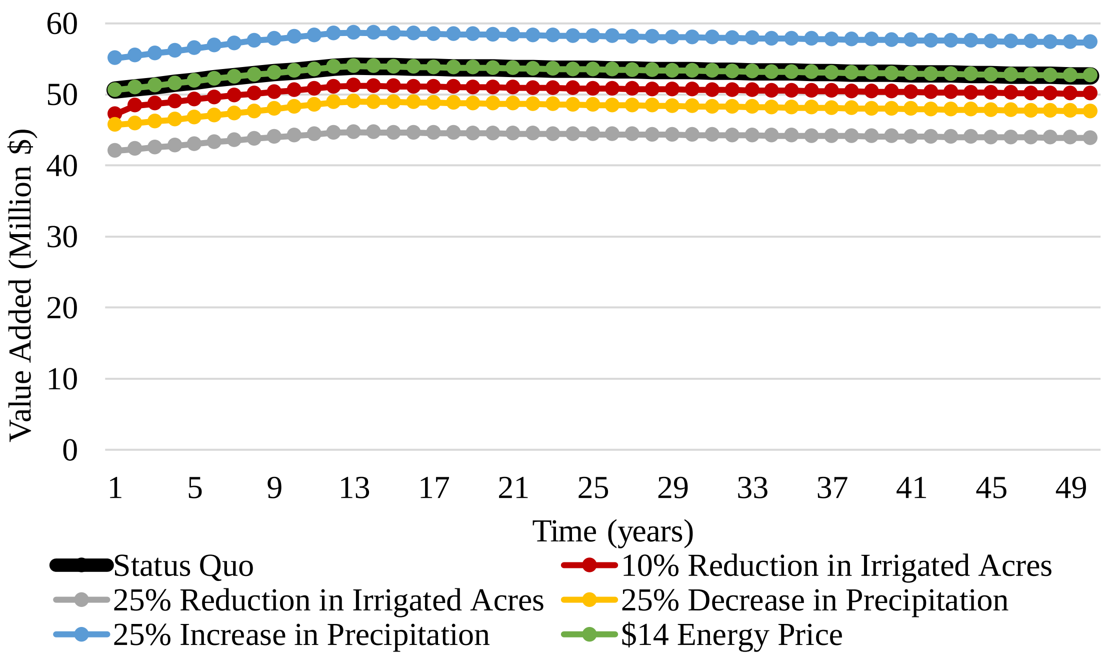

Figure 2-18. Total annual value added under each scenario in Lynn County over the 50 year study period.

Conclusions

The possible policy approaches, management strategies, and precipitation scenarios evaluated in this study allow for the results to the evaluated in terms of both maintaining producer profitability and the level of water conservation in terms of total water use and saturated thickness. Counties with the lowest water availability are more likely to adopt efficient technology to extend the life of the aquifer (Wright et al., 2013). However, the earlier policies are implemented the greater the impact the policy will have in terms of preserving water availability. A clear example is the difference that acreage reduction scenarios have with varying initial saturated thickness. As saturated thickness declines, so does the impact of acreage reduction scenarios.

In Hartley County, the increase in precipitation is the only scenario where the sum of producer profit over 50 years increases as compared to the status quo scenario. A 10 percent reduction in irrigated acres has the smallest decrease in profit of the scenarios evaluated. When looking at value added, an increase in precipitation also provides the greatest increase over the planning horizon, however, precipitation cannot be controlled and will vary based on climate projections. Focusing on total water use and ending saturated thickness, the scenario that provides the greatest decline and increase, respectively, is the increase in fuel price. Yet, the increase in fuel prices also results in the greatest decline (46 percent) in projected profits as well as a smaller decline (6 percent) in value added, Table 2-6. Overall, the 25 percent reduction in irrigated acres provides the third highest water savings (6 percent), with a minimal impact on producer profit (8 percent), while positively impacting the regional economy (4 percent).

An increase in precipitation also results in the greatest projected increase in profit and value added for Lynn County. The increase in fuel prices results in the lowest decline in profitability and no change in value added. The scenario that results in the smallest decline in value added was the 10 percent acreage reduction scenario which ranks third when considering producer profitability. As the Double Mountain Fork Watershed has considerably lower starting well capacities and saturated thicknesses, the two acreage reduction scenarios are the only scenarios in which there is any water savings as indicated by total water use and ending saturated thickness. However, the 25 percent acreage reduction scenario has a significant negative impact on producer profit and the regional economy, Table 2-7.

It should be noted that the policies that conserve the greatest amount of water may not be the most ideal situation for producers, particularly when it has become more and more challenging to operate a profitable farm. In the same way, what is best for the producers, may not be ideal for the regional economy. The community as a whole will put a higher value on the conserved groundwater than the producer, as the community has a greater incentive to ensure that water is available into the future.

Discussion

The depletion of the Ogallala Aquifer is affecting the ability to fully irrigate crops, which is already a reality for some parts of the study area. These models provide stakeholders a greater degree of information on the potential impacts of conservation efforts under consideration. Policies restricting water use aim to suppress short-term production with the long-term goal of preserving, or even augmenting, water supply in the future.

While this study compares various scenarios to the status quo, it does not put a monetary value on the conserved groundwater, similar to other temporal allocation studies including Amosson et al. (2009) and Vestal et al. (2017). However, Amosson et al. (2009) suggested that a 'price tag' be given to conserved water. One method involved taking the different in cumulative net returns over the modeling period and dividing it by the cumulative groundwater use (Golden and Johnson, 2013). While this method was developed from stakeholder input at the time, it also undervalues the conserved water if there is assumed increase in crop yield. Golden and Guerrero (2017) used a modified version of this method where the value of conserved groundwater is the difference, during the last year of the modeling period, in the "non-discounted cumulative net returns divided by the cumulative groundwater use". Moreover, this model implicitly assumes that the profit impact to the producer is the most relevant consideration. While value added regional impact on the rural economy was included as a portion of the results, work by Golden and Guerrero (2017) suggest that value added may be another relevant objective function in addition to output and employment for the rural economy, and is certainly a place were further work would prove valuable.

In this study, it was assumed that there was no technologic growth in crop yields. An increase in the yields of both irrigated and dryland crops would change the profit for each crop, particularly moving farther into the planning horizon. Additionally, irrigation is a unique input as the amount applied may be adjusted throughout the growing season.

This model decides the amount of irrigation applied based on average growing season precipitation which does not reflect the year-to-year variability faced by producers.

Moreover, prices and costs are considered to be constant over the planning horizon. Should prices drop, the switch to dryland will occur sooner than indicated in the results. With lower prices, irrigation may not be feasible for a greater number of producers as the costs incurred from irrigation will not able to be recovered upon the sale of the crop. On the other hand, if prices are higher there is a greater incentive to irrigate at a higher rate.

This is certainly a topic that will continue to be of much debate in the region and it is not one with a clear or one-size-fits-all solution. The decisions made to preserve groundwater must be undertaken with the future in mind and Groundwater Conservation Districts, local policymakers, and stakeholders must work together to find a balance of conserving the continuously declining availability of water and maintaining the economy.

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CHAPTER III: ECONOMIC FEASIBILITY OF CONVERSION TO MOBILE DRIP IRRIGATION IN THE CENTRAL OGALLALA REGION

Sydney Reynolds[1], Bridget Guerrero[1], Bill Golden[2], Steve Amosson[3], Thomas Marek[3], and Jourdan M. Bell[3]

[1]Department of Agricultural Sciences, West Texas A&M University, Canyon, TX 79016

[2]Department of Agricultural Economics, Kansas State University, Meridian, TX 76665

[3]Texas A&M AgriLife Research and Extension Center, Amarillo, TX 79106

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Introduction

Many rural communities overlying the Ogallala Aquifer rely heavily on irrigated agriculture, and this is undoubtedly true in the central region of the aquifer. This area is facing the challenge of maintaining agricultural production with the current rate of decline in aquifer depth. The Central Ogallala region is a key producer of several agricultural products that have been traditionally irrigated from the aquifer including corn, cotton, sorghum, and wheat. Irrigated yields from 2014 to 2018 for these crops in the Texas Panhandle have averaged 12,428 kg/ha for corn, 1222 kg/ha for cotton, 5837 kg/ha for sorghum, and 3497 kg/ha of wheat (National Agricultural Statistics Service 2019). These crops received an average price, over the same five-year period, of $0.15, $1.41, $0.14, and $0.17 per kg, respectively (Texas A&M AgriLife Extension Service 2019), Table 3-1.

Table 3-1. Average prices and yields for alternative crops, 2014-2018 (National Agricultural Statistics Service 2019; Texas A&M AgriLife Extension Service 2019)

Crop	Unit	Price ($/kg)	Yield (units/acre)
Corn	kg	0.15	12,428
Cotton	kg	1.41	1222
Sorghum	kg	0.14	5837
Wheat	kg	0.17	3497

In this region that averages less than 0.51 m of rainfall annually, the aquifer is being depleted beyond sustainable levels (Kansas State University 2019). To cope with the limited water availability, producers are considering more efficient irrigation systems as a feasible method of reducing water use. The application efficiency of irrigation methods varies considerably between systems. Amosson et al. (2011) reported traditional furrow irrigation systems to have only 60% efficiency whereas subsurface drip irrigation (SDI) is the most water-efficient irrigation system overall with an application efficiency of 97%. In between these systems, low elevation spray application (LESA) from a center pivot provides a nominal reported application efficiency of 88%. While the effectiveness of an SDI system is a definite advantage, the significant costs associated with the installation and maintenance of an SDI system can be prohibitive to producers. A relatively new development in irrigation, mobile drip irrigation (MDI), has been reported in research trials to provide similar application efficiency to SDI. O'Shaughnessy and Colaizzi (2017) reported the efficiency of MDI to be greater than that of LESA. Although the authors discussed MDI and SDI, there are no current direct comparisons between these systems reported in the literature. However, the efficiency of MDI reported by O'Shaughnessy and Colaizzi (2017) for corn was comparable to the efficiency of SDI for corn reported by Howell et al. (1997). Of significance, Howell et al. (1997) discussed that efficiencies of SDI are dependent on crop emergence. In semi-arid environments with variable precipitation, it is often challenging to germinate a crop with SDI, whereas higher germination may be possible with MDI. Additionally, the installation cost of MDI is lower per hectare, including the advantage of using center pivots that may already be in place. While these new application systems have increased water use efficiency for many producers, it must be economically feasible for widespread adoption.

This study examines the economic feasibility of producers investing in the conversion to MDI. Specifically, three levels of investment for converting an existing center pivot to MDI are evaluated, and the changes in total variable costs per hectare when converting from LESA to MDI are calculated for low, medium, and high-water use crops. Under each level of investment, the discounted payment method was used to determine the number of years for payback of the investment in MDI technology for each crop, holding yield and commodity prices constant.

Materials and Methods

Study Area

The study area was the central region of the Ogallala Aquifer, and the researchers specifically focused on the Texas Panhandle and Southwest Kansas, Figure 3-1. The Handbook of Texas (Rathjen 2010) outlines the Texas Panhandle as the 26 northernmost counties bounded by New Mexico to the west, Oklahoma to the north and east, and the southern border of Swisher County to the south. Southwest Kansas is defined in this study as the 12 counties that comprise Kansas Groundwater Management District 3, which stretches from the northernmost border of Hamilton County, east to Finney County, and then south to the Oklahoma border and also includes Ford County. The Ogallala Aquifer is the primary source of water for irrigated agricultural production in the region, accounting for approximately 30% of all groundwater used for irrigation in the United States. Underlying portions of eight states in the Great Plains, the aquifer stretches across roughly 453,248 square kilometers of land that produces nearly a fifth of the

United States' wheat, corn, cotton, and cattle (National Resources Conservation Service 2012; McGuire 2017).

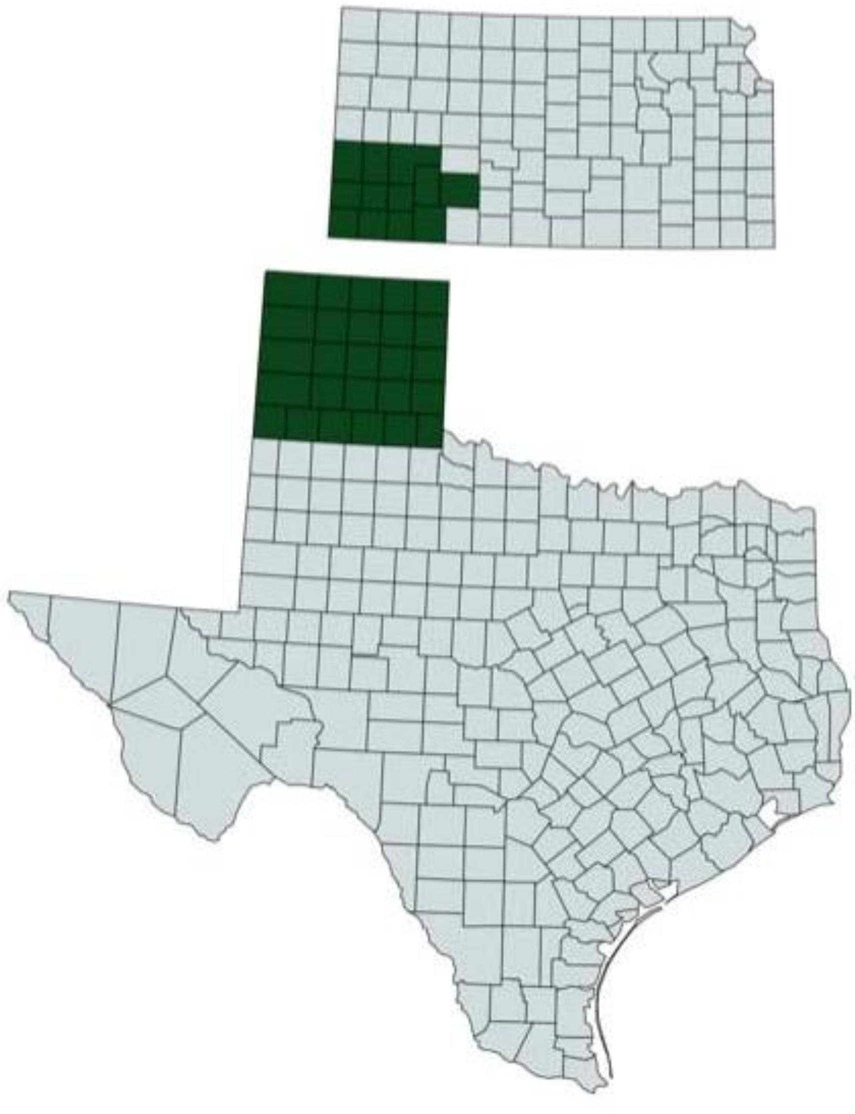

Figure 3-1. Central Ogallala Region Study Area

Characteristics of LESA and MDI Irrigation Systems

In this study, LESA was used as the baseline irrigation application system. This system utilizes a center pivot that disperses water from an applicator 0.30 to 0.46 m above the soil surface, ideally spaced no more than 2.03 m apart (Amosson et al. 2011). Each of the applicators is connected to a drop hose extending from a furrow arm off the mainline with a weight directly above the nozzle to assist with limiting hose movement from wind and allowing the applicators to work even with crops planted in straight rows. Generally, LESA systems wet less foliage allowing for greater water use efficiency and, potentially, less insect damage on damp crops. LESA application efficiency rates are between 85 and 90%; however, it may be lower on broadcast or lower profile crops (Amosson et al. 2011). In this study, an application efficiency rate of 88 percent was used for analysis. As the application rate may exceed that of the rate of soil infiltration, low soil–water uniformity has been observed with the redistribution of applied water (Kisekka et al. 2017).

MDI technology combines the high irrigation efficiency of SDI with more conventional center pivot technology. Initial work was done as early as the 1970s, but current MDI technology was first patented in 2001 (Thom 2001). In this type of system, existing sprinkler nozzles are replaced with drip hoses which drag behind the center pivot such that water is applied directly on the soil surface. In theory, this process should reduce evaporation losses and possibly increase crop yields. Overall, this system has the potential to reduce water losses significantly due to reduced wind drift, soil water evaporation, and canopy evaporation due to the more direct application of water with the goal of capturing the efficiency of drip irrigation at a lower cost than some other micro-irrigation methods, particularly in lower-value crops (Kisekka et al. 2017).

Additionally, with many soils and cropping systems, excessive center pivot wheel track depth can be problematic. Since MDI drip hoses apply irrigation water behind the wheels, the tires run on dry ground, preventing or reducing expensive drive train repairs and end of season wheel track maintenance. The MDI system contains weights on the lower end of the draglines which serve to provide consistent placement of the hoses as they move around the center pivot (Thom 2001). However, Olson and Rogers (2008), Kisekka et al. (2017), and O'Shaughnessy and Colaizzi (2017) all noted the potential problem of MDI hoses traveling into the crop; although in field trials, this damaged corn leaves but did not harm the ears. Reversing the pivot system can also be an issue with MDI, particularly on the outer regions of the pivot where hose length is longer. Other issues that have been noted by producers are that of varmint damage to the draglines (Yost et al. 2019). Maintenance estimates for these MDI based issues have not been documented.

Initial studies of MDI systems indicated positive efficiency advantages were not significant enough to overcome management issues that occurred such as decreased water flow due to clogging (Olson and Rogers 2007). More recent studies have shown design improvements to overcome these initial issues with no significant yield or labor differences, and MDI was shown to increase soil water storage levels (Kisekka et al. 2016, 2017). Moreover, the additional benefits of reduced wheel track rutting, improved field conditions, and reduced runoff potential have resulted in considerable producer interest (Olson and Rogers 2019).

Economic Analysis

The economic comparison relies on techniques developed by Delano et al. (1997), O'Brien et al. (1998), Amosson et al. (2011), and Lamm et al. (2015). Partial budgeting and net present value (NPV) analysis were applied to assess the economic feasibility of modifications to the new irrigation technology. Net present value comparison is a standard method used to compare long-term projects. The calculation discounts future cash flows to present values and sums the flow of all money over time, to be evaluated in present-day dollars. The use of net present value is a reasonable method to use when comparing investments or project costs. Comparable to Guerrero et al. (2016), a cost–benefit analysis was performed to assess the number of years of use that would be required to cover the cost of conversion to MDI.

Investment costs vary significantly between producers. Based on communication with producers and irrigation equipment distributors, a range of investment costs from $185 to $556 per hectare was established (Dragonline Irrigation Personal Communication 2019; Teeter Irrigation Personal Communication 2019; H. Grall Personal Communication 2019; T. Moore Personal Communication 2019; Gaines 2017). Furthermore, T-L Irrigation (Personal Communication 2018) quoted an extensive partial retrofit of an existing 0.40 km center pivot at just over $20,250, or $400 per hectare for a 51 hectare field. The actual cost incurred by an individual producer is dependent on several factors including the design and age of the current center pivot, the spacing of drip hoses, location and size of fields, filtration or chemical requirements of wells, and any additional equipment required for conversion. To account for these varying levels of investment cost, a baseline cost of $371 per hectare (medium) was used, in addition to $185 per hectare (low) and $556 per hectare (high) in conversion costs. This allowed for the payback period to be calculated based on several different levels of investment to provide a range of possible outcomes.

Discount rates of 0, 3, and 6% were used to calculate the net present value at each level of investment. The discount rate varies by producer depending on if conversion funds were borrowed for payment of the system, the amount borrowed, and the interest rate obtained. Moreover, the producer’s level of risk adversity or uncertainty about future cash availability will also change the effective discount rate. A higher discount rate results in a higher net cost under each level of investment. Amosson et al. (2011) estimated a useful life for center pivot and subsurface drip irrigation systems to be 25 years with a salvage value of 20%. Although some system components can last 25 years or more, depending on many factors such as care and maintenance, conservative measures for MDI system life and salvage value were utilized in this study. Thus, a 10% salvage value, the useful life of 10 years for the MDI components (Yost et al. 2019), and a 15% marginal tax rate were assumed. With an investment cost of $371 per hectare, the net investment after including both the discounted salvage value and discounted net tax benefits was $283.55, $297.74, and $308.73, under a 0, 3, and 6% discount rate, respectively, Table 3-2. Both the three and six percent discount rates are used for the remainder of the analysis.

Table 3-2. MDI net investment Cost ($/hectare)[a]

Conversion Cost	Discount Rate		
	0%	**3%**	**6%**
185 (small)	141.79	148.86	154.37
371 (medium)	283.55	297.74	308.73
556 (large)	425.34	446.59	463.10

[a] Assumes a marginal tax rate of 15%, a useful life of 10 years, and a salvage value of 10% of the cost of conversion

To assess crops with differing water use, corn, cotton, sorghum, and wheat were analyzed. Cotton represents a low water use crop, wheat and sorghum represent an intermediate level of water, and corn represents high water use. LESA irrigation application in m^3/ha by crop was used as the baseline (Amosson et al. 2011). To calculate the relative application for MDI, the ratio of application efficiencies for the two systems was applied to the baseline LESA irrigation application, assuming MDI has a 96% application efficiency rate. While there is limited field trial data available in the study region, the efficiency is assumed to greater than LEPA (95%) due to the more concentrated application, as discussed above, but less than SDI (97%) likely due to potential surface evaporation, particularly in the early part of the growing season. It was also assumed that MDI would have the same variable costs per hectare as LEPA. Variable costs of the two systems were obtained (Amosson et al. 2011) and updated to current dollars using the Producer Price Index from the Bureau of Labor Statistics (2019). As in Guerrero et al. (2016), the pumping costs were obtained for a 107-m pumping lift.

Variable costs included fuel, lubrication, maintenance, repairs, and labor. Total variable costs (TVC) per hectare were then calculated by multiplying the cost per m^3 applied by the total m^3 applied per hectare by crop, Table 3-3.

Table 3-3. Irrigation water application and variable costs for LESA and MDI by crop

	Corn	Cotton	Sorghum/ Wheat
LESA[a]			
Irrigation applied (m^3/ha)[b]	5080	2032	3556
Variable costs (\$/m^3)	0.12	0.13	0.12
Total variable costs ($/hectare)	605.58	261.02	433.30
MDI[c]			
Irrigation applied (m^3/ha)[b]	4656	1862	3259
Variable costs (\$/m^3)	0.12	0.13	0.12
Total variable costs ($/hectare)	553.07	237.22	395.05

[a] 88% application efficiency (Amosson et al 2011)
[b] Baseline crop water application (Amosson et al 2011)
[c] 96% application efficiency

MDI systems may initially require more time for management than a conventional center pivot setup. While MDI systems may not be more complicated than that of a center pivot system, they do require a different set of procedures and as a result, may have higher operating costs. Earlier systems required increased maintenance throughout the year (O'Shaughnessy and Colaizzi 2017), but the redesigned system and hoses as explained by Kisekka et al. (2017) has been able to overcome this, showing little to no difference in labor costs. One of the primary concerns was clogging of the hoses, but O'Shaughnessy and Colaizzi (2017) found that nearly all clogging was eliminated through the use of a disk filter. There is additional labor at the end of the season, where producers have found that the hoses should be tied up or removed for storage over the winter to prevent damage from rodents or deer when the system is not in use (Dragonline Irrigation Personal Communication 2019). However, in several aspects, the labor required for an MDI system will be lower. Notably, wheel tracking problems are significantly reduced or eliminated, which accounts for a considerable portion of reduced costs.

Based on Amosson et al. (2011), the only difference in variable costs per m^3 applied to a single crop when pumping from a set depth was due to differences in labor. In this study, the difference in variable costs due to labor was minimal and dependent upon the crop when comparing LESA to MDI. However, field trials comparing irrigation systems conducted at T&O Water Technology Farm in Southwest Kansas in 2016 demonstrated an additional average savings of $14.38 per hectare as the result of the lack of drive train repairs for pivots retrofitted with MDI technology. This was added to the change in variable costs due to decreased labor, resulting in cost savings ranging from $16.43 to $16.53 per hectare, depending on the crop, Table 3-4. The more prominent change in variable costs was due to increased efficiency, which ranged in savings from $21.75 to $50.46 per hectare, with more savings resulting from the high water use crop, corn. This additional savings per hectare resulted in total reduced variable costs of MDI when compared to LESA, of $66.89, $38.18, and $52.63 per hectare for corn, cotton, and sorghum/wheat, respectively, Table 3-4.

Table 3-4. Change in variable costs from LESA to MDI ($/hectare)

	Corn	Cotton	Sorghum/Wheat
Change in TVC due to decreased labor	-16.43	-16.43	-16.53
Change in TVC due to increased efficiency	-50.46	-21.75	-36.10
Total Change in TVC	-66.89	-38.18	-52.63

To be economically feasible, the costs of converting to a MDI irrigation system must be counteracted by decreased variable costs, including the cost of labor and increased water application efficiency. The net present value of the cost of conversion combined with the decreased TVC was used to determine the payback period in years that would be required for each of the three levels of investment for each crop, using the discounted payback method (Bhandari 1986).

Results and Discussion

Comparing MDI to LESA, the crops representing three water-use levels averaged a savings in TVC of $52.57 per hectare. The reduced TVC can be split into the changes as the result of decreased labor and increased efficiency. The majority of the cost advantage comes from increased efficiency, particularly in intermediate and high-water use crops, Table 3-4. The water-use efficiency of MDI allows for 424 fewer m^3/ha to be applied to corn and 297 fewer m^3/ha to be applied to sorghum/wheat while maintaining the productivity of the crop, Table 3-3.

Results indicate that for the high-water use crop, corn, a payback period of 2.3, 4.9, and 7.6 years for the small, medium, and large investment costs, respectively, is required. As the water use of the crop drops, the payback period rises as it takes longer to realize the gain in system efficiency. For sorghum/wheat, the intermediate-water use crops, a payback period of 3.0 years is required for the small investment cost. As the level of investment rises, 6.3 and 9.9 years is required for the medium and large levels, respectively. The lowest water use crop, cotton, showed the longest payback period. Cotton required 4.2, 9.0, and 14.6 years for the small, medium, and large investment costs, respectively. The increased efficiency of MDI provides for greater cost savings as the amount of irrigation water applied increases as this accounts for the majority of the change in variable costs per hectare. This is particularly important to note for producers or areas where less water than assumed is applied as it will increase the payback period for each crop. Results of this study show that the payback period, under the three percent discount rate, can range from as little as 2 years to more than 14 years, depending on the crop and investment level (Table 3-5).

Table 3-5. MDI payback period (years) for alternative crops with a three percent discount rate

Gross Investment ($/hectare)	Net Investment ($/hectare)	Corn	Cotton	Sorghum/Wheat
185	149	2.3	4.2	3.0
371	298	4.9	9.0	6.3
556	447	7.6	14.6	9.9

The payback period was also calculated using a 6% discount rate, Table 3-6. The increased discount rate results in an increased payback period, particularly as the investment cost rises. The crop representing the highest water use, corn, requires 2.6, 5.6, and 9.2 years for the small, medium, and large investment costs, respectively. On the other hand, cotton, the lowest water use crop, requires 4.8 years for the small investment cost and 11.4 years for the medium investment cost. The years rise considerably under the high investment cost, requiring more than 22 years to payback the system. Thus, the actual cost of conversion for an individual operation should be carefully considered before MDI is installed on a center pivot to ensure an accurate payback period calculation based on the actual net investment cost and water application by crop.

Table 3-6. MDI payback period (years) for alternative crops with a six percent discount rate

Gross Investment ($/hectare)	Net Investment ($/hectare)	Corn	Cotton	Sorghum/Wheat
185	154	2.6	4.8	3.3
371	309	5.6	11.4	7.4
556	463	9.2	22.3	12.9

One of the benefits of the MDI system is improved water use efficiency as measured by either decreased costs or increased yield per m^3 of applied irrigation. The benefits of MDI technology may even be more apparent in a dryer year, as found by O'Shaughnessy and Colaizzi (2017). In their two-year study, yield remained similar between both MDI and LESA irrigation systems, but, in the drier year of the study, MDI showed significantly higher water use efficiency. With water application being concentrated to a smaller area, there is a greater amount of dry soil that is still available to capture rainwater to take advantage of any precipitation during the growing season. Lamaoui et al. (2018) noted decreased plant stress with increased frequency of irrigation application, which is especially important in a limited water-use area or in areas with coarse soils. While typically the main benefit is seen as increased water-use efficiency, some producers have seen yield increases with the installation of an MDI system (Gaines 2017; T Moore Personal Communication 2019). In this study, yields and prices were held constant to allow for analysis of the payback period as a result of decreased variable costs. However, if producers are able to increase yields or if prices were to rise, the payback period for MDI conversion could be reduced, and this is certainly an area where additional work would prove valuable.

Additionally, there is the possibility that MDI technology will be approved for the United States Department of Agriculture—Natural Resources Conservation Service (NRCS) Environmental Quality Incentives Program (EQIP) cost share payments (Washington, D.C., USA). Since this analysis does not account for several potential factors, including EQIP or other potential government cost-share payments, the results are considered to be conservative estimates of the investment payback period considering the potential benefits of an MDI system.

Particularly in heavily water-limited areas, MDI shows the potential to increase the productivity of agricultural land and increase the efficiency of reduced water application without the extensive capital investment required from SDI systems. While the results of this study evaluate a pumping lift of 107 m, producers should consider that a lower pumping lift will increase the payback period and a higher pumping lift will decrease the payback period. Finally, with little long-term use of MDI there are still questions about the longevity and performance of the system over time. In this study, the payback period for cotton under the $556 per hectare investment exceeds the assumed useful life of 10 years. Additional research and demonstration efforts in this area could provide new data for a more accurate assessment, particularly if MDI systems are proven to have a longer average useful life.

Conclusions

Depletion of the Ogallala Aquifer and diminished well capacities will make irrigating crops to their full water requirements impossible, as many have already been seen in some areas of the Central Ogallala region. The challenge is to manage the demands on the Ogallala, balancing economic success and the conservation of natural resources. MDI is one such technology that is bridging the gap between increased water use efficiency and economic productivity. However, producers can be reluctant to invest in a new irrigation system when the initial investment costs are high. The overall savings from labor and increased efficiency may warrant an investment in conversion to a MDI application system, particularly in areas where water is drastically limited or for producers who are facing reduced well capacities currently or in the future.

This study evaluates the economic feasibility of converting to MDI under several crop scenarios and investment levels. The payback period for conversion varies considerably under these different conditions and is shortened with higher-water use crops as the change in total variable cost saving rises from increased water use efficiency.

Consequently, crops such as corn would provide the most feasible scenario for adoption by producers in the Central Ogallala region. Intermediate-water use crops, sorghum and wheat, are also feasible for producers, particularly under lower investment levels. Thus, producers growing high-value, high-water use crops are the most feasible operation in which to convert to MDI.

Conversion to any irrigation system is one that requires careful evaluation of multiple aspects of an operation. The analysis conducted was based on average producer information for the study area, but this may not accurately reflect every potential situation. Careful assessment should be made as to how the assumptions and scenarios match a producer's operation. Future research should be conducted with MDI addressing other alternative crops, government programs, pumping rates, and long-term usage.

Acknowledgements

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Compliance with Ethical Standards

Conflict of Interest

The authors declare no conflict of interest. The funding sponsors had no role in the design of the study, analysis or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

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APPENDIX A

RESULTS FOR HANSFORD COUNTY

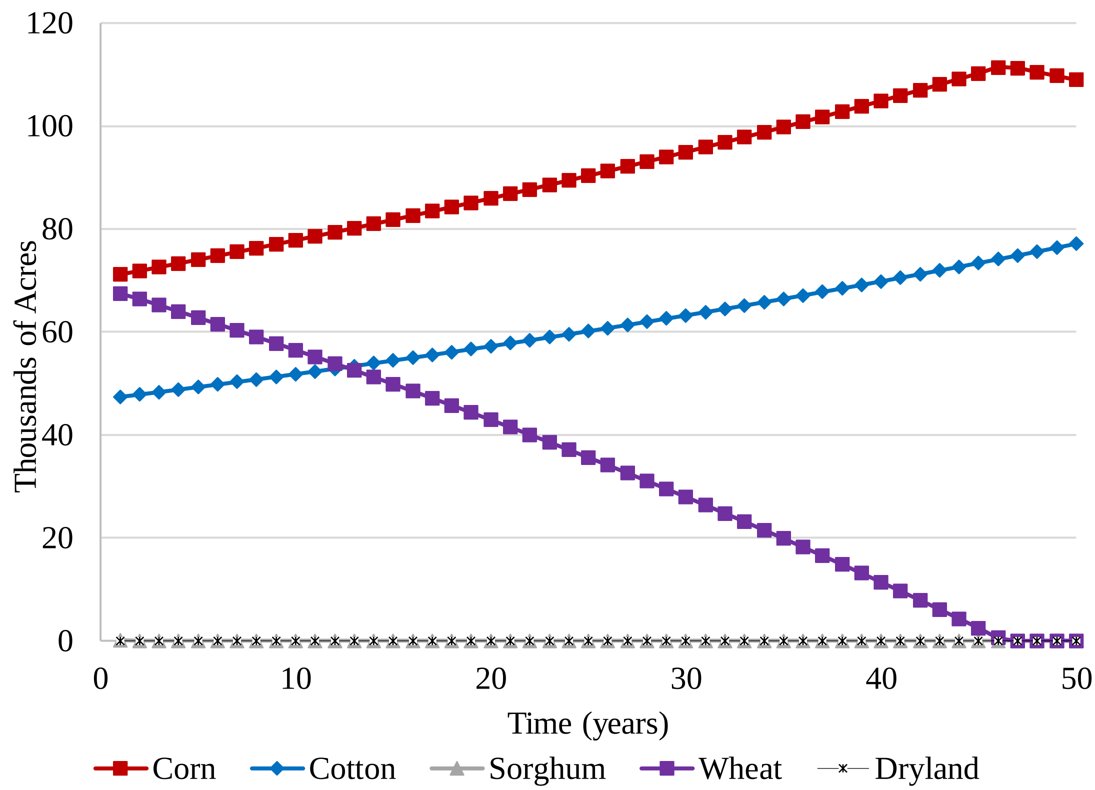

Figure A-1. Number of acres planted to each crop in Hansford County under the status quo scenario over the 50 year study period.

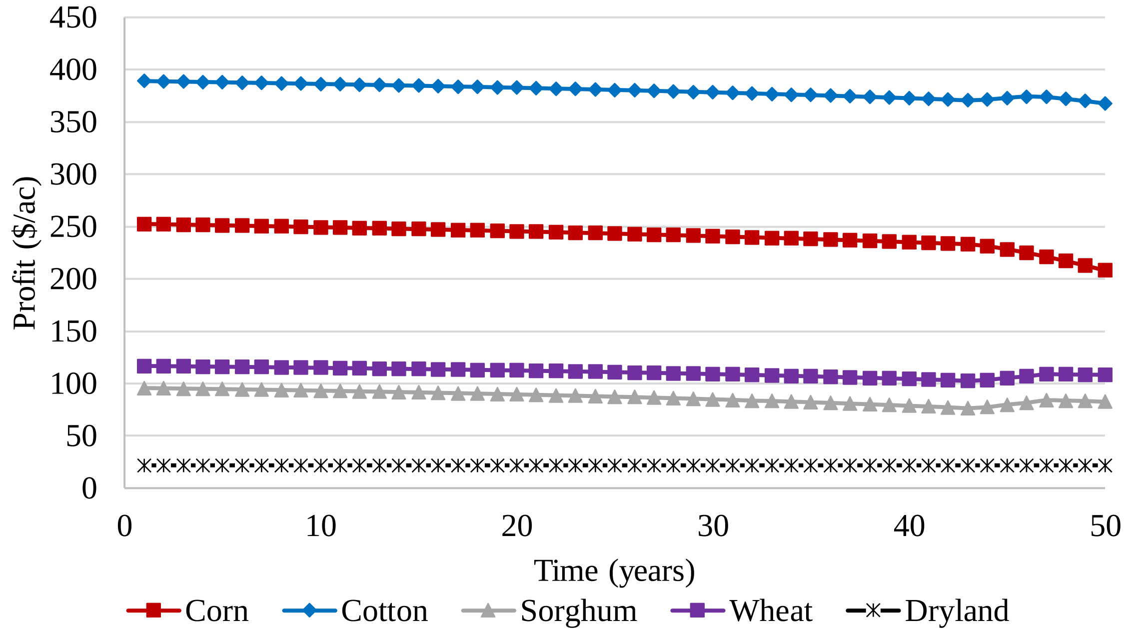

Figure A-2. Profit per acre for each crop in Hansford County under the status quo scenario over the 50 year study period.

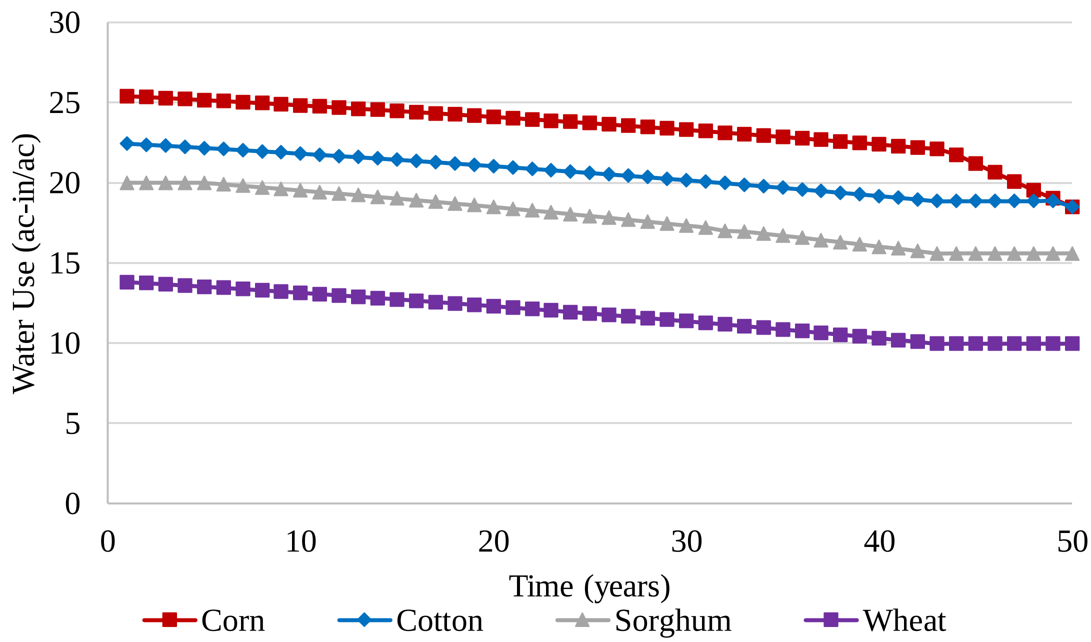

Figure A-3. Annual water use (ac-in/ac) for each crop in Hansford County under the status quo scenario over the 50 year study period.

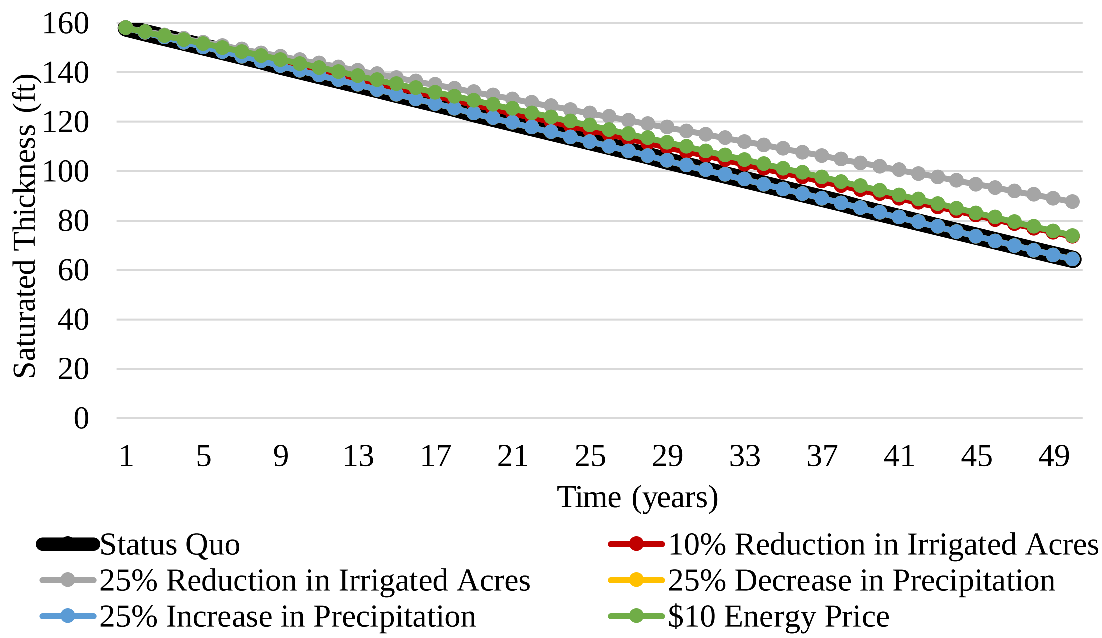

Figure A-4. Saturated thickness (feet) under each scenario in Hansford County over the 50 year study period.

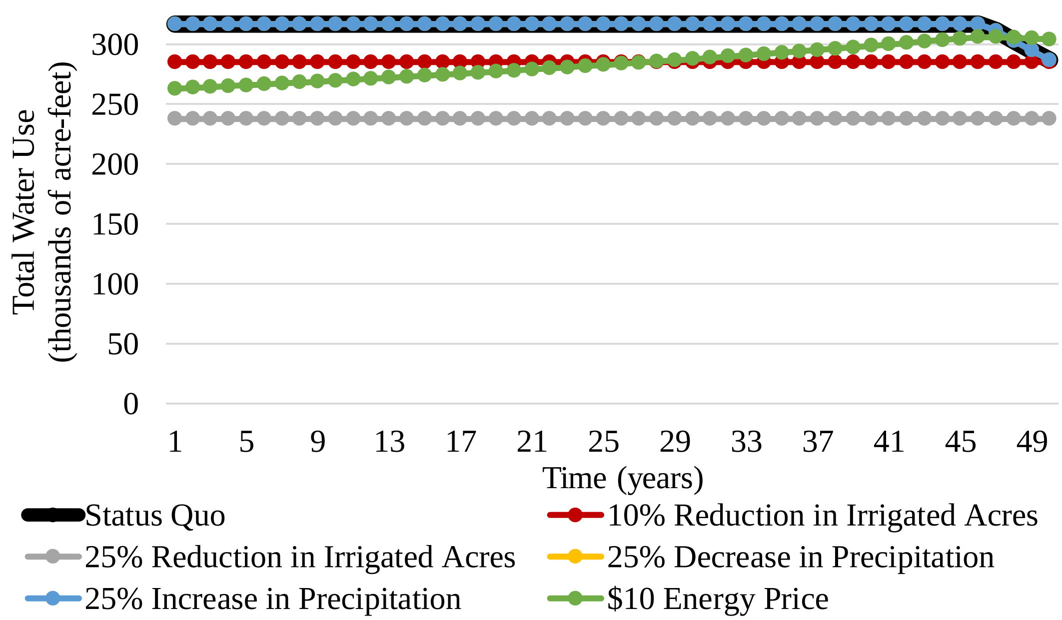

Figure A-5. Total annual water use (acre-feet) under each scenario in Hansford County over the 50 year study period.

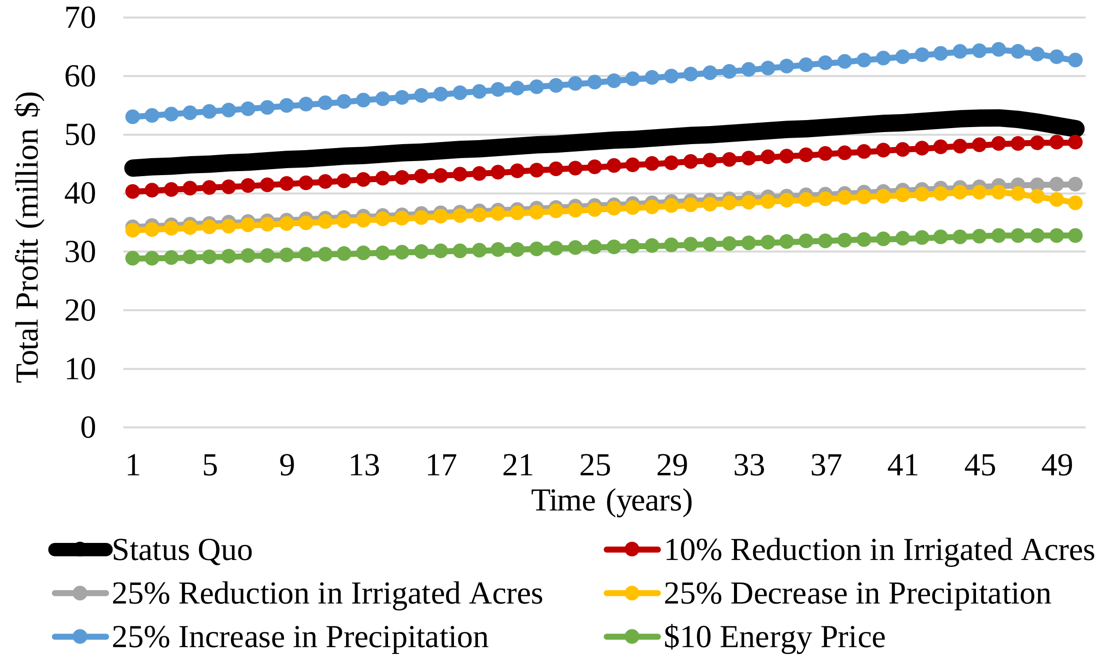

Figure A-6. Total annual profit under each scenario in Hansford County over the 50 year study period.

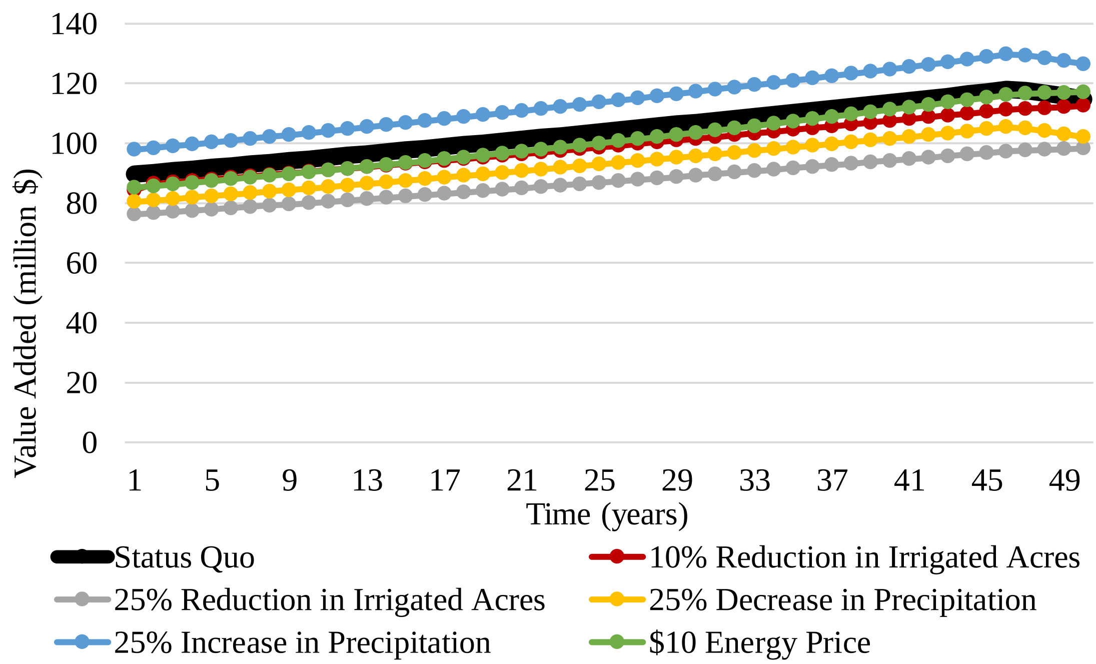

Figure A-7. Total annual value added under each scenario in Hansford County over the 50 year study period.

Table A-1. Comparison of profit, value added, total water use, and ending saturated thickness for all scenarios in Hansford County over the 50 year study period.

Scenario	*Profit (mil $)*	*% Change in Profit*	*Value Added (mil $)*	*% Change in VA*	*TWU (1,000 ac-ft)*	*% Change in TWU*	*Ending ST (ft)*	*% Change in ST*
Status Quo	2,442	-	5,212	-	15,774	-	64.3	-
10% Acreage Reduction	2,229	-8.7%	4,958	-4.9%	14,261	-9.6%	73.4	14.2%
25% Acreage Reduction	1,898	-22.3%	4,363	-16.3%	11,885	-24.7%	87.5	36.1%
25% Decrease Precipitation	1,857	-24.0%	4,662	-10.6%	15,774	0.0%	64.3	0.0%
25% Increase Precipitation	2,951	20.9%	5,708	9.5%	15,774	0.0%	64.3	0.0%
$10 Fuel Price	1,541	-36.9%	5,047	-3.2%	14,212	-9.9%	73.9	14.9%

APPENDIX B

RESULTS FOR HOCKLEY COUNTY

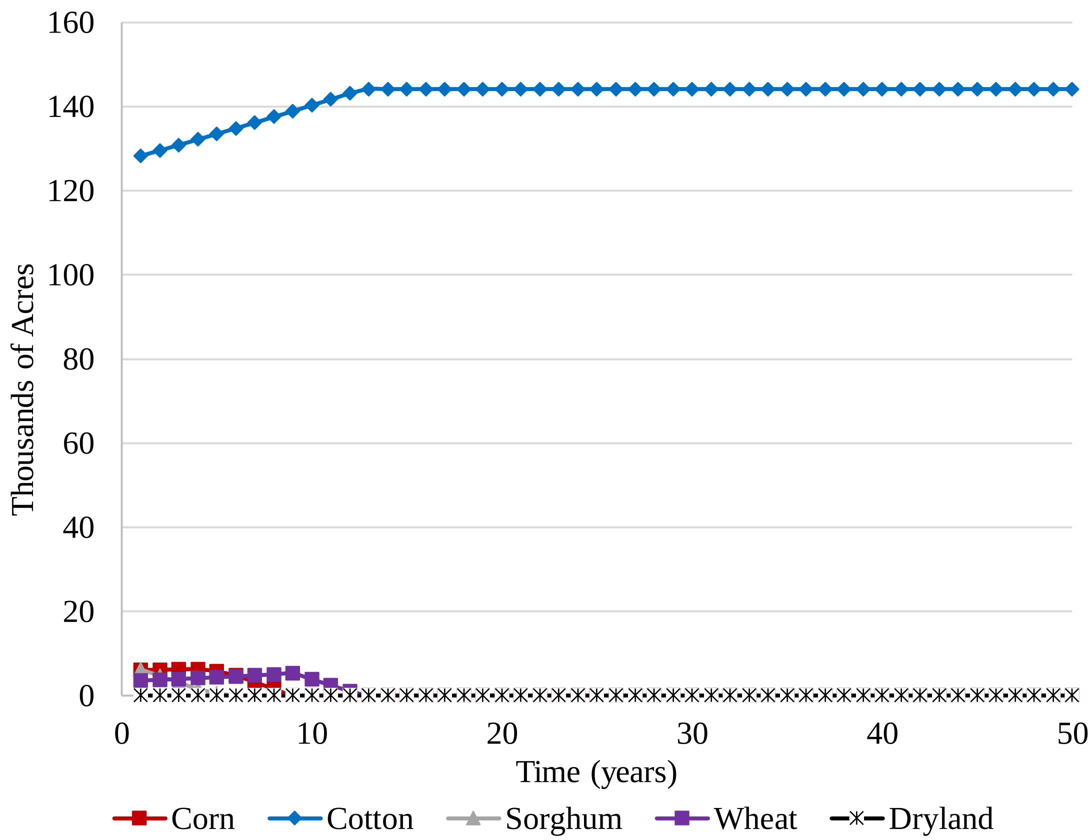

Figure B-1. Number of acres planted to each crop in Hockley County under the status quo scenario over the 50 year study period.

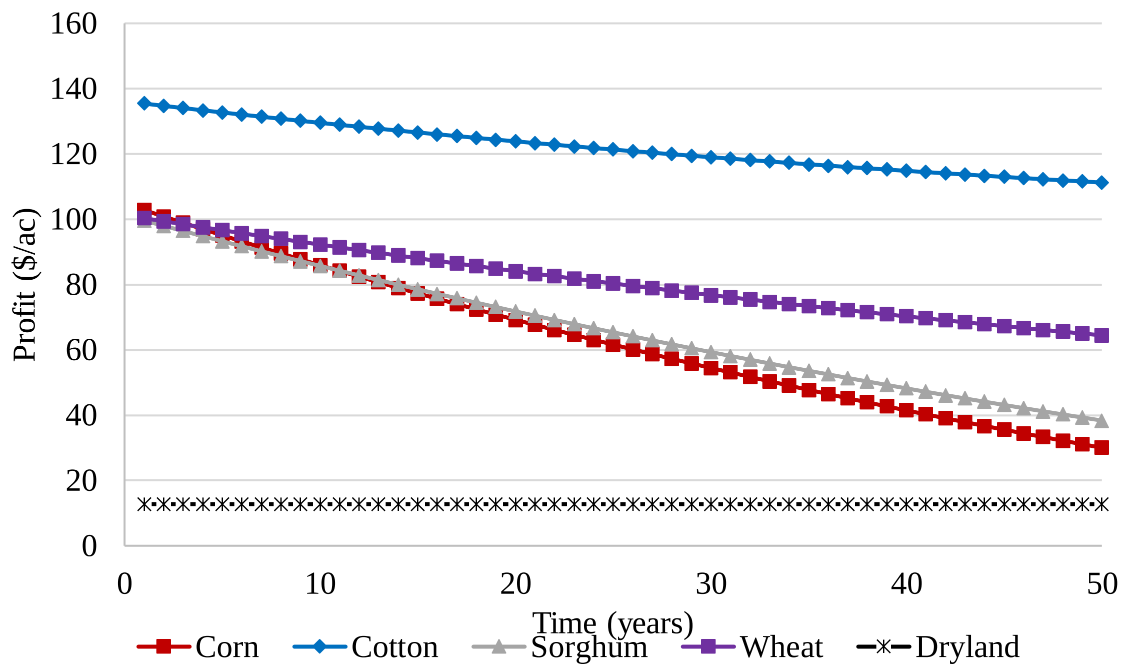

Figure B-2. Profit per acre for each crop in Hockley County under the status quo scenario over the 50 year study period.

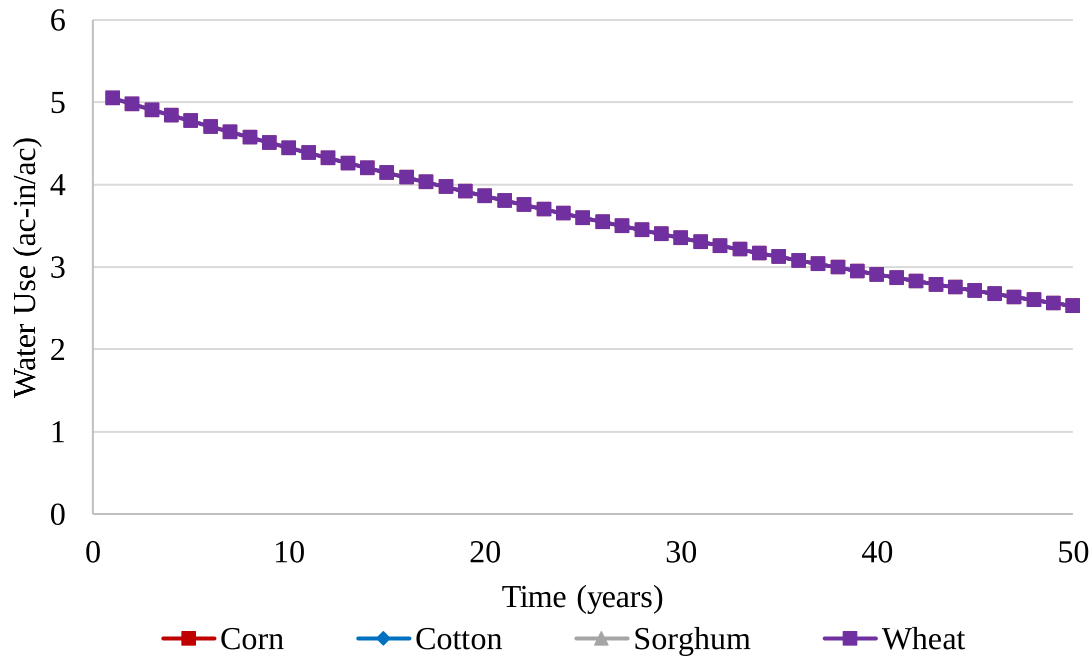

Figure B-3. Annual water use (ac-in/ac) for each crop in Hockley County under the status quo scenario over the 50 year study period.

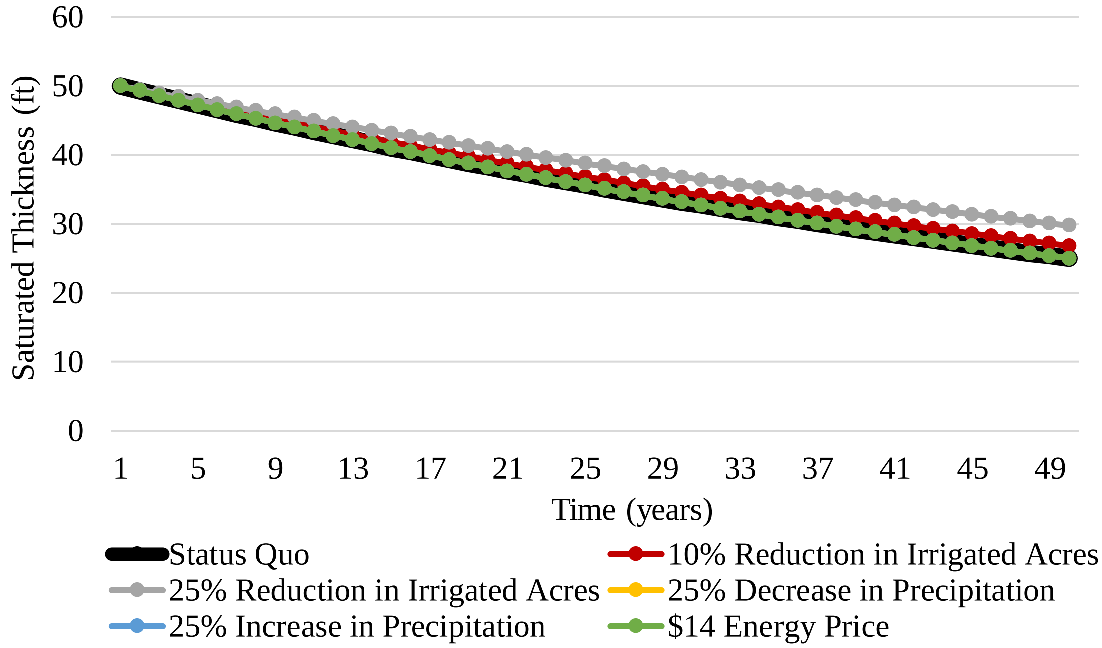

Figure B-4. Saturated thickness (feet) under each scenario in Hockley County over the 50 year study period.

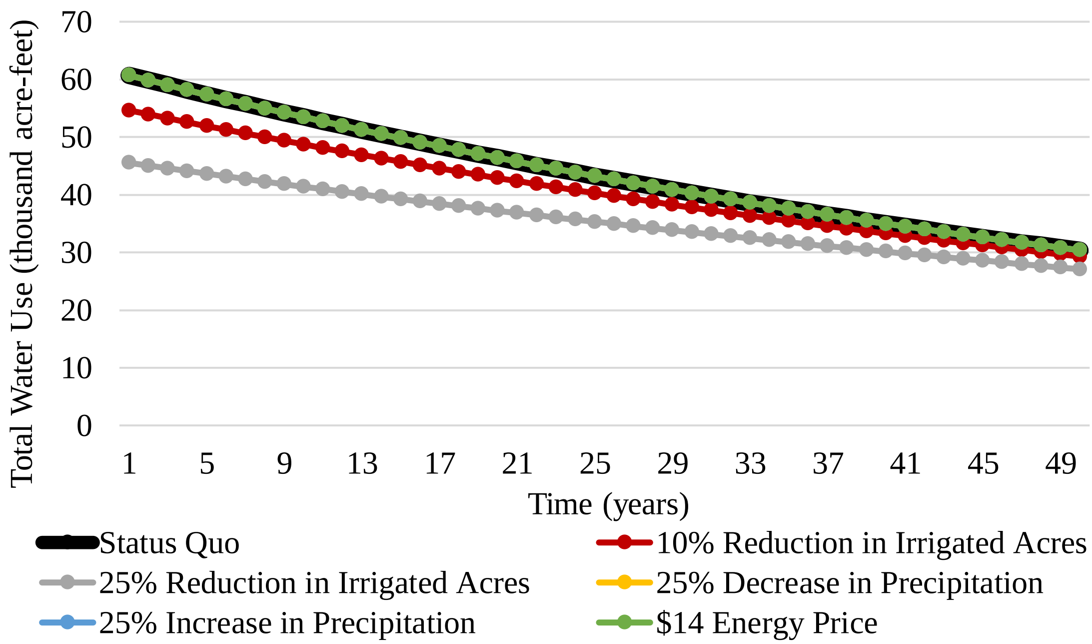

Figure B-5. Total annual water use (acre-feet) under each scenario in Hockley County over the 50 year study period.

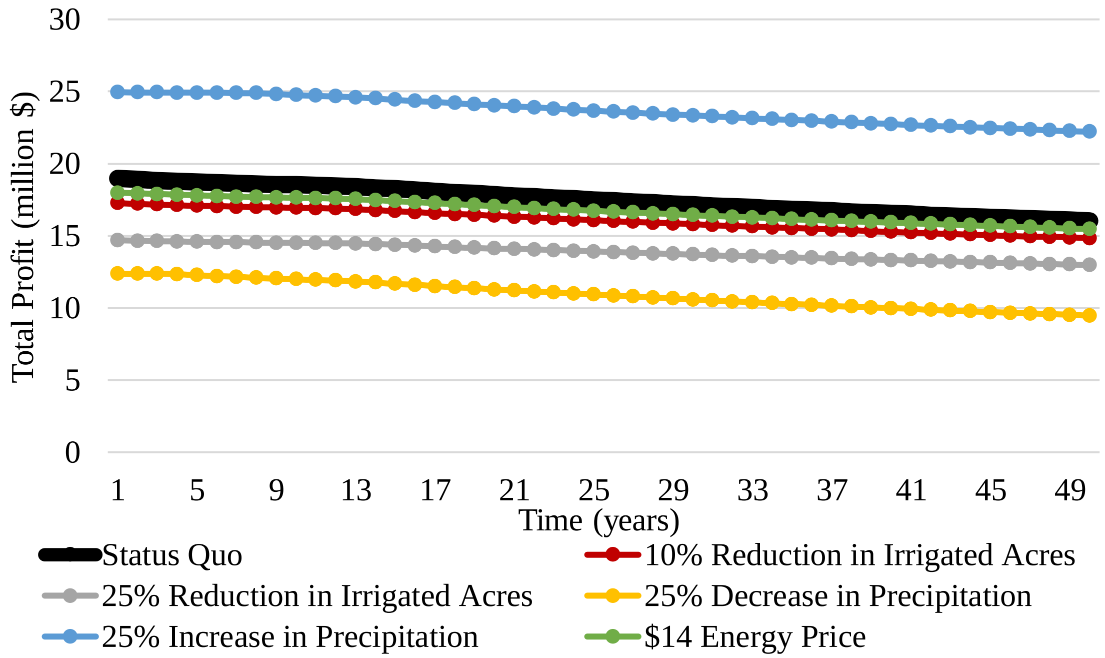

Figure B-6. Total annual profit under each scenario in Hockley County over the 50 year study period.

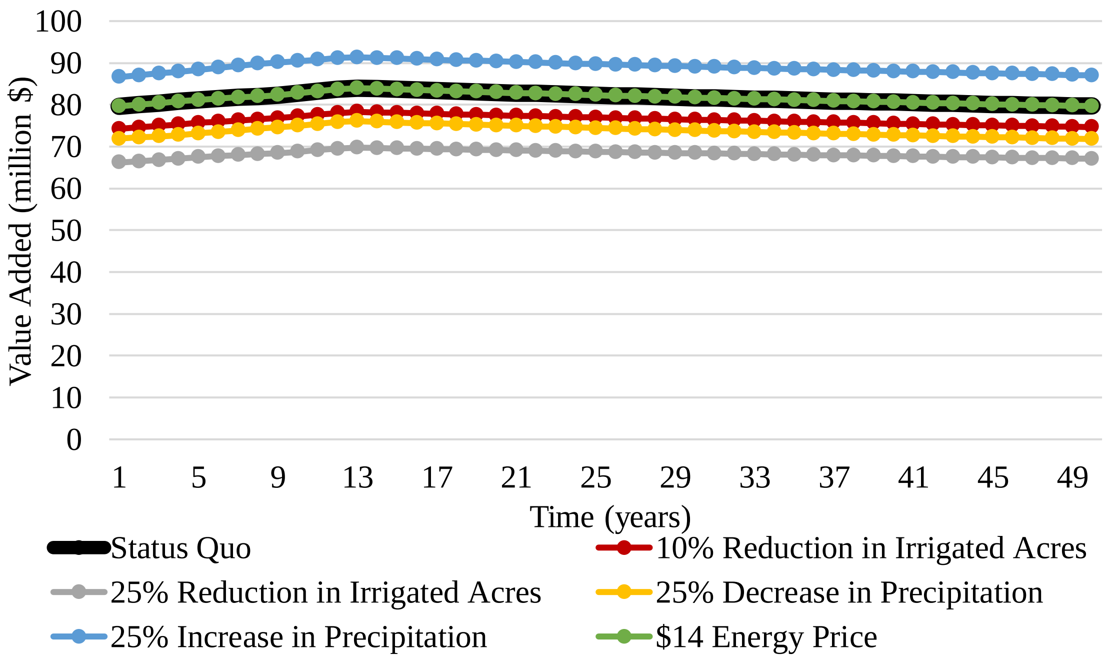

Figure B-7. Total annual value added under each scenario in Hockley County over the 50 year study period.

Table B-1. Comparison of profit, value added, total water use, and ending saturated thickness for all scenarios in Hockley County over the 50 year study period.

Scenario	*Profit (mil $)*	*% Change in Profit*	*Value Added (mil $)*	*% Change in VA*	*TWU (1,000 ac-ft)*	*% Change in TWU*	*Ending ST (ft)*	*% Change in ST*
Status Quo	875	-	4,081	-	2,191	-	25.0	-
10% Acreage Reduction	804	-8.1%	3,814	-6.5%	2,034	-7.2%	26.8	7.2%
25% Acreage Reduction	694	-20.6%	3,411	-16.4%	1,777	-18.9%	29.8	19.0%
25% Decrease Precipitation	547	-37.5%	3,688	-9.6%	2,191	0.0%	25.0	0.0%
25% Increase Precipitation	1,184	35.3%	4,451	9.1%	2,191	0.0%	25.0	0.0%
$14 Fuel Price	837	-4.4%	4,081	0.0%	2,191	0.0%	25.0	0.0%

APPENDIX C

RESULTS FOR MOORE COUNTY

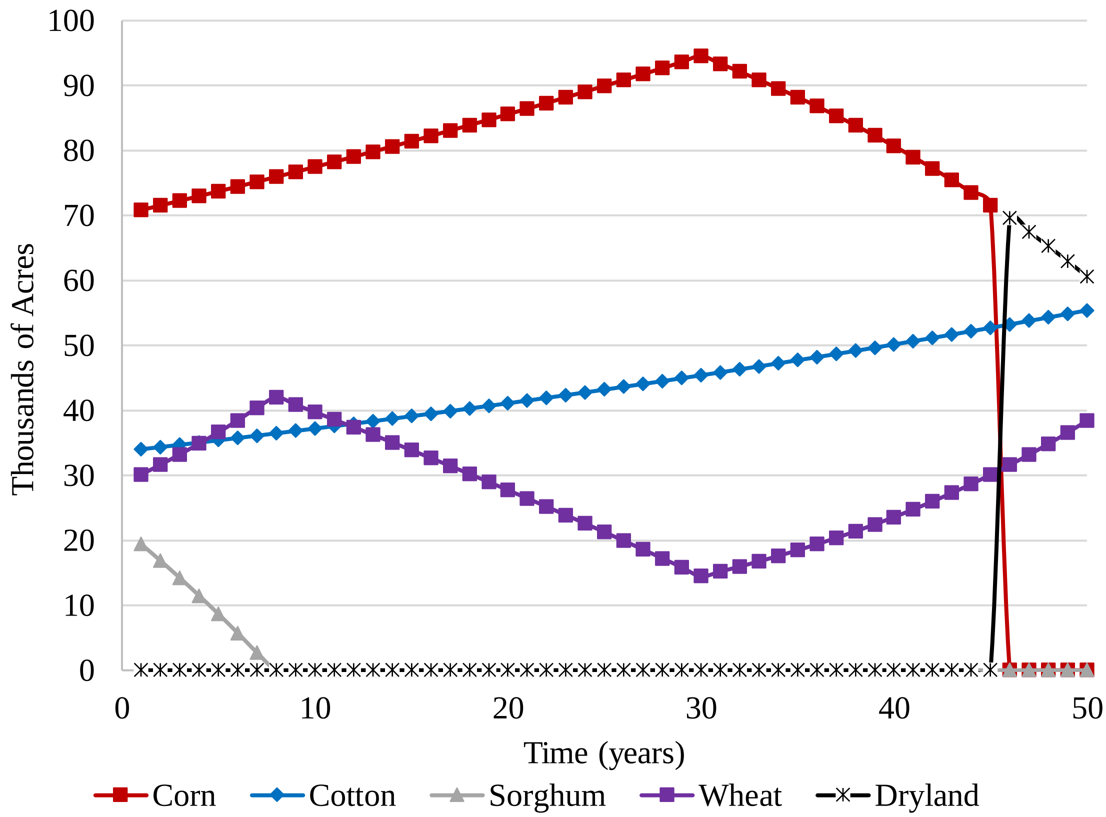

Figure C-1. Number of acres planted to each crop in Moore County under the status quo scenario over the 50 year study period.

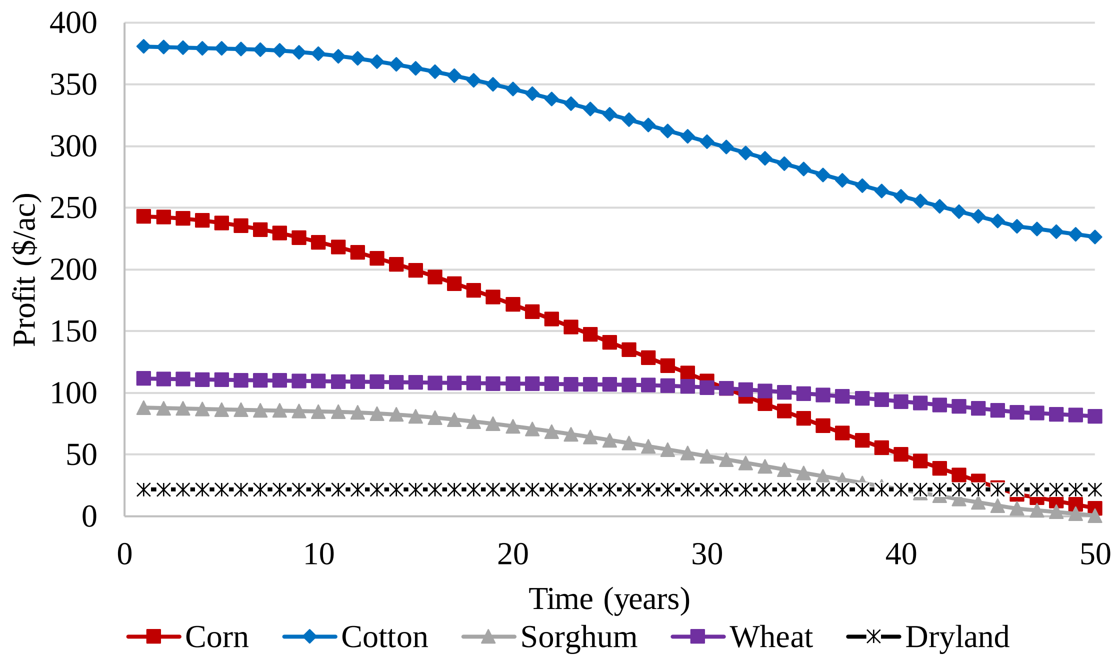

Figure C-2. Profit per acre for each crop in Moore County under the status quo scenario over the 50 year study period.

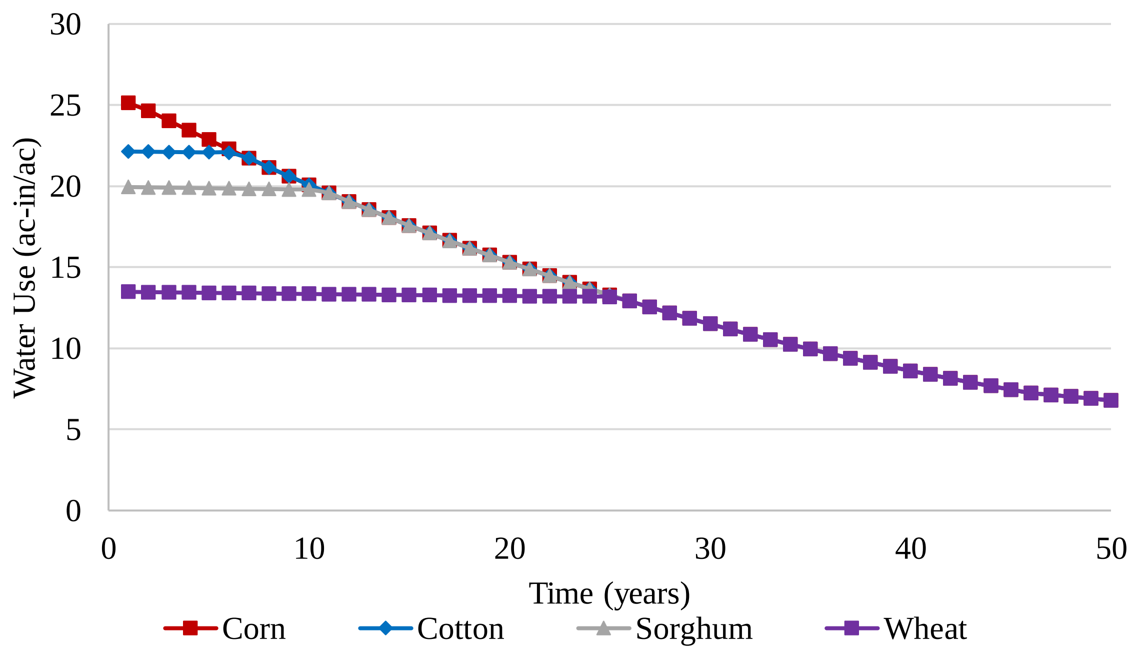

Figure C-3. Annual water use (ac-in/ac) for each crop in Moore County under the status quo scenario over the 50 year study period.

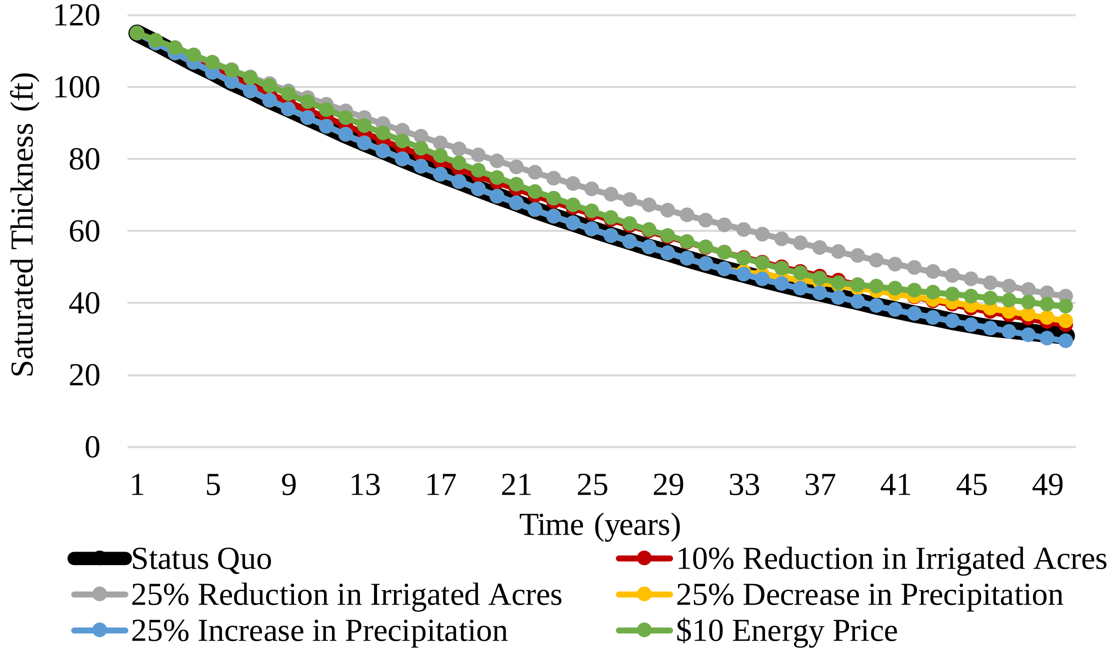

Figure C-4. Saturated thickness (feet) under each scenario in Moore County over the 50 year study period.

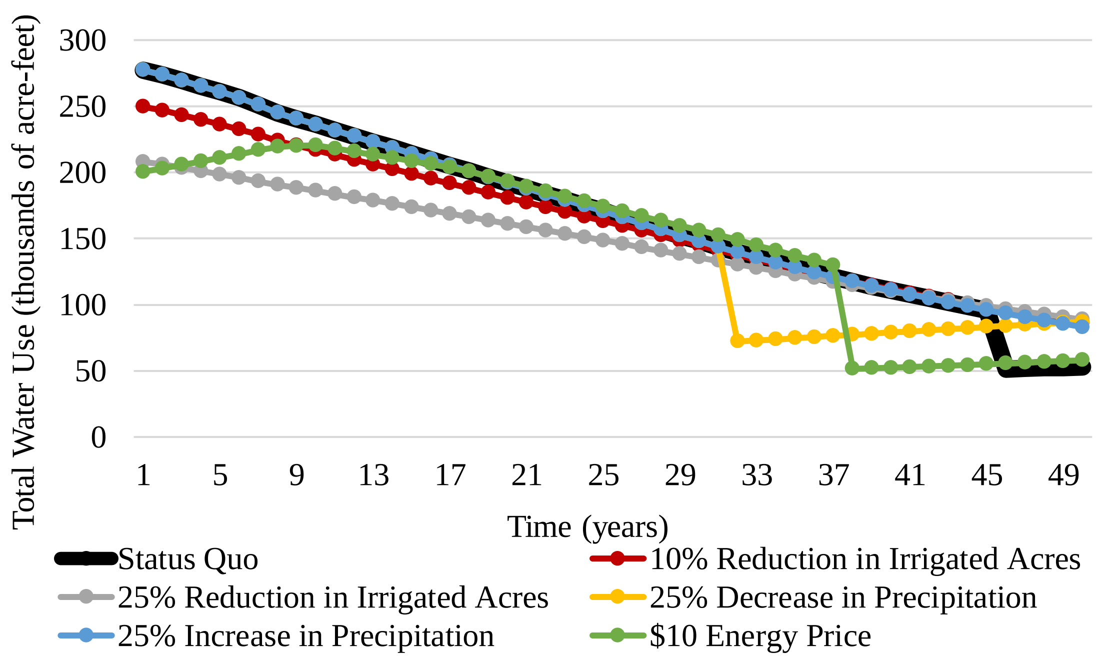

Figure C-5. Total annual water use (acre-feet) under each scenario in Moore County over the 50 year study period.

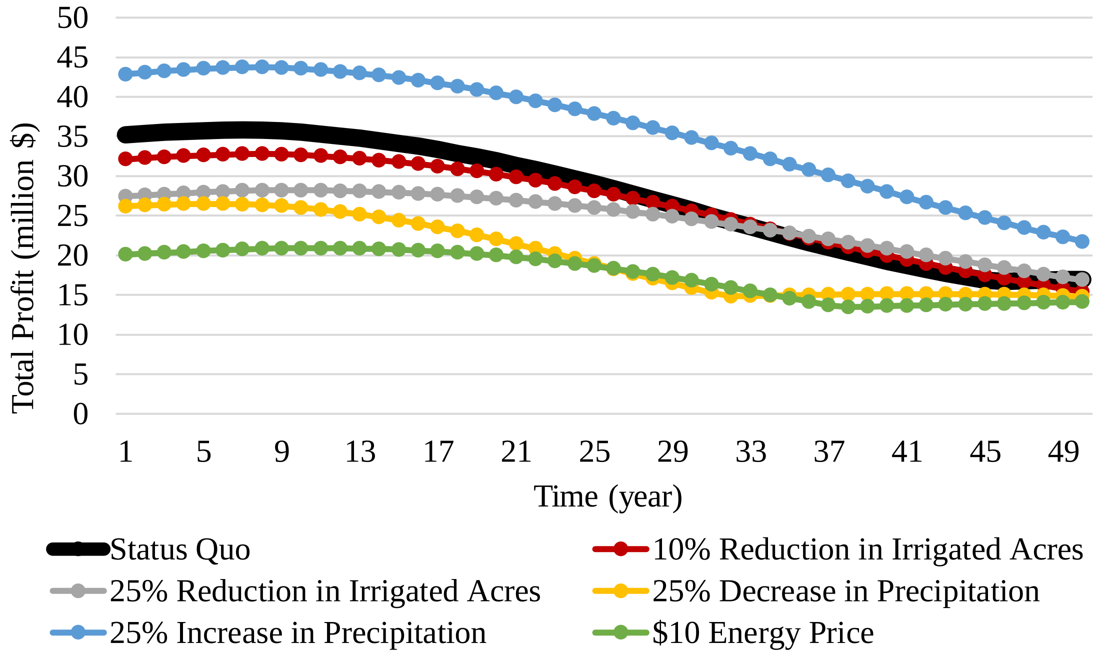

Figure C-6. Total annual profit under each scenario in Moore County over the 50 year study period.

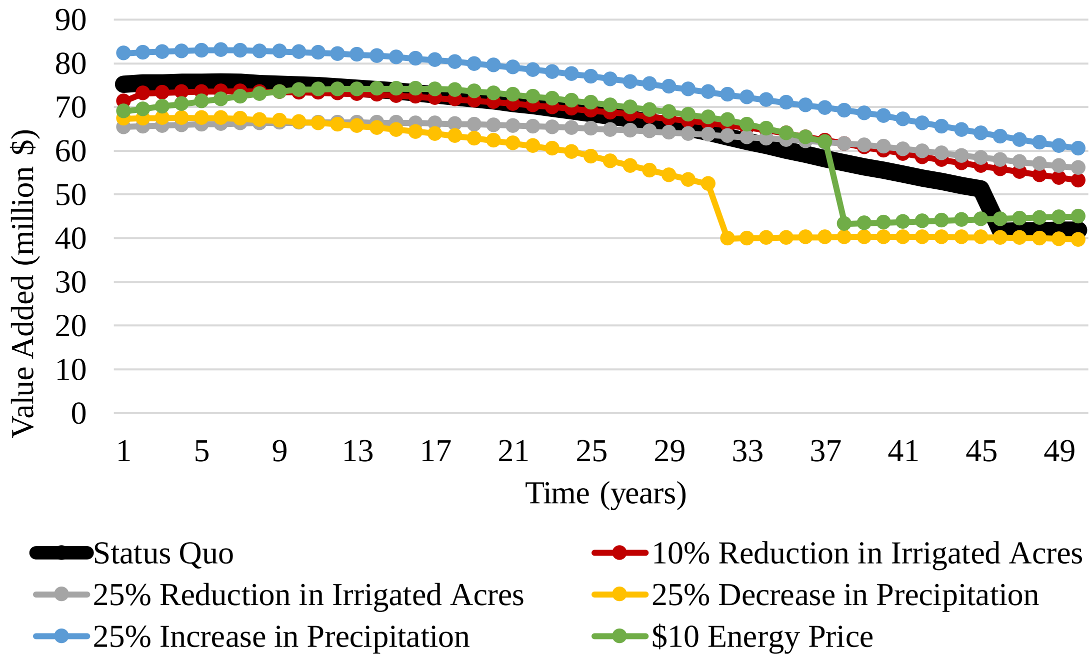

Figure C-7. Total annual value added under each scenario in Moore County over the 50 year study period.

Table C-1. Comparison of profit, value added, total water use, and ending saturated thickness for all scenarios in Moore County over the 50 year study period.

Scenario	*Profit (mil $)*	*% Change in Profit*	*Value Added (mil $)*	*% Change in VA*	*TWU (1,000 ac-ft)*	*% Change in TWU*	*Ending ST (ft)*	*% Change in ST*
Status Quo	1,374	-	3,240	-	8,411	-	30.9	-
10% Acreage Reduction	1,318	-4.1%	3,341	3.1%	8,149	-3.1%	33.9	9.6%
25% Acreage Reduction	1,227	-10.7%	3,178	-1.9%	7,360	-12.5%	41.9	35.4%
25% Decrease Precipitation	991	-27.9%	2,712	-16.3%	8,034	-4.5%	35.1	13.4%
25% Increase Precipitation	1,786	30.0%	3,749	15.7%	8,592	2.1%	29.4	-4.9%
$10 Fuel Price	880	-35.9%	3,190	-1.5%	7,609	-9.6%	39.0	26.3%