CLIMATE, WATER, WATER MARKETS, AND TEXAS AGRICULTURE:

THREE ESSAYS

A Dissertation

by

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ABSTRACT

Water availability and favorable weather conditions can greatly improve crop yields. Absence of irrigation water or unfavorable weather conditions can cause damages to crops and farmer income. Focusing on two agriculturally productive regions in Texas, this dissertation explores agricultural output when irrigation water decreases either due to economic market forces or aquifer depletion. Further, this work considers future climate impacts and the effect of a warmer and drier climate on agricultural output, crop mix, farmer income and aquifer characteristics.

In the first region, I assess the effect of water markets that have arisen in the Edwards Aquifer. Aquifer water is used by agricultural, municipal, and industrial users. Since 1997, users have traded water in an interregional market through sales and leases. A growing population and increasing economic activity have increased marginal use values causing large transfers of water out of irrigation. An analysis on the effects of this market on the regional economy is done using econometric, panel data model. The results show that increased water market transfers negatively affected the agricultural industry as captured through changes in agricultural payroll.

In the second region, I address water issues in the Texas High Plains where water from the Ogallala aquifer is used to irrigate crops. Water levels in the Ogallala aquifer are declining as irrigation pumping rates have far exceeded recharge thereby lowering water levels, decreasing aquifer life, and increasing pumping costs. I build a mathematical program to forecast expected agricultural output, income, and aquifer characteristics in the

Texas High Plains from present day until 2080 under existing conditions and expected climate change. The model results show that dryland cropland and rangeland cattle production will replace irrigated agriculture over most of the study area by 2050. Adaptation scenarios are included to show a range of possible responses to a changing climate. I then use regional input output modeling to examine the impact of expected future depletion and climate-induced changes to agricultural output and crop mix on the regional economy. Results show that future adjustments due to climate change will have a negative effect on the regional economy.

DEDICATION

This work is dedicated to anyone who chooses to roll the dice and go all the way

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I would like to thank Dr. Bruce McCarl for his patience, guidance, and willingness to serve as my dissertation adviser. He literally opens his home to his students, invests in their success, and trains students to think. I will always appreciate his authentic style for feedback, mentoring, and research.

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CHAPTER I

INTRODUCTION

Water is an important input to agricultural production. Irrigation has substantially enhanced yields and provided both a margin of safety under low rainfall events and the capability to grow crops in regions where rainfall would ordinarily be insufficient to meet the crop water needs. In Texas, groundwater resources in the Texas High Plains (THP) and a small area outside of San Antonio support irrigated cropland and a regional agricultural economy. In both places, groundwater has greatly enhanced agricultural incomes; however, the future of groundwater use for agriculture is threatened by a regionally specific mix is of issues including aquifer depletion, competition from nonagricultural use and environmental protection.

In the THP, 49 counties depend on water derived from the Ogallala aquifer for production of corn, cotton, sorghum, wheat, and rangeland cattle. However, since the 1960s, there has been concern that annual withdrawals were exceeding annual recharge rates leading to increased pumping depths, water stock depletion and a general concern about the usable life of the aquifer. As a result, researchers began investigating the monetary value and projected usable life of the aquifer plus means to extend the life. General concerns about aquifer sustainability are validated by the results of geological surveys that estimate water availability has fallen by 50% in some areas (Colaizzi et al, 2009) an observed pumping lifts that in regions have increased by as much as 100 feet over a ten-year period. Advances in irrigation efficiency and cropping strategies, coupled with conservation strategies, have prolonged the Ogallala aquifer's life and consequently the extent of irrigated agriculture in this region of Texas supports continued depletion.

Future climate change is expected to reduce regional rainfall and increase crop water demands, thereby shifting the withdrawal-recharge equation further into the deficit range and posing an additional threat to the sustainability of irrigated agricultural production. In Texas, there is concern that a trend is emerging towards a more arid climate including increased temperatures, lower soil moisture, and increased frequency of extreme events which will increase water demand for crop production.

In the THP, it is inevitable that climate change and declining Ogallala aquifer levels will lead to changes in regional agricultural production. Solutions that will preserve the aquifer in the face of growing climate change remain to be discovered. Both the Ogallala aquifer and the atmospheric build-up of greenhouse gases (GHG) are classic example of common pool resources that are rival and non-excludable. Without incentives to discourage pumping, rational individuals not cooperating or colluding with others have no reason to pump less. Similarly, rational individuals across the globe are have no incentives to limit their individual release of carbon dioxide and other GHGs which in turn has been argued to increase temperatures and alter rainfall patterns (IPCC, 2014). Thus, in the near-term, learning more about how these developments will impact the regional agriculture will aid in future planning and stimulate adaptive actions to lessen the effects. Furthermore, aquifer depletion will likely lower regional agricultural production and in turn lower economic activity particularly in agriculturally dominated regions.

Moving south to the Edwards/San Antonio study region, since 1997 water users in the Edwards Aquifer (EA) region outside of San Antonio have been able to trade their water rights. Overwhelmingly, market trades have been dominated by agricultural water leases and sales to non-agricultural users. As a result, the amount of aquifer water used for irrigation has declined. The extent of this is difficult to determine as water use is influenced not only by the sales but also by the regional climate conditions and is thus highly variable. Water markets across the United States have commonly facilitated the sale of mainly agricultural water largely to non-agricultural users. In turn such sales have led to decline in agricultural production and have induced regional losses within the rural economy (Howe, Lazo, and Weber, 1990). For this region of Texas, there is concern that irrigated cropland which produces grain, cotton and high-valued vegetable crops could be diminished because of increasing input costs and water sales resulting from lower marginal water use values compared to the prices paid for fresh water by non-agricultural user groups.

In theory, the introduction of a water market increases market efficiency as it allows for water use by those with the highest marginal value (Livingston, 1995). Namely, if non-agricultural users are willing to offer a price per unit water that is greater than the net present value of the difference in net returns between irrigated and dryland agricultural production divided by the amount of water used, then it is rational for producers to switch to dryland production and sell their water rights. However, this does not consider the larger impacts of declining agricultural output on rural communities and food security. Declining agricultural production in a rural economy which doesn't have a diverse income base can be detrimental. Further, lower agricultural production could pose a threat to future food supplies.

Recognizing the importance of water resources for agricultural use, this thesis will use two regions of Texas as case studies to explore the impact of water availability on current and future agricultural output. The overall objective of this dissertation is to explore the response of agriculture in two regions of Texas to aquifer depletion, climate change and water markets. This will be done by pursuing three sub objectives:

- to explore regional economic implications of water market sales in the context of the Edwards aquifer;
- to determine and simulate consequences of potential actions that can maintain regional agricultural productivity and revenue in the THP;
- to explore the regional economic implications of climate change and aquifer depletion in the context of the THP plus examine the consequences of a set of adaptation actions.

To carry out the proposed analysis, I will first do an econometric analysis over historical data to examine the effect of the Edwards aquifer water market on the regional agricultural economy. This will be done using regional agricultural payroll data. Then, to answer the questions inherent in the last two sub objectives, I will create a regional model in the THP of groundwater hydrology and agriculture that I will used to analyze regional agricultural and overall economy implications under ongoing depletion and then with the external force of climate change plus some future adaptation scenarios. The work will be carried out in three essays:

1) The first essay addresses the effect of water trading under the EA water market on the regional agricultural economy and explores possible long-term impacts.
2) The second examines farm production performance, aquifer vulnerability, depletion, climate change implications and possible adaptation in the THP. This involves construction of a regional dynamic mathematical programming model which links Ogallala aquifer hydrology and agricultural production including crop mix and land-use choice and then use that model to analyze what will happen in the future under current conditions and those under climate change with and without select adaptation activities.
3) The third analyzes the regional economic effect of future scenarios for THP agricultural output. In this essay, scenarios will be formed based on the results from Chapter 2 and regional input output modeling will be used to examine more general economic effects.

CHAPTER II

IMPLICATIONS OF THE EDWARDS AQUIFER WATER MARKET

Introduction

Water markets are an established mechanism that has been used to respond to water scarcity, increase economic efficiency, avoid market failures related to common pool resources, and manage interests of multiple user groups (Debaere et al., 2014). In 1993, a lawsuit aimed at protecting endangered species in the water scarce Edwards aquifer (EA) region near San Antonio motivated the State of Texas to establish the Edwards Aquifer Authority (EAA) and an associated water market to assign rights to aquifer groundwater (McCarl et al, 1999; Dabaere et al, 2014). The EAA was charged with overseeing management of the groundwater resource, monitoring and restricting pumping based on aquifer levels, and creating a water market that allowed the sale and lease of water rights. In setting up that market, protection of endangered species habitat associated with springflow was a major concern. Additionally, there was concern that the effect of water use on springflow were not the same for eastern versus western areas of the aquifer (Hardberger, 2016). To reflect differential effects on springflow, geographically and user-class based water market trading restrictions were imposed (which had differential features depending on the location of pumping withdrawals relative to location of Cibolo Creek--the defined east-west dividing line). The regulations impose additional hurdles that must be met when submitting water rights transfers from the western part of the aquifer to the eastern part of the aquifer. The restrictions also limit movement of water out of agricultural use.

This work seeks to extend the literature by identify the impacts of water transactions in the EA on, the spatial distribution of irrigated acreage, water use, and regional economic productivity. Using an econometric model using county-level panel data, this research will identify not only the primary impacts of the water market but also the geographic effects of agricultural water sales and policies which restrict trading based on use or location.

Background

Since the first water transaction in 1998, an accumulated total of 2,213,064 acre-feet years[1] of water have been sold and 1,846,801 acre-feet of water have been leased with 69,904 acre-feet leased and 94,506 acre-feet sold on average each year. Over time, users gained information and experience trading in the water market with the number of transactions growing each year. In 1998, only two transactions occurred but in 2014 and 2015 there were over 500 new transactions. Based on the volume of water sold and the number of transactions, it is arguable that the water market has allowed water to be used by those with the highest willingness-to-pay thereby increasing economic efficiency. At the same time, irrigated acreage, including acreage in high-valued vegetables, has decreased for counties in the EA (Edward Aquifer) water market (Table 2.1).

[1] This includes within county transfers and sales are summed over all years. If 100 acre-feet were sold in 2000, it is counted as 100 acre-feet of sales in each subsequent year.

Table 2.1: Total irrigated vegetable and all irrigated acres in production by county.

	Vegetable Acres				All Irrigated Acres			
	1997	2002	2007	2012	1997	2002	2007	2012
Atascosa	1,115	480	1,433	1,173	29,515	21,878	22,644	26,658
Bexar[2]	989	794	NR[1]	416	13,370	19,015	14,091	8,271
Caldwell	20	58	NR	4	958	1,866	909	633
Comal	NR	NR	NR	NR	136	373	517	422
Guadalupe[2]	11	10	17	9	1,351	3,025	1,094	1,941
Hays[2]	17	11	17	12	573	388	941	1,032
Medina[2]	3,041	1,909	1,605	1,849	47,021	55,516	41,210	51,418
Uvalde[2]	5,038	4,109	3,964	4,122	55,827	54,725	45,344	49,531
Total	10,231	7,371	7,036	7,585	148,615	156,413	126,233	139,484

[1]Not reported (NR)
[2]Counties where majority of irrigated acres use water from the EA.
Source: United States Department of Agriculture Census

Historically, counties in this area produced specialty vegetable crops that commanded a high market price. As indicated in Table 2.1, at the same time that water market transactions increased, vegetable production for counties in the water market declined. Looking at the sales and leases of water rights, (Table 2.2), the data show a large percent of water moved out of agricultural use to other sectors. This trend exists both in the lease and sale transactions and persists from 2000-2015.

Table 2.2: Percent of total volume of water transactions among agricultural users versus movement out of agricultural use at 2000, 2010, and 2015.

	Year	Agricultural Use to Agricultural Use	Out of Agricultural Use
Leases	2000	4%	42%
	2010	20%	36%
	2015	31%	25%
Sales	2000	1%	50%
	2010	33%	24%
	2015	37%	23%

This suggests that, as predicted, the market allowed water to move out of agricultural use. Despite short term financial gains from water transactions, decreased irrigated vegetable and other crop acreage could have a long-term impact on the local agricultural economy and support industries. Total irrigated acreage has decreased in counties trading water rights during the time that the water market was operational.

Despite numerous studies that show declines in agricultural productivity due to reallocation of water rights to other industries (Knapp et al, 2003; Howe, Lazo, and Weber, 1990), no study could be found which to analyzes the effects of the EA water market on regional agricultural output or the local agricultural industry. Furthermore, no follow-up analysis could be found to show if water transfer restrictions to protect agricultural users were successful in preserving agricultural water rights.

Water Market Literature

Similar to other natural resources, water embodies many attributes that lead to inefficient allocation and market failure. These attributes include uncertainty in availability, quality, and quantity as well as distributional issues such as transferability (Livingston, 1995). Establishing a water market whereby water rights are allocated and can then be traded is commonly accepted as a solution to maximize efficiency and account for externalities because in theory the water will be used by the group with the greatest marginal value (Howe, Schurmeier, and Shaw, 1986). Theoretically, the market structure can include provisions which protect other natural resources, user groups, and support socially optimal objectives (Howe, Schurmeier, and Shaw, 1986; Colby, 1990).

For these reasons, the popularity of water trading in the United States (US) has grown since the 1980s (Brewer et al., 2007) and analysis shows efficiency gains (Brookshire et al., 2004) as well as other environmental benefits (Dinar and Letey, 1991).

A number of studies have examined water market characteristics in terms of the amount of water transfers and the impacts of market activity in the western US (Brewer et al., 2007; Howitt and Hansen, 2005). Although markets generally have different institutional structures, the observed trades overwhelmingly involve agricultural water with much of it going to non-agricultural users (Brewer et al., 2007). Brewer et al. (2007) analyzed market transfers from 12 US states from 1987-2005 and found that water is sold at a higher price if the water is transferred from agriculture to another use compared to transactions that occur from agriculture to agriculture use. Due to differences in price, they also found that transfers with agriculture water as the origin of the water comprised 78% of trades and movement from agriculture to other uses comprised 56% of all trades. Moreover, in terms of volume, 18% of the water transferred in the market was from agricultural use to urban (Brewer et al., 2007).

In a number of markets, agricultural water has been heavily traded to municipal and industrial use including markets in the Northern Colorado Water Conservancy District, and the Edwards Aquifer (Debaere et al., 2014). As theory suggests, these transactions could be allocating water to groups with a higher willingness-to-pay but secondary impacts are a concern (Livingston, 1995). In California, other consequences such as lower water table levels in the aquifer and effects on the regional economy suggest further restrictions on water transfers may be necessary (Knapp et al., 2003). In the Arkansas River Valley of Colorado, transfer of water from agricultural to urban uses was found to be the source of financial benefits for urban areas and financial losses to rural areas (Howe, Lazo, and Weber, 1990). The incidence of water market induces financial losses in rural areas has led to suggestions that transitional support or financial assistance may be necessary to help build rural economies as they transition out of irrigated agriculture (Howe, Lazo, and Weber, 1990). Additionally, in particularly international cases, long-term impacts on food security and production are a concern (Rosegrant and Ringler, 2000).

In Texas, there are concerns that movement of water out of agriculture and into urban or industrial use may have negative consequences on the local economy. A study of potential economic impacts to Hale and Burleson Counties from shifting production from irrigated to dryland production as a result of water sales to urban areas found net negative impacts to Hale County would occur along with net positive impacts to Burleson County when direct, indirect, and induced economic effects were considered (Dudensing, 2017). In a study of Uvalde County, which is in the EA water market, Whited (2010) estimated potential losses of 750 jobs and $34 million of reduced sales of agricultural inputs as a result of moving 65,250 irrigated acres to dryland winter wheat production. Although these studies only modeled potential impacts of water transfers, both demonstrated the value and importance of irrigated agriculture to the regional economy. In recognition of the potential impacts to agricultural rights holders, when the market was created the Texas legislature disallowed the total sale of agricultural water and required users retained agricultural water rights of 1-acre foot per acre.

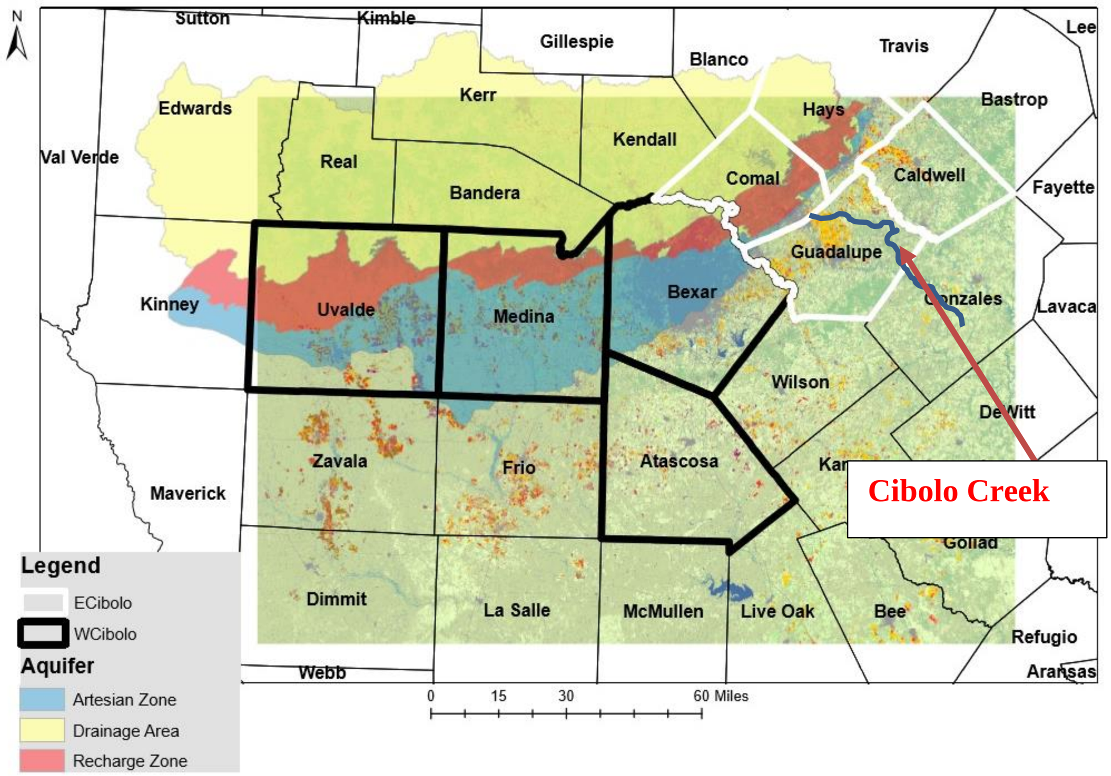
Edwards Aquifer Water Market History

The Edwards Aquifer is a karst aquifer underlying 8 counties in southern Texas. Water from the aquifer led to economic development in the region and supports agriculture, industry, as well as municipalities including San Antonio (Boadu, McCarl and Gillig, 2007). At the same time, the aquifer supports endangered species in springs on the eastern side of the aquifer. The geologic structure of the aquifer creates a system whereby water levels fluctuate quickly potentially necessitating governmental intervention if spring flow is to be preserved (Boadu, McCarl and Gillig, 2007). As early as the 1950s, a groundwater conservation district was established in an attempt to manage the resource; however, efforts were not successful (McCarl et al., 1999). Competing interests in water use led to a federal lawsuit spurred by concerns for endangered species protection that resulted in an order that the spring flows needed to be protected. This motivated the Texas legislature to pass Senate Bill 1477 (TSB 1477) which created the EAA. In that bill, the EAA was given the authority to create a water market by establishing water rights, dictating pumping limits, and setting up water rights transfer rules (McCarl et al., 1999). In the initial allocation, agricultural users were to be protected as water rights were allocated based on historic use and limits for transfers to non-irrigation uses were proposed (McCarl et al., 1999).

Since SB 1477 the EAA created a water market and put in place pumping restrictions based on historic use. The EAA monitors two wells (J-17, J-27) and two springs (San Marcos, and Comal Springs) and enacts pumping reductions or bans for the two pools in the aquifer based on well water level and or spring flow (Edwards Aquifer

Authority, 2017). In the aquifer, a differential spring flow effect of pumping in the western and eastern part has been noted with reduced pumping in the west having less effect than that in the east (Keplinger, 1996). This raised concerns about west to east water transfers. As a result, beginning in 2007 the EAA also put in place limits on water transfers from east of the Cibolo Creek to west of the Cibolo Creek in an attempt to protect spring flows (Edwards Aquifer Authority, 2017). The Cibolo Creek transfer restrictions stipulate that if transfers occur, then additional water needed to be placed in the EAA groundwater trust based on ratios determined regarding pumping effects in the water source county. As a result of this additional restriction, a price differentiated market has developed with water in the eastern counties commanding a higher price (Hardberger, 2016). Figure 2.1 shows the Edwards Aquifer, counties in the water market, as well as counties restricted in the east versus west trading as outlined by the Cibolo Creek Transfer restriction (ECibolo, WCibolo). Cibolo Creek lies on the Bexar County eastern border. The base layer in Figure 2.1 shows the distribution of cropland.

Figure 2.1: Map of Edwards Aquifer, water market, Cibolo Creek and agricultural land.



Economic Theory

Economic intuition regarding the value of water in competing uses comes from production theory. A general form for the production function whereby water is used as an input for agricultural production is given in Heady and Dillon (1972) as:

$$Y = f(X_L, X_K, X_{T,} \dots X_{m,}\ X_{water}) \quad (2.1)$$

Where Y is an agricultural output and $X_L, X_K, X_T \dots X_m$ are inputs such as labor, capital, land, fertilizer, etc. and X_{water} is the input of water. In this case we assume that as the quantity of the water input declines, so does output. Under this specification, other inputs are not perfect substitutes for water.

Following Hornbeck and Keskin (2015), farmers in choosing water application rates are assumed to maximize profit:

$$Max \ \ \prod = \ YP_Y - \ w_m X_m \quad (2.2)$$

Whereby $\prod$ is farm profits arising from production of Y using inputs X_m where $P_Y$in the price of the output and w_m the costs of inputs. Also Y and X are related via equation 1. Profit is assumed to be greater if farmers in a given county have access to the input X_{water} . Thus, economic activity is higher in counties with access to water as seen in prior studies (Hornbeck and Keskin, 2015; Howe, Lazo, and Weber, 1990).

Agricultural output created from profit maximizing farmers generates spillovers into other industries and supports the regional economy (Hornbeck and Keskin, 2015; Dudensing, 2017). Generally agricultural activity has direct, indirect, and induced effects within the regional economy and this is the case in the Edwards Aquifer region (Whited, 2010). Therefore, changes in water input availability should be reflected in changes in farmer profits, agricultural output, input use and regional economic indicators. Generally, water is assumed to increase profitability. As water input declines, so does profitability and acres farmed which is expected to reduce the use of other factors of production, and overall output. These reductions, in turn, cause induced effects in the regional economy.

Data and Empirical Analysis

Study Region

The EAA manages Edwards Aquifer water use in Atascosa, Bexar, Caldwell, Comal, Guadalupe, Hays, Medina, and Uvalde counties. Restrictions on water transfers due to the Cibolo Creek transfer rules constrain water movement from sellers in Uvalde, Medina, Atascosa, and Bexar counties to buyers in Caldwell, Comal, Guadalupe, and Hays counties. In our econometric estimation all 8 counties listed in the EA water market will be designated *treated* counties meaning they are subject to the water market. Additionally, to utilize an experimental design, additional control counties outside of the water market are included in the data set. Counties were chosen based on historic agricultural output and proximity to the Edwards Aquifer. Counties included and designated as *control* are: Bandera, Bastrop, Bee, Blanco, Fayette, Frio, Gillespie, Gonzales, Karnes, Kendall, Kerr, and Wilson.

All of the counties included in this analysis historically produce agricultural products. As seen from Table 2.3, except for Comal County (in the water market) all counties produce USDA reported amounts of agricultural crops. Control counties selection was based on their proximity to the water market treatment counties and represent a range of agricultural activity and economic contribution. The market value of crop sales varies across the control counties with Frio County having the highest and Kerr County the lowest.

Table 2.3: 2012 market value of crops sold by county.

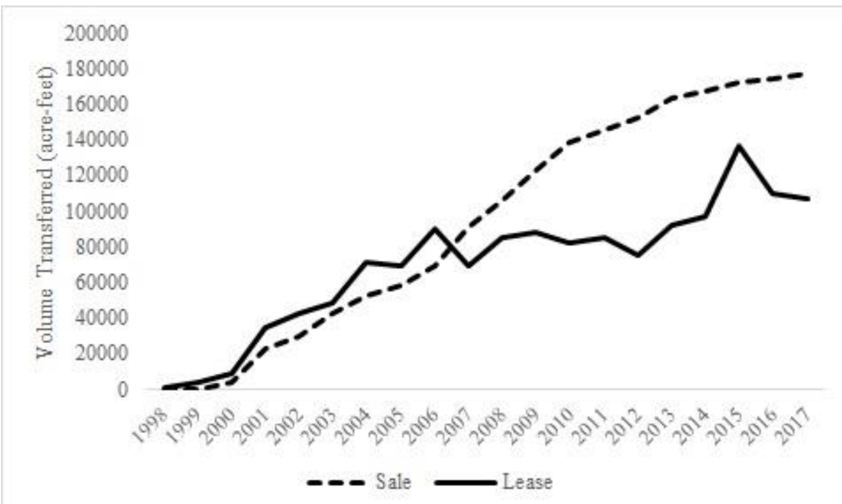
County	Value of Products
Atascosa	27,793
Bandera	1,263
Bastrop	11,901
Bee	9,939
Bexar	54,705
Blanco	9,052
Caldwell	11,178
Comal	(D) [1]
Fayette	13,794
Frio	109,089
Gillespie	11,311
Gonzales	23,246
Guadalupe	30,332
Hays	7,313
Karnes	10,705
Kendall	2,115
Kerr	1,313
Medina	64,889
Uvalde	61,890
Wilson	27,914

[1] Data are not reported by USDA due to disclosure issues

Water Market Data

Water market data was obtained from the EAA for all lease and sale transactions occurring from 1998-2017. The following information was available for each transaction: type of transaction (lease or sale), transfer start date, transfer end date, initial use, county of water source, source pool, county of water use, use pool, use before and after transfer right, and transferred amount in acre feet. Inconsistent price data was available for some transactions and those data was removed from the final dataset. As shown in Figure 2.2, the volume of water sold or leased in the market increased over time. The variable *aftransferred* sums the total number of acre-feet of water transferred through sales and leases in the water market for each year. There is a slight decline in water traded through lease transfers around the time of the Cibolo Creek restrictions occurred but in 2015, the amount of water traded via leases spiked noticeably. At the same time, the amount of water traded through sale transfers has steadily increased over time.

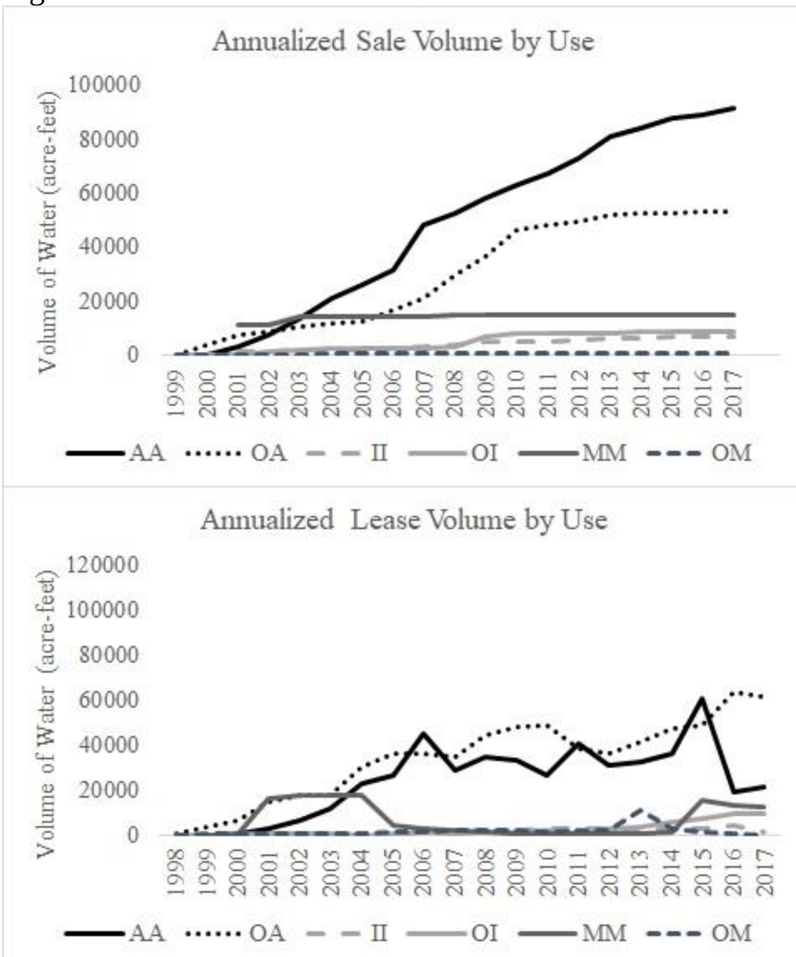
Figure 2.2: Annualized water transfers in the Edwards Aquifer water market by type of transaction.



In 2016, 325,300 acre-feet of water were pumped from the EA. Of this water, 26% was for municipal use (232.6 thousand acre-feet), 6% for irrigation (54.7 thousand acre-feet), 3% for industrial use (24 thousand acre-feet), and 2% was for unreported usages (Hydrologic Data Report, 2016). Prior to the water market, there was no formal movement of water or exchange of water rights other than those transferring with land sales. In 1996 (the year prior to the water market), 705.6 thousand ace-feet were pumped with 37% for municipal use (261 thousand acre-feet), ~2% for domestic use (12.3

thousand acre-feet), 25.7% for irrigation (181.3 thousand acre-feet), 6% for industrial (38.8 thousand acre-feet) and 30% for springflow (212 thousand acre-feet) (Hydrologic Data Report, 1996). As shown, the amount of total pumping plus the water used for irrigation has fallen drastically from the time before the water market was in place. Figure 2.3 shows the use of water transferred in the market over time. The figure is split into two panels with the amount sold by type of seller on the top and the amount leased by type of lessor on the bottom. It can be seen that for water volume transferred by leases, more water is characterized as agriculture to agriculture (AA) transactions than for any other types. The amount of water transferred out of agriculture (OA transactions) increased until 2010 and then leveled off. MM use is the next largest transfer by volume. For lease volume, OA transfers are the greatest by volume except for in 2006, 2011, and 2015. Early in the market water moved from industry to other uses.

Figure 2.3: Annualized sale and lease volume in the Edwards Aquifer water market.[1]



[1]AA (agriculture use to agriculture use), OA (agriculture to other use), II (industry use to industry use), OI (industry to other use), MM (municipal use to municipal use), and OM (municipal use to other use)

Movement of water among counties is also an important consideration. Some counties may be suppliers of water where others may be demanders of water. As seen in Table 2.4, while there are many trades within a given county, Medina and Uvalde counties are substantial suppliers of water to Bexar County, home to San Antonio, the largest city in the study area. Further, more water was transferred from Uvalde County through leases than sales while Medina County transferred close to equal amounts of water through leases compared to sales. Now spring flows are closely monitored and levels are not allowed to drop below a certain threshold before pumping restrictions are imposed. However, as large geographic changes occur in water use the threat of spring flow disruptions grows as described in Keplinger (1996).

In addition to the volume of water transferred, the total number of transactions was also recorded. As right-holders learn about the water market and gain experience transferring rights, it is expected total number of transfers will increase. As mentioned previously, the number of transactions grew from 2 transactions in the first year of the water market to over 500 in later years. To capture the increase in participants in the market, a variable called *numberoftransfers* was created. In comparison to a binary variable to identify pre- and post- water market years, the *numberoftransfers* variable will capture participation in the market which may be more reflective of water market activity and the effect of the policy.

Table 2.4: Lease and sale volume by county for the Edwards Aquifer water market (1998-2017).

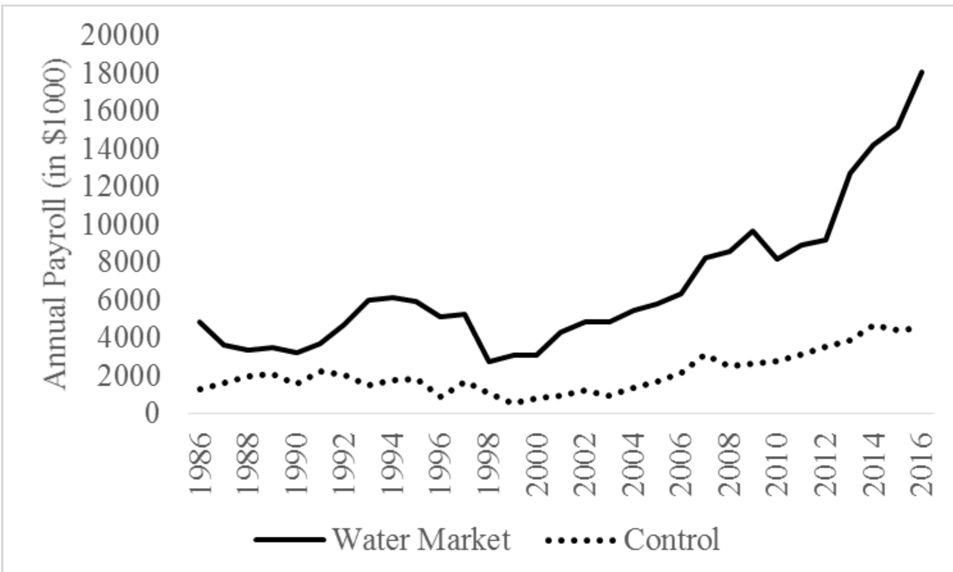
			Use County							
			Atascosa	Bexar	Comal	Guadalupe	Hays	Medina	Uvalde	Total
Water Sales	**Source County**	Atascosa	11284	334				2164		13781
		Bexar		709707	25770	1060	307	32586	18726	788155
		Comal		3	46710		1185			47898
		Guadalupe				1805				1805
		Hays			98		4336			4434
		Medina		207759	233		1879	347609	8986	566465
		Uvalde		341789	33		15041	125301	308361	790526
		Total	11284	1259592	72844	2865	22748	507660	336073	2213064
			Use County							
			Atascosa	Bexar	Comal	Guadalupe	Hays	Medina	Uvalde	Total
Water Leases	**Source County**	Atascosa	6016	5779				4775		16571
		Bexar	918	571330	2175	326		27746	7971	610466
		Comal		5702	12910	346	7125	1161		27244
		Guadalupe			500	136				636
		Hays	42	69	9532	8	10065			19716
		Medina	833	298371	4889	200	40	266411	11831	582575
		Uvalde	545	299448	611	184		15945	272860	589593
		Total	8355	1180699	30618	1200	17230	316039	292662	1846801

Regional Input Sales Data

It is hypothesized that as water use for agriculture declines, so does the demand for inputs to agricultural production. County business pattern (CBP) data gathered by the US Census Bureau provides an indicator for the economic impact of sales of agricultural inputs and size of the associated industry (United States Census Bureau, 2018). The US Census Bureau reports annual payroll by type of industry along with number of establishments, and number of employees. This reporting is based on county-level data collected from employers through the Internal Revenue Service and Employer Identification Numbers (United States Census Bureau: Methodology, 2018). Employers are grouped by industry type classifications. Other studies have used CBP data to describe how segments of industry have responded to various items (Kim, 1995; Brown and Greenbaum, 2017; Holmes and Stevens, 2002).

This work uses annual CBP payroll data (in 2018 dollars) to reflect changes in the agricultural sector as a proxy for sales activity over time. Industries are classified by the North American Industry Classification System (NAICS) for 1997-2016. Also, older data were obtained that used the Standard Industrial Classification (SIC) codes from 1986-1996. Concordance tables provided by the US Census Bureau were used to match SIC and NAICS codes. Median annual payroll from agricultural and support firms appears in Figure 2.4. Although codes change over time, in 2016 the following NAICS codes were used: 115111, 115112, 115113, 115114, 115115, 115116, 115210, 311119, 311211, 311410, 311412, 311421, 311422, 311611, 311940, 311941, 311942, 311999, 325310, 325311, 325320, 325400, 423820, 424480, 424510, 424520, 424590, 442291, 444210, 444220, 541320, 541690, 541940, 561730, 812910. Graphically the comparison generally shows activity in the counties in the water market (treatment) and that in those not in the water market (control) exhibit a similar trend until 1998 when water market transfers begin but then diverges.

Figure 2.4: Median annual payroll by water market and control counties.



Using these data we will later estimate an econometric model but we first need to discuss all the data used.

In addition to agricultural and associated industry payroll, total payroll was calculated yearly for each county in the study region. From 1986-2016, the regional economy grew rapidly. In order to capture overall changes to the regional economy as well as account for any measurement error in the CBP datasets as reclassification occurred during multiple times over the time-series, annual county-level payroll will also be included as an explanatory variable.

Other variables

Other determinants for annual payroll are included in the econometric model specification. Input prices and output market prices for agricultural output are included to capture larger changes to agricultural markets. Given that county level yearly data is sparse, USDA national input and output price indexes were used. Specifically, the national production input prices paid by farmers' index was used to capture changes in production input prices. This region of Texas produces fruits, vegetables, and field crops. Thus, we also used a national market output price received by farmers' index selecting one that covered field crops, fruits and nuts, as well as vegetables.

Regional demographic and economic variables were also included. The oil industry is a competing source of employment in the region. Annual payroll for the oil industry was included as agricultural employment may be influenced by larger business cycles in the oil industry. Finally, the real minimum wage rate was included as an explanatory variable.

Model and Estimation Technique

The econometric model used loosely follows an experimental design based on a difference-in-difference (DiD) model as this is an established econometric technique to assess the impacts of policy changes (Meyer, Viscusi, and Durbin, 1995; Carpenter, 2004; Pischke 2007). Following this methodology, the model used to assess the impact of the water market transactions on water availability in a county and the subsequent effect on the regional agricultural economy is as follows.

$$Payroll_{it} = \beta_0 + \beta_1 aftransferred_{jt} + \beta_2 numberofcontracts_{jt} + \beta_5\, inputpriceindex_t + \beta_6\, outputpriceindex_t + \beta_7\, netwater_{it} + \beta_8\, economywide_{it} + \alpha_t + \varepsilon_{it} \qquad (2.3)$$

Where, $payroll_{it}$ is annual payroll from the agricultural and associated support industries and the dependent variable of interest to capture the effect of the water market. The variables $aftransferred_{jt}$ and $numberofcontracts_{jt}$ characterize water market activity and are specified over years (t) for counties in the water market (j) and zero otherwise. This specification controls for differences between counties in the water market and control groups as well as year-to-year differences in the number of water market transactions and volume of water transferred. Two variables are used to quantify the effect of the water market. First, *numberofcontracts* captures the growing popularity and experience trading in the market. It is assumed that the effect of the water market will not be instantaneous and thus not accurately captured in a binary, (0,1) specification. Then, as the volume of water sold or committed to multi-year leases increases, it is expected to have a longer effect on agricultural and related industry payroll than the initial effect in the first year of the contract. Thus, the variable *aftransferred* quantifies the volume of water transferred in the market and how that impacts agriculture and related industry payroll.

Then, total water movement in and out of a county is given by $netwater_{jt}$ As discussed previously, differences between annual payroll in control versus treated counties must be the same and consistent before the policy change to show the effect of the water market.

As discussed above input and output price indicators, and other economy wide variables were included. The variable $inputpriceindex_t$ gives the national production input price paid price index in year t. Also included as another input price index is the $wagepriceindex_t$. The $outputpriceindex_t$ is the agricultural output prices received by farmers index in year t, and consists of separate indexes for vegetables, fruits and nuts, and other crop prices. Other economy wide variables include: 1) $oilpayroll_{it}$ which captures annual payroll from the oil industry by county (i) and year (t); 2) $minwage_t$ is the real minimum wage in year t; and 3) $Totalpayroll_{it}$ is the total payroll by county and year which captures other economy-wide changes to payroll over the study region and time period. Then, α_t are year dummies, and ε_{it} is the associated residual.

Variables and Summary Statistics

Summary statistics and detailed descriptions of the variables used are given in Table 2.5 and Table 2.6. The average annual payroll for agricultural and support industries for the sample is $16,022,770 (in 2018 dollars). The wide range in net water amount transferred in a county and year can be seen as with water some counties sell more than they purchase (with a max net of -55,236 acre-feet) while others are net purchases (with a max net gain of 73,092 acre-feet). On average, the number of water transaction contracts in each year was 336 and the average total acre-feet transferred was 42,360 over the entire study region.

Table 2.5: Variable description and sources.

Theoretical Model	**Variable**	**Description**	**Source**
Output	agpayroll	county annual payroll for agriculture and related industry	US Census Bureau
WaterMarket	aftransferred	Yearly total acre-feet of water transferred in the water market from sales and leases	EAA
	numbercontracts	Yearly number of sale and lease contracts in the water market	EAA
NetWater	netwater	net transfer of water	EAA
InputPriceIndex	wageindex	yearly national index for agriculture wage	USDA
	inputspriceindex	yearly national index for inputs to production	USDA
OutputPriceIndex	vegetablepriceindex	yearly national index for market vegetable prices	USDA
	fruitnutpriceindex	yearly national index for market fruit and nut prices	USDA
	croppriceindex	yearly national index for market field crop prices	USDA
EconomyWide	minwage	real federal minimum wage	Federal Reserve Bank St. Louis
	oilpayroll	county annual payroll for oil and related industry	US Census Bureau
	totalpayroll	County annual payroll for all industries	US Census Bureau
α_t	y86,y87,y88…y16	year dummy	Generated

Table 2.6: Summary statistics.

Theoretical Model	**Variable**	**Obs**	**Mean**	**Std.**	**Min**	**Max**
Output	agpayroll	564	16022.77	53073.58	152.71	395564.7
WaterMarket	aftransferred	564	42359.92	85829.17	0	309010.2
	numbercontracts	564	336.18	714.39	0	2528
NetWater	netwater	564	0	11217.55	-55236.05	73091.79
InputPrice-Index	wageindex	564	76.98	22.39	42.6	115.9
	inputspriceindex	564	67.31	23.74	40.1	114.1

Table 2.6 Continued

Theoretical Model	**Variable**	**Obs**	**Mean**	**Std.**	**Min**	**Max**
OutputPrice-Index	Vegetableprice-index	564	81.27	17.27	53.1	108.8
	Fruitnutprice-index	564	80.28	25.46	54	138.8
	croppriceindex	564	71.40	16.44	52.6	107
EconomyWide	minwage	564	6.39	1.30	3.12	8.29
	oilpayroll	375	19298.87	50912.5	34.10	480810.6
	totalpayroll	564	1538770	5359886	20688.44	34264668

Results

Five model variants for agricultural and associated industry payroll were estimated. The model specifications add additional variables starting with the simplest specification to characterize the water market and progressing to add variables related to the general economy, agricultural production, and ending with the final specified model. The results show that the implementation of increasing volume water transfers had a negative impact on annual payroll for agriculture and support industries as seen in the *aftransferred* coefficient (Table 2.7). The impact was negative and significant at the 1% level in all models. Interpretation of the coefficient in the final model (4) suggests that for each additional acre-foot that was transferred in the water market, annual payroll for agriculture and support industries decreased $231 (in 2018 dollars). The second variable to capture the effect of the water market is *numberofcontracts* and is positive and statistically significant across all models. The coefficient indicates that as the number of water market transfer contracts increases by 1, the expected agricultural and associated payroll increases by $297,800. As shown, the volume of water transferred highly favors water moving out of agricultural use. As the volume of water sold and committed to multi-year leases increases, this has an increasing effect on the agricultural industry. Meanwhile, the mere number of contracts or years that the water market has been in operation, doesn't capture the determinantal effect of decreased water available for agricultural production.

At the same time, the *totalpayroll* variable captures larger changes that were occurring at the same time. The coefficient on *totalpayroll* is positive and statistically significant at the 1% level across all models. While the magnitude of the coefficient is lower (.01-.008), it is statistically significant and indicates that payroll was increasing over the study period.

Table 2.7: Regression results.

	(1)	(2)	(3)	(4)	(5)
	agpayroll	agpayroll	agpayroll	agpayroll	agpayroll
numbercontracts	29.387	31.104	28.596	29.536	29.777
	(5.05)***	(3.07)***	(2.70)***	(3.08)***	(3.10)***
aftransferred	-0.221	-0.243	-0.223	-0.234	-0.231
	(4.55)***	(2.87)***	(2.53)**	(2.90)***	(2.87)***
totalpayroll	0.01	0.009	0.008	0.008	0.008
	(113.53)***	(59.04)***	(44.86)***	(45.75)***	(45.75)***
minwage		396.506			
		-0.75			
oilpayroll		0.101	0.094	0.094	0.095
		(5.06)***	(4.77)***	(4.99)***	(5.00)***
netwater			0.552	0.549	0.554
			(6.40)***	(6.42)***	(6.48)***
wageindex			143.005		
			-1.03		
inputspriceindex			327.447		
			-1.54		
vegpriceindex			-247.484		
			(-1.92)*		

Table 2.7 Continued

	(1)	(2)	(3)	(4)	(5)
fruitnutpriceindex			-164.531		
			-1.65		
croppriceindex			-167.624		
			-1.37		
trend				83.828	
				-1.05	
constant	682.315	-2,401.59	13,269.97	-199.01	851.525
	-1.36	-0.73	(2.00)**	-0.16	-1.22
N	564	375	375	375	375
R2 within	0.8068	0.8276	0.8262	0.824	0.8242
R2 between	0.9992	0.9986	0.9971	0.9971	0.997
R2 overall	0.9617	0.9645	0.9686	0.9682	0.9681
Wald	14051	10025	11225	11194	11190

* p<0.10; * p<0.05;** p<0.01***

Note: coefficient value is noted above, z-score is noted below in parenthesis if statistically significant at least the 1%, 5%, or 10% level

Model (2), (3), and (4) explore additions of labor price changes, regional labor competition, production price indices, and output price indices as explanatory variables. Results suggest that minimum wage and input price indices are not statistically significant and should not be included in the model. F-test for joint significance of output price indices (*vegpriceindex, fruitnutpriceindex, croppriceindex)* were jointly statistically significant$(\chi_3^2 = 5.49, P = .139)$. The coefficients on output price index variables are mixed and statistically insignificant. Other specifications included dummy variables to control for year effects and a linear time trend but found to be individually and/or jointly statistically insignificant.

The *netwater* variable is positive and statistically significant at the 1% level indicating that additional water positively impacts agriculture and support industry payroll. Based on the results, each additional acre-inch of water available for use for a permit holder in a water market county increases agriculture and support industry payroll by $554 (in 2018 dollars). Although the methodology for computing the price of an acre inch (by acre-foot) of water differs than the computation of a net value of an acre-inch described here, Brewer et al. (2007) found values of $29-$114 per acre-foot leased and $1,747-$4,366 per acre-foot sold. It is likely that the net value of an acre-inch here is inflated due to additional omitted variable bias; however, the positive effect of water availability in any given county on agricultural and related support industry suggests that water is valuable input to agricultural production.

Finally, the coefficient on oil payroll is positive and statistically significant at the 1% level. This suggests that changes to the oil industry does have a negative impact on agriculture and related industry payroll. As hypothesized, this research suggest that oil and agricultural payroll are negatively related.

Conclusions

Ideally water markets allow water to transfer to users with higher marginal use values. In most recent cases, such trades have corresponded with movement of water out of agricultural use which are anticipated to have negative effects on the regional agricultural economy. Results from this work indicate that the effect of the increased water transfers in the EA water market on agriculture and supporting industry payrolls is complex. Consistent with theory and prior studies, we find that as the volume of water transferred in the market increases, the value of agriculture and the payrolls in supporting industries fell. Additionally, we find that the value of an acre-inch of water for annual payroll for agriculture and support industries is $554 (2018 dollars). We also find that other variables such as total regional payroll, oil industry payroll, and number of water market contracts are also statistically significant factors that help explain agriculture and supporting industry payroll over time.

This is the first work to attempt to quantify the real effect of the EA groundwater market on elements of the regional agricultural economy and is one of few studies addressing a groundwater market. Estimates suggest that while the regional economic effects to the agricultural industry are not as severe as those found in other impact studies, given the movement of water out of agriculture, future studies should be conducted to consider if additional support or restrictions on water movement would be necessary to support agriculture production in the regional economy into the future. This research doesn’t analyze the impact of declining agricultural payroll on the overall regional economy. It also doesn’t quantify the effect of water market trades on agricultural output. There are also some remaining omitted variables that might improve the analysis if included. For example, this analysis doesn’t consider the effects of users holding multiple permits or water rights across different counties. Exploring the characteristics and distribution of water rights holders would improve the estimates. The analysis was also unable to incorporate the effect of the price of water in the market as it was unavailable in the data set utilized and incorporation of price information would be a valuable extension that could be carried out in future work.

Initial estimates suggest that future work is needed to comprehensively assess the impact of the water market on the local economy. While impacts to a specific industry are important for rural communities, broader impacts of the water market to assess net regional impacts could be explored to determine if losses to agriculture and support industries were offset by gains in other sectors as suggested in Howe, Lazo and Weber (1990). Additional variables to characterize regional changes in the full set of sectors within the economy should be considered.

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CHAPTER III

CLIMATE CHANGE AND TEXAS HIGH PLAINS AGRICULTURE: EFFECTS AND ADAPTATION

Introduction

Access to water resources substantially impacts agricultural productivity and the value of output produced. The Ogallala aquifer is a large groundwater resource underlying the central United States (US) that since World War II has afforded overlying counties with high levels of agricultural productivity and economic prosperity (Hornbeck and Keskin, 2014). Irrigation is key to the observed high yields but pumping rates have exceeded annual recharge and Ogallala aquifer water levels are declining. Regional studies have attempted to value the aquifer water to assist conservation efforts and determine a market value for the water. Using a willingness-to-pay framework, a study by De Silva and Williams suggests the value of water is $2.41 per acre-inch (De Silva and Williams, 2015). A broader based study focusing on the differential value of land with access to the water versus that did not have access found that buyers paid a premium of $25 billion in 1960 for land with aquifer access but due to depletion, the premium value fell to $10 billion by 2002 (Hornbeck and Keskin, 2014).

The value of the water from the Ogallala aquifer is closely tied to its use and value of products produced. In the Texas High Plains (THP), water is mainly used by agriculture (over 90% according to De Silva and Williams, 2015) and thus its economic value is closely tied to agriculture. A 2008 report estimated that the THP cultivated 13.5

million acres, 4.6 of which are irrigated using 5.6 million acre-feet of water each year (Weinheimer et al, 2013). Water from the Ogallala aquifer has led the THP to be a global leader in cotton production and the state's center for grain production (USDA Texas Fact Sheet). In 2012, 50% of the agricultural commodity sales in Texas came from THP counties where irrigation is a key contributor to agricultural productivity and farm income. Access to water from the Ogallala aquifer for irrigation has greatly benefited the THP communities and is to a great extent responsible for the agricultural importance of the region.

Despite decades of water extraction, the current pumping levels in the THP, and for many areas of the multistate Ogallala aquifer, are unsustainable. Water storage in the THP portion of the Ogallala aquifer declined an estimated 158.2 million acre-feet between 1950 and 2013 (McGuire, 2014). Additionally, current depletion is substantial with an estimated 13.2 million acre-feet reduction in water storage during 2011-2013 (McGuire, 2014). Area-weighted average aquifer water levels indicate average reductions of 41.2 feet from 1950-2013 and 3.5 feet from 2011-2013 (McGuire, 2014). In terms of affected area McGuire (2014) indicates there is been a loss "of 10 percent or more [of the initial available water] in 25 percent of the area, a decrease of 25 percent or more in 15 percent of the area, a decrease of 50 percent or more in 5 percent of the area..." with a few areas experiencing increases. These findings confirm that substantial portions of regional irrigated acreage is threatened by future water availability.

Additionally, future climate change is expected to increase temperatures and alter precipitation patterns as well as increase the frequency of extreme events. In Texas, models suggest that climate change will raise temperatures, increase the probability of extreme temperatures, decrease rainfall, and increase the likelihood of storms or extreme precipitation events (What Climate Change Means for Texas, 2016). Soil moisture projections under the more extreme climate scenarios indicate large decreases (Seager et al., 2007; Cook et al., 2015). Such alterations will stress agriculture and lead to declining productivity for many crops and livestock (McCarl et al., 2016). The potential magnitude of the impacts may be foreseen by examining past effects of drought conditions. In 2011, Texas experienced a severe statewide drought which caused direct losses that were estimated at $3.2 billion for livestock, $2.2 billion for cotton, and $736 million for corn amounting in total to a sector wide loss of $7.62 billion (Guerrero, 2011). While these figures represent state-wide impacts the THP incurred a large share of these losses.

The THP is an agriculturally productive region that is heavily irrigated using Ogallala water. In the next 100 years, declining aquifer levels and climate change are expected to reduce regional agricultural productivity and increase per acre water use (Reilly et al 2003). The response of agriculture to changing climatic conditions and less water for irrigation is likely to be a reduction in irrigated land with acres transitioning to either dryland or range lands. However, there are potential adaptation strategies to reduce the effects of climate change and reduce water consumption that may permit the region to maintain agricultural output and incomes with some of these yet to be fully developed, analyzed, and implemented (Amosson et al., 2009). Understanding how water use and climate interacts in the THP under various climate, adaptation and conservation strategies could be useful for both policymakers and agricultural stakeholders interested in maintaining the regional agricultural economy.

Objectives

The objective of this paper is to analyze climate change vulnerability and possible adaptation scenarios for agriculture in the THP. This is done by first building a mathematical-programming based model that portrays both agriculture and aquifer hydrology. This work will explore the response of the aquifer to continued pumping along with the crop mix, dryland/irrigated mix and grazing land-based cattle production to declining aquifer levels under a business-as-usual scenario as well as the scenarios that capture the effects of climate change and potential adaptations. Time evolving estimates of total water extracted, land use change, levels of agricultural output, production costs, total revenue, agricultural income and aquifer characteristics in the region will be represented. As revealed in the literature review below, previous regional modeling work has unified hydrological and agricultural modeling a small scale but have not included the full region. Previous studies have also not included climate change and adaptation scenarios. The model used herein will the solve for the period from 2018 to 2080 and depict the interrelationships among hydrology, agriculture, and the economic market. Adaptation scenarios will be included to show how their adaptation can improve agricultural productivity under climate change.

Literature Review

The geographic size and economic importance of the Ogallala aquifer has generated a number of economic studies that focus on: the economic effects of the water

(Hornbeck and Keskin, 2015), appraisal of means to prolong the life of the aquifer (Johnson et al., 2009), the effect of declining water levels on the regional economy (Almas et al., 2004), effect of climate change (Wang, 2012), and overview of strategies to maintain agricultural productivity while extending aquifer life (Colaizzi et al., 2009). Overwhelmingly, research surrounding the Ogallala aquifer focuses on estimating potential effects or finding solutions to declining aquifer levels. Some research uses econometric analysis (Hornbeck and Keskin, 2014), but many employ dynamic optimization and mathematical programming models as reviewed below.

Early THP related linear programming models from the late 1960s used representative farm models to predict agricultural output and water use (Short, 1980). In the 1970s, recursive regional models began to progress and dynamic optimization models on the Ogallala aquifer predicted declining aquifer levels, increased pumping costs, and fewer irrigated acres as soon as the 1990s (Short, 1980). Anticipating future declines in aquifer levels, models expanded data inputs, conservation scenarios, and methodologies with the introduction of water management strategies for a model in Oklahoma (Warren et al., 1982) and a nonlinear water-yield response function added to a model Ogallala aquifer in Kansas (Chanyalew et al., 1989).

Feng (1992) created what others cite as the first dynamic optimization model for the Texas portion of the Ogallala aquifer (Wheeler, 2008; Wang, 2012). Using Lubbock County as the study region, Feng (1992) simulated optimal water extraction over a 50-year time horizon and concluded that if water allocation was optimal, irrigated cropland would remain in production for 20-30 years from the initial period. The Feng model solved for irrigation methods and cropping practices to maximize total benefits of groundwater extraction over future time periods. Feng’s optimization model also relied on equations which specify pumping cost as a function of lift and water-yield response functions developed from the Environmental Policy Integrated Climate (EPIC) crop simulation model.

Feng’s dynamic optimization specification for Lubbock County has been expanded and updated to include: technological constraints, new irrigation technology, and crops (Terrell et al., 2002), relevant groundwater management scenarios (Johnson, 2003; Das et al., 2010), economic impacts to a subset of counties in the region (Johnson, 2009), other geographic regions of the Texas Plains (Wheeler, 2008), and water buyout proposals (Wheeler, 2008). The introduction of geospatial data in Wang (2012) removed the assumption that saturated thickness, or water availability, is constant in any given county or area. Wang’s model covered agriculture in three counties in the northern part of the aquifer. The counties studied were divided into five zones which represent alternative amounts of saturated thickness. This approach enhanced the modeling of water availability in any given area and produced a water depletion induced response in acreage and agricultural revenue. Wang (2012) also added climate change projections. This addition provided a range of responses that can help inform results and anticipate regional changes as a result of climate change.

Despite advances to the methodology and data included in regional hydrological and agricultural dynamic optimization models in the THP, the current models fail to encompass the entire agricultural region. Additionally, Wang's model ignores the important factor of initial depth to water. This study expands the modeling to include all 49 THP counties which rely on the Ogallala aquifer for irrigation water. Further, although Wang (2012) included climate change projections into the dynamic optimization model, she did not deal with adaptation—a key component to modeling future possible effects of climate change. Other studies using agricultural and regional models such as Butt et al. (2006) have shown that adaptation strategies can lessen the effects of climate change and thus alter final results under climate projections. Adding in adaptation scenarios into a model with climate change effects will provide a more comprehensive range of possible effects. Possible adaptation strategies can include changes to management techniques (Aisabokhae, McCarl, and Zhang, 2012), crop mix (Aisabokhae, McCarl, and Zhang, 2012), or varieties and other genetic modifications (Singh et al., 2014).

Methodology and Data

As introduced above, the model presented below relies heavily on previous work by Feng (1992), Arabiyat (1998), Terrell et al. (2002), Johnson (2003), Das et al. (2010), Wheeler (2008), and Wang (2012) with climate effects and adaptation approaches motivated by Reilly et al. (2003) and Butt et al. (2006). This work expands the analysis in the following ways:

1) The study area is expanded to include all 49 Texas counties that overlay the Ogallala aquifer which will capture the entire effect of declining water levels and the heterogenous responses across the region

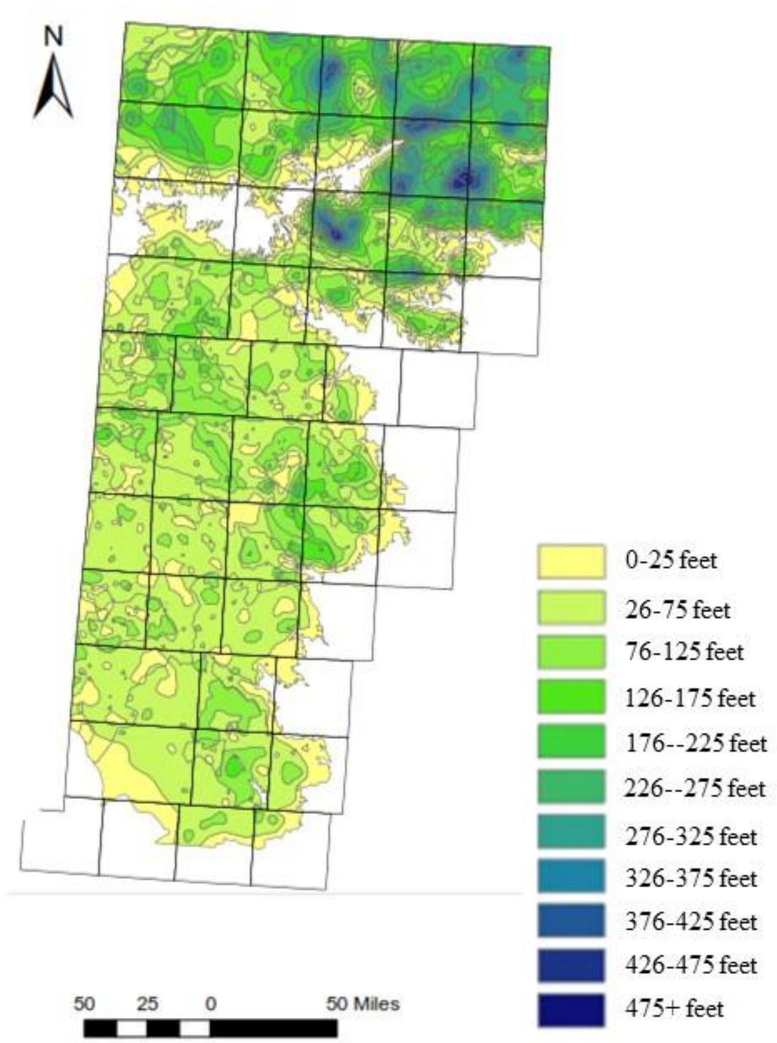
2) Increased characterization of aquifer by modeling zones based on saturated thickness and initial pumping lift
3) The addition of rangeland cattle production
4) Possible land use change between irrigated cropping, dryland cropping and rangeland
5) Climate change impacts on:
    i. Yields of corn, cotton, sorghum, and wheat under both irrigated and, where appropriate, dryland conditions.
    ii. Grassland production
    iii. Rangeland cattle production
6) Adaptation scenarios

Hydrology of Ogallala aquifer

The Ogallala aquifer has been and is well studied. The United States Geological Survey (USGS) maintains geospatial data on characteristics of the aquifer including saturated thickness and specific yield. Using that geospatial data initial water availability can be estimated. To specify the water data within the model, the study area is classified into zones based on the water availability as defined as initial saturated thickness and estimated lift. Pumping lift was calculated based on 2013 monitoring well depths drawn from the Nebraska Water Science Center. Depth to water from individual wells were interpolated over the entire study region to form a continuous ArcGIS layer that estimated pumping lift across the study area. A 2009 USGS study to measure saturated thickness across the study region was also used.

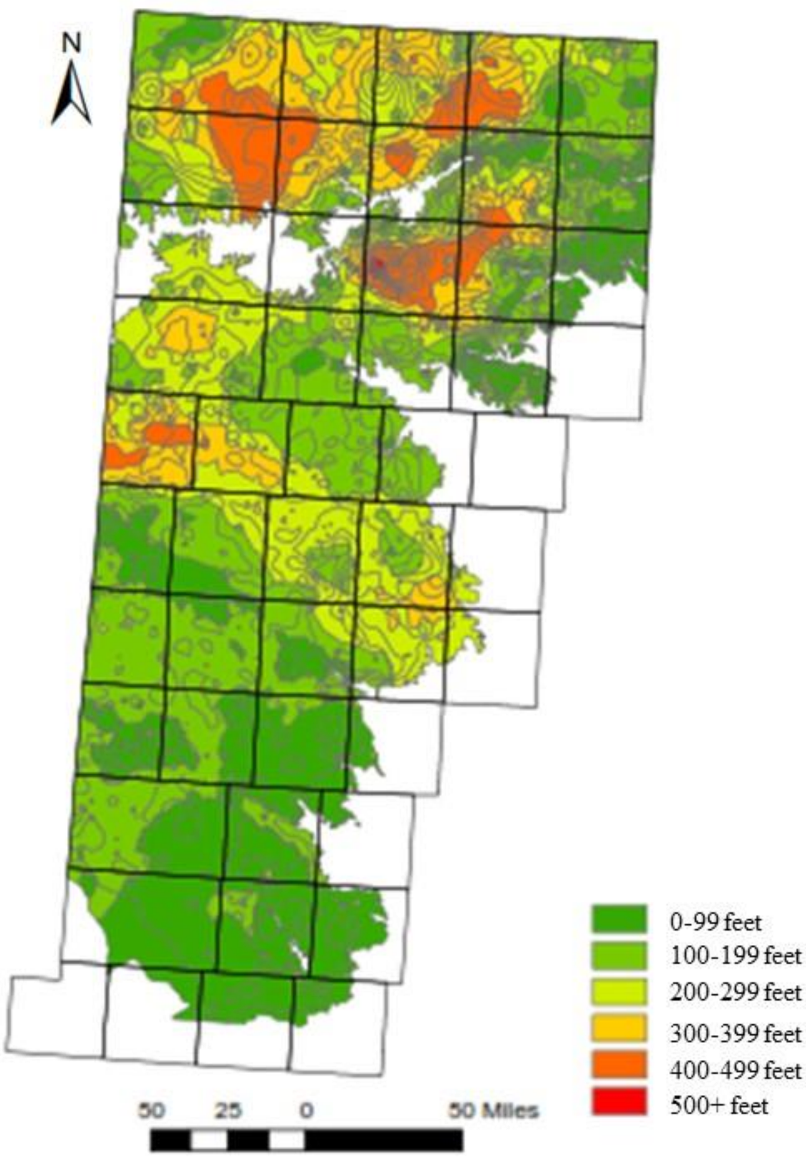
Within the study area, the range of saturated thickness was divided into 11 intervals each being a 50-foot range with the exception of the first zone which is 0-25 feet and the last zone which is 475 feet or more (Figure 3.1).

Figure 3.1: Estimated saturated thickness in the Texas High Plains in 2009.



The study area was further classified into 6 pumping lift zones broken up into 100-foot intervals from 0-600 feet (Figure 3.2).

Figure 3.2: Estimated pumping lift in the Texas High Plains in 2013.



Combining the saturated thickness and pumping lift zones yields 66 combinations of saturated thickness and pumping lift possibilities. Counties are defined by the number of acres within each zone. Each combined saturated thickness and lift zone generalizes water availability and cost of pumping. Within each county the number of acres having a specific range of saturated thickness and lift that falls into the ranges defining the zone are entered into the model. Zones are further grouped for result reporting into combinations of low (0-125), medium (126-325), and high (326+) saturated thickness and low (0-199), medium (200-399), and high (400+) lift. Thus 9 generalizations are created to generalize results: low lift/low saturated thickness (LLLS), low lift/medium saturated thickness (LLMS), low lift/ high saturated thickness (LLHS), medium lift/low saturated thickness (MLLS), medium lift/medium saturated thickness (MLMS), medium lift/high saturated thickness (MLHS), high lift/low saturated thickness (HLLS), high lift/medium saturated thickness (HLMS), and high lift/high saturated thickness (HLHS).

Land use and total area

Geospatial data from USDA was used to determine the total area of each county and the area in agricultural production. Yearly land use data is available from USDA National Agricultural Statistics Service (NASS). Land use data was used to determine the crop and related agricultural acreage in each county. Acreage by county was classified as in production for: corn, cotton, sorghum, wheat, and grassland (rangeland). Land use can also be associated with hydrologic zones to determine available water for each agricultural acre currently in production. This forms the baseline information for where agriculture is occurring and so that agriculture can be linked with available water resources.

Pumping cost equation

The majority of the equations for calculating pumping cost are taken from Guerrero et al. (2010), Amosson et al. (2011) and personal correspondence with Dr. Steven Amosson. Pumping cost for an acre-inch of water is calculated as a function of pumping lift. This involves calculating the amount of natural gas required to lift one acre-inch of water from a given depth. Intuitively, as water is used, saturated thickness drops, pumping lift increases, and the cost of pumping increases. The following equation for total head is used:

$$Total\ head\ (H_T) = PL + \left(\frac{2.31\ ft}{psi} * OP\right) \tag{3.1}$$

Where

PL pumping lift in feet

psi pounds per square inch

OP operating pressure of the system and assumed to be a weighted average based on available system reported PSI and frequency of use. Weighted average used: 16.85.

Table 3.1: Irrigation systems used and associated psi to be used to construct weighted-average.

System Type	Percent	PSI
Center Pivot-LESA	56	15
Center Pivot-LEPA	23	15
Center Pivot-MESA	19	25
Furrow	1	10
SDI	1	15

Source: correspondence with Dr. Steven Amosson.

Total head is then used to compute horsepower as:

$$Horsepower\ (HP) = \frac{GPM * H_T}{3960 * E_p * E_{GH}} \tag{3.2}$$

Where:

GPM gallons per minute, assumed to be 600 for the system

E_p pump efficiency, assumed to be 60%

E_{GH} gearhead efficiency assumed to be 95%

The final formula for pumping cost as a function of lift is given by:

$$\frac{Mcf}{Acre - Inch} = \frac{GPM * PL + \left(\frac{2.31\,ft}{psi} * OP\right)}{3960 * E_p * E_{GH}} * \frac{2545\ BTU}{HP - HR} * \frac{Mcf}{1{,}000{,}000\ BTU} * \frac{1}{E_E} * \frac{450}{GPM} \tag{3.3}$$

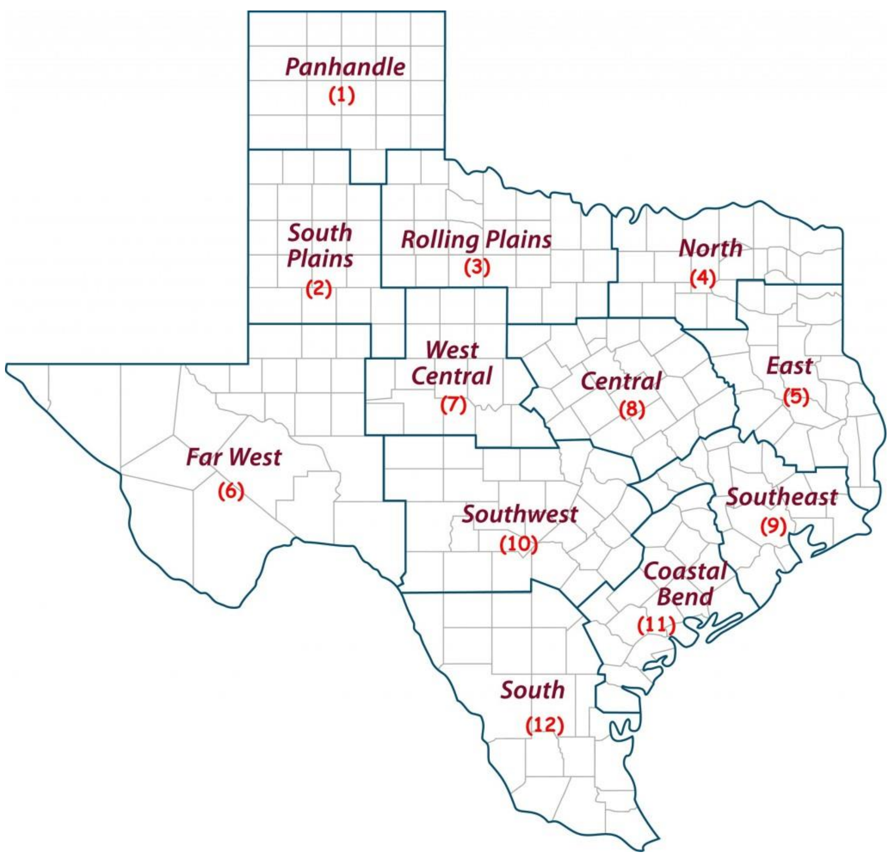
Where:

E_E engine efficiency, assumed to be 21%

Cost of production

Production costs were gathered from the Texas A&M AgriLife Extension website for wheat, sorghum, cotton, and corn in crop reporting districts 1, 2, 3, 6 (Figure 3.3).

Figure 3.3: Texas A&M Agrilife Extension Districts.



Source: Texas A&M Agrilife Extension (2012).

Separate budgets were used for dryland versus irrigated production. To account for costs in rangeland cattle production, district-specific cow-calf budgets were used. Budgets include both fixed and variable costs of production including: seed, labor, machinery depreciation, rent and lease fees, fuel costs, and irrigation cost.

Yields and Rangeland Cattle Productivity

There are two components to the yield and rangeland cattle productivity data. The first component is the current crop yield, irrigation water use and rangeland cattle production under current climate conditions. This forms the current baseline. Yield and water use information are gathered from USDA Quickstats and Texas A&M Agrilife Extension budgets for the current period.

The second component of this data is yield, water use and cattle productivity data gathered from other studies. Crop yields and water use was modeled using DSSAT (Hoogenboom et al., 2017) at 3 locations in the study region by Texas A&M student Kritika Kothari under representative concentration pathways (RCP) 4.5 and 8.5 using average climate change estimates from 9 climate models: BCC-CSM1.1, CCSM4, CNRM-CM5.1, CSIRO-MK3.6, GFDL-ESM2M, IPSL-CM5A-LR, MIROC5, MRI-CGCM3, NorESM1-M. Yield and water use is modeled on the county level. Thus, data from the closest DSSAT location was used. Data for the cattle productivity and stocking rates were simulated by current Texas A&M student Paul Goetze under RCP 4.5 and 8.5 using results drawn across an average of the same 9 climate models. Results from the separate cattle model are reported on a county-level. Crop yield, irrigation water use, rangeland net primary production, and stocking rates are altered to account for future climate change effects.

Scenarios

A total of 15 scenarios were constructed to show a range of possible future conditions and account for possible adaptations. One scenario (base) starts from and maintains conditions as they existed in 2016. Two scenarios (RCP4.5, RCP 8.5) are built to reflect the response of crop yields, rangeland productivity, and rangeland cattle stocking rates to two climate scenarios. RCP 4.5 assumed stabilization of radiative forcing at 4.5 W/m2 at 2100 and RCP 8.5 allows for growth of radiative forcing without any special mitigation effort reaching 8.5 W/m2 in 2100 (IPCC summary for policymakers). Each RCP describes a future emission scenario. RCP 4.5 assumes emissions peak close to 2050 and then declining emissions. RCP 8.5 assumes emissions do not peak and continue to grow past 2100 (IPCC summary for policymakers). Thus, the scenarios RCP 4.5 and RCP 8.5 reflect two bounds of possible responses to climate change.

Six adaptation scenarios were constructed to estimate potential responses of crop varieties to climate change. Each adaptation scenario was modeled under RCP 4.5 and RCP 8.5 These were drawn from Kothari et al. (unpublished). Table 3.2 describes each scenario.

Table 3.2: scenario descriptions and associated abbreviation used in this analysis.

Scenario	Abbreviation	Description
Base	Base	No additional climate change effects
RCP 4.5	RCP 4.5	Assumes climate effects according to RCP4.5

Table 3.2 Continued

Scenario	Abbreviation	Description
RCP 8.5	RCP 8.5	Assumes climate effects according to RCP 8.5
Heat Tolerant under RCP 4.5	H4	Increases temperature that crop fails and optimum temperature for important stages of growth.
Heat Tolerant under RCP 8.5	H8	Increases temperature that crop fails and optimum temperature for important stages of growth.
Drought Tolerant under RCP 4.5	D4	Root density and soil water availability were improved to make crops more drought tolerant
Drought Tolerant under RCP 8.5	D8	Root density and soil water availability were improved to make crops more drought tolerant
Drought and Heat Tolerant under RCP 4.5	DH4	Individual drought tolerant and heat tolerant changes were combined
Drought and Heat Tolerant under RCP 8.5	DH8	Individual drought tolerant and heat tolerant changes were combined
High Yield under RCP 4.5	HY4	Alterations were made to grain attributes so that yield was improved
High Yield under RCP 8.5	HY8	Alterations were made to grain attributes so that yield was improved
Long Maturity under RCP 4.5	L4	Length of the growing season was increased
Long Maturity under RCP 8.5	L8	Length of the growing season was increased
Short Maturity under RCP 4.5	S4	Length of growing season was decreased
Short Maturity under RCP 8.5	S8	Length of growing season was decreased

Historic Data

Historic crop data on acres harvested for each crop and yields at a county level were gathered from USDA Quickstats and Texas A&M Agrilife Extension Crop Budgets. Those data are used to implement the historic crop mix approach for aggregation presented in McCarl (1982). Using this approach, it is assumed that each producer is profit maximizing and that observed historic crop mixes represent the extreme points of production in each year. With this, we then require that the current crop mix is a convex combination of the historic crop mixes observed. This ensures that the feasible set is based on past observations at least in the recent future to represent the many resource, machinery, rotation, and other considerations involved with switching crops. Later, after 2060, we allow the model to select crops and production practices outside of historic observations. If included in the possible choice set for the model, production practices or crops not observed historically can be in the final solution (Adams et al., 2005).

Mathematical Representation of the High Plains Simulation (HPSIM) Model

The HPSIM model is programmed as a multi-period nonlinear programming problem. The model assumes that farmers maximize the net present value of profit over the duration of the model. The specification expands on the model of Wang (2012). The objective function for a single county is:

Maximize $NPV = \sum_{t=1}^{T}(1+r)^{-(t-1)}\,\pi_t$ (3.4)

Where:

$$\pi_t = \Sigma_z \Sigma_i \, \Sigma_l [ACR_{zilt} * (P_{it}\, Y_{ilt} - C_{zilt})] + \Sigma_z [PASTLAND_{zt} * (B_t - D_t)] \quad (3.5)$$

Defined as:

NPV	net present value of profit,
r	discount rate,

π_t net return at time t, defined as the difference between total revenue and total cost in time t,

P_{it} price of crop i at time t,

Y_{ilt} yield of crop i on land using water application type l in time t,

ACR_{zilt} acreage in zone z of crop i on land using water application type l in time t,

C_{zilt} variable and fixed cost of production in zone z of crop i on land using water application type l in time t,

$PASTLAND_{zt}$ acreage of pasture land devoted to cattle in zone z and time t,

B_t benefits accruing to rangeland cattle production as given by price of cattle multiplied by stocking rate in time t,

D_t cost accruing to rangeland cattle production as given by cost per acre of rangeland cattle in time t,

z subscript denoting saturated thickness zone,

i subscript denoting crop,

l subscript denoting land water application type (dryland or irrigated),

t subscript denoting time running from 1 to a fixed time horizon.

In addition to the pumping cost formula, lift as a function of water use is given by the following formula:

$$LIFT_{zt} = LIFT_{z0} + \frac{\left(Recharge_{zt} + \left(\sum_i WATUSE_{zt} * ACR_{zilt}\right)\right)}{AREA_{zilt} * Yield_z} \quad \text{for all z and t} \tag{3.6}$$

$LIFTz_0$ Initial Lift for each zone,

$WATUSE_{izt}$ Total water used for crop i by zone and time period,

$AREA_z$ Total land available in zone z,

$Yield_z$ Specific yield of water in zone z which gives the amount of water available based on saturated thickness in that zone,

$Recharge_z$ recharge from precipitation in that zone,

A constraint is imposed to represent crop yield as a function of water use:

$$Y_{ilt} = f(WATUSE_{izt}) \tag{3.7}$$

The amount of water pumped is a function of the water used per acre multiplied by the acreage in each county and zone. Total water pumped is constrained by the availability in any zone so that water use is constrained:

$$\Sigma_{it} WATUSE_{izt} \leq TOTWATR_{z0} \tag{3.8}$$

where:

$TOTWATR_{z0}$ total water available in a given zone at the start of the model

As described above, historic crop mix constraints are imposed to constrain current crop mix choices to historic observed crop mixes to impose realistic solutions. Following McCarl (1982) and Onal and McCarl (1989) deviations from historic crop mixes are allowed over the time horizon of the model. The crop mix equation is given as:

$$ACR_{zilt} = \Sigma_j CROPMIX_{zljt} * histcrop_{zilj} \tag{3.9}$$

where:

$CROPMIX_{zljt}$ amount of land placed under historic crop mix constraint for a given zone, land water application type, historic crop mix, and time, with constraint relaxing over time,

$histcrop_{zilj}$ proportion of crop in cropmix for a zone, crop, land water application type, and historic crop mix,

j subscript indicating historic crop mix.

Finally, a land constraint is imposed.

$$\sum_{il} ACR_{zilt} + PASTLAND_{zt} \leq AREA_z \quad \text{for all z and t} \qquad (3.10)$$

Results

From 2016-2080, land in the THP moves from irrigated to dryland agricultural production including dryland cropping and rangeland. Saturated thickness in the Ogallala aquifer declines as water is used to produce crops. Differences exist in agricultural output among districts. Comparison across the scenarios shows the impact of climate change and adaptation on agricultural output and a wide range of possible responses depending on the future extent of climate change or response of crops.

Converted Land

Under scenarios without adaptation, land is converted from irrigated to dryland agriculture as water levels decline (Table 3.3). In the base scenario, more land is converted in the beginning of the study period with more acreage converted in District 2 than District 1. Under the climate scenarios, more land is converted under RCP 8.5 than under RCP 4.5 or the base scenario; however, differences exist among the districts. In District 2, more land is converted under the base and RCP 4.5 than under RCP 8.5 over the study period. Although the total amount converted is relatively constant across all three scenarios, the amount of land converted in District 2 is more than double the amount of land converted in the other districts. In District 6, more land is converted under the base than RCP 8.5 and the least is converted under RCP 8.5. More land is converted in zones with less saturated thickness as water levels decline.

Table 3.3: Converted land in the Texas High Plains from irrigated to dry cropland and rangeland cattle production at from 2016-2030, 2016-2050, and 2016-2080 under the base, RCP 4.5 and RCP 8.5 scenarios (in 1000 acres).

Scenario	District	2016- 2030	2016- 2050	2016- 2080
Base	D1	299	944	1,236
	D2	1,717	2,655	2,725
	D6	14	23	38
	Total	2,030	3,622	3,999
RCP 8.5	D1	580	1,097	1,321
	D2	1,713	2,654	2,725
	D3D6	14	23	38
	Total	2,306	3,773	4,084
RCP 4.5	D1	540	1,078	1,291
	D2	1,425	2,499	2,634
	D6	14	22	38
	Total	1,978	3,599	3,962

In District 1, 27% more land is converted to dryland under RCP 8.5 than the base scenario. In fact, over the entire study period more land is converted under RCP 8.5 than the other scenarios. Weather in RCP 8.5 is hotter and drier than RCP 4.5 or the base. Thus, land conversion is greater under RCP 8.5 as crops demand more water and crop yields change more dramatically compared to current conditions.

Land conversion is expected to occur at different time horizons across scenarios and districts. Under the base, less land is converted by 2030 than under RCP 8.5 but more than under RCP 4.5. Under the base scenario, in District 1 most land is converted in 2030-2050 as opposed to the other two time periods. Conversely in District 2, more land is converted from present day to 2030. Initially, less water is available for use in District 2 causing more land to be converted earlier in the study period. In District 1, which starts out with more water available, these changes happen later under the base scenario. Under all the climate change scenarios, the amount of acreage using irrigation declines. Under RCP 4.5 and 8.5, the combined effects of climate change and declining aquifer levels are shown with more total land converted over the study period.

Comparing land conversion across scenarios shows that more land is converted under the adaptation scenarios than the base, RCP 4.5 or RCP 8.5 (Table 3.4). In general, more land is converted under adaption scenarios which assume a climate of RCP 8.5 than those with the climate of RCP 4.5. The scenarios that convert the most land are: D8, DH8, H8, L8, S8. Adaptation scenarios increase crop yields making the dryland crops more profitable than under the scenarios without adaptation which in turn stimulates the land conversion.

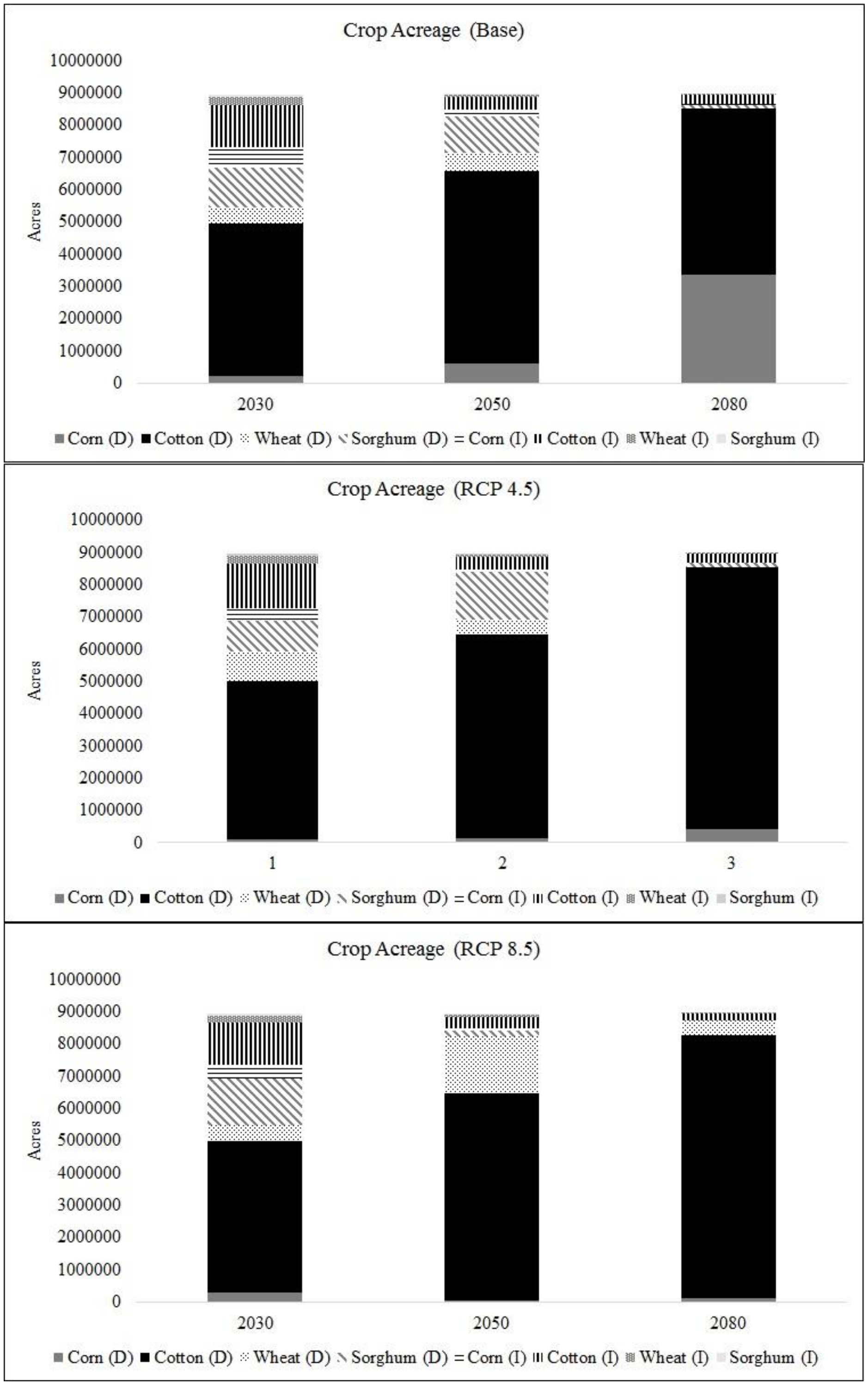
Table 3.4: Converted land in the Texas High Plains from irrigated to dry cropland and rangeland cattle production at from 2016-2030, 2016-2050, and 2016-2080 under all scenarios.

	2016-2030	2016-2050	2016-2080
base	2,029,665	3,621,547	3,999,422
D4	2,290,464	3,879,189	4,126,267
D8	2,297,063	4,177,440	4,306,096
DH4	2,194,427	3,806,872	4,079,637
DH8	2,241,457	3,883,631	4,305,994
RCP 8.5	2,306,113	3,773,490	4,084,010
RCP 4.5	1,978,469	3,598,936	3,961,782
H4	2,154,236	3,806,476	4,076,011
H8	2,249,301	3,895,521	4,305,994
HY4	2,278,565	3,847,144	4,092,545
HY8	2,272,335	4,107,850	4,306,096
L4	2,171,675	3,773,990	4,086,192
L8	2,349,267	4,102,649	4,301,944
S4	2,305,305	3,882,267	4,145,776
S8	2,325,877	4,269,529	4,306,096

Cropping

Crop mixes are expected to change over the study period as water levels decline and crop yields change due to future climate. While the total number of crop acres remains relatively constant, crop mix varies across scenarios and districts (Figure 3.4). In all scenarios, dryland acreage increases over time and in most scenarios, dryland cotton is the most prevalent crop at 2030, 2050, and 2080. In the base scenario at 2030, all crops and production practices are still utilized but most irrigated acreage has shifted to cotton. A large number of acres has moved to dryland cotton, irrigated cotton, and dryland sorghum. By 2050, dryland cotton acreage has increased, irrigated cotton acreage has decreased, dryland sorghum and dryland wheat acreage has remained constant, and dryland corn acreage has increased. By 2080, almost all cropland acreage is dryland cotton, dryland corn, and some irrigated cotton remains. Declining aquifer levels and relative yields currently observed motivate expected shifts in relative crop acreage.

Figure 3.4: Estimated crop acreage and production type in the Texas High Plains at 2030, 2050, and 2080 under the base, RCP 4.5 and RCP 8.5 scenarios.

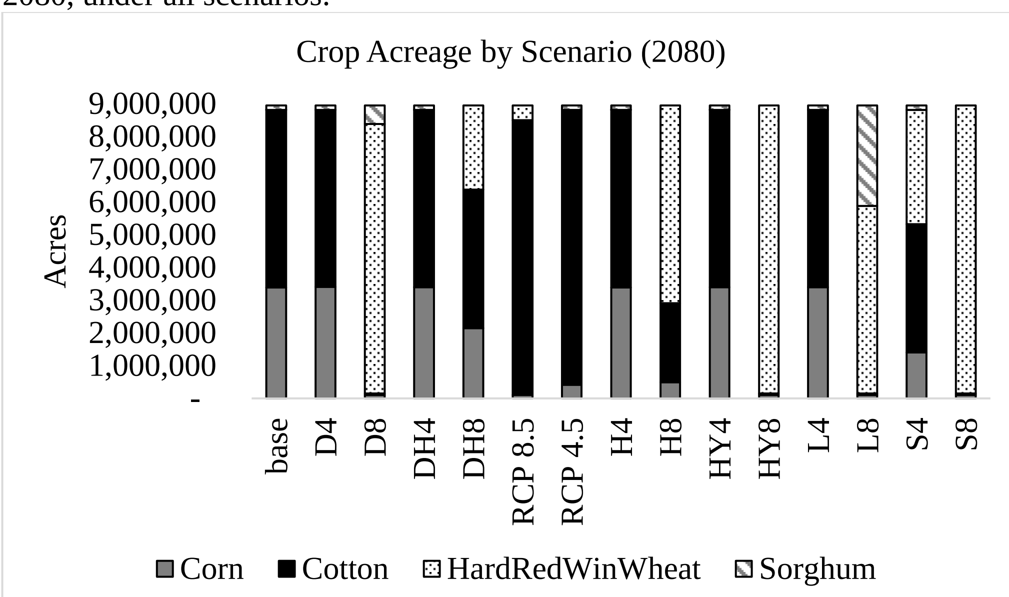


In the RCP 4.5 and 8.5 scenarios, declining water levels as well as yield responses due to climate change are reflected in the crops planted. Similar to the base scenario, under RCP 4.5 at 2030, all crops and production practices are still present although dryland cotton dominates. Dryland wheat and irrigated corn are planted in greater acres than under the other scenarios at 2030. By 2050 under RCP 4.5, along with dryland cotton, dryland sorghum is predicted as well as smaller proportions of less water intensive crops including irrigated cotton and dryland wheat. By 2080, almost all crop acreage is expected to be dryland cotton although some irrigated cotton and dryland sorghum acreage remains. Compared to RCP 4.5, under RCP 8.5 at 2030, along with dryland cotton, dryland sorghum and irrigated cotton are the most common crops. By 2050, other crops and water intensive production practices become less common with most acreage in dryland cotton and dryland wheat although some irrigated cotton and dryland sorghum remains. By 2080, almost all acreage is dryland cotton with some dryland wheat and irrigated cotton remaining.

Differences in crop mix among scenarios can be explained by climate change effects whereas changes from irrigated to dryland production are largely driven by declining aquifer levels. Although dryland cotton is prevalent across the base, RCP 4.5 and RCP 8.5, differences in other crops (dryland wheat versus dryland sorghum) can be explained by relative yield responses to climatic conditions. Further, while irrigation water declines rapidly in District 2 forcing most acreage to dryland cotton early in the study, increased water availability in District 1 allows for variability in the crops planted and production practices.

Yield responses to adaptation vary widely by crop (Figure 3.5). In most scenarios, cotton (dryland) remains the most prevalent crop at 2080; however, when adaptations are included, other crops dominate. This is largely due to underlying crop simulation model results. In the adaptation scenarios that assume a climate of RCP 8.5, wheat acreage increases. Conversely, if a climate of RCP 4.5 is assumed, cotton and corn yields are likely to increase relative to other crops and thus acreage will be greater. Similar to the scenarios without adaptation, crop choice varies by district and time. Across all scenarios, District 1 maintains a more diverse crop mix longer than District 2 due to increased water availability.

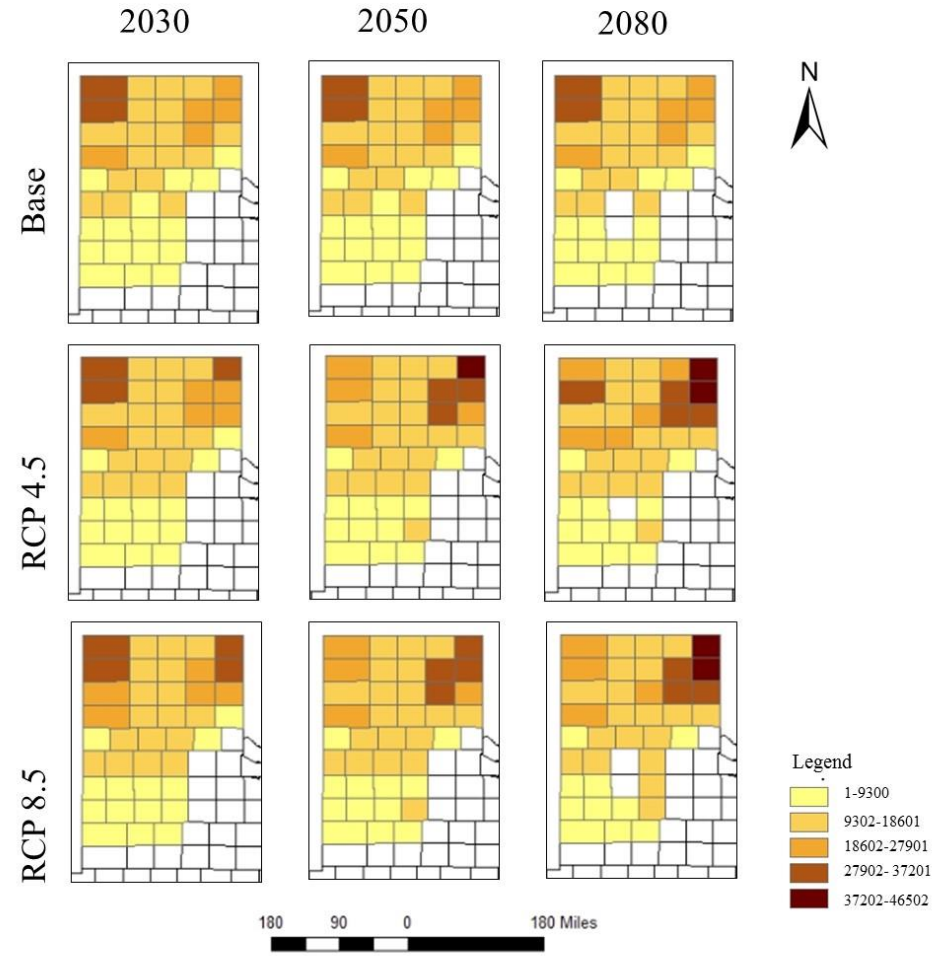
Figure 3.5: Estimated crop acreage and production type in the Texas High Plains at 2080, under all scenarios.



Cattle Production

Productivity of rangeland grasses are expected to be altered due to climate change and impact stocking rates. Due to declining aquifer levels restricting irrigated crop production, rangeland acreage expanded as did the number of cattle produced over the study period under all three scenarios (Figure 3.6). Fewer cattle are expected under the base compared to RCP 4.5 and RCP 8.5 or the adaptation scenarios. Cattle production is expected to be greater in the northern counties of the study region at 2080 under the base scenario with Dallam, Hartley, Hemphill, Lipscomb, and Roberts counties producing the most cattle. Under RCP 4.5 and RCP 8.5, production switches to the northeast region at the end of 2080 to favor Liscomb, Hemphill, Roberts, Gray, and Wheeler counties. Cattle production is driven by grassland availability and cattle returns relative to other crops. Hotter and drier conditions under RCP 8.5 limit rangeland grass and cattle production whereas in RCP 4.5 conditions are more favorable.

Figure 3.6: Estimated cattle in the Texas High Plains as land transitions from irrigated and dryland cropping to rangeland production at 2030, 2050, and 2080 under the base, RCP 4.5 and RCP 8.5 scenarios.



Similar to the base and RCP 4.5 and RCP 8.5, under the adaptation scenarios, more cattle are expected to be produced at the end of the study period as more land switches from irrigated to dryland agricultural production (Table 3.5). There is little difference in the total number of cattle under the adaptation scenarios at 2030, 2050, or 2080; however, differences in exist between the number of cattle predicted under RCP 4.5 compared to RCP 8.5. At 2050, scenarios that assume a climate of RCP 4.5 predict more cattle than scenarios that assume a climate of RCP 8.5. Compared to the climate change scenarios without adaptation, by 2080, scenarios with adaptation predict more cattle in production under an RCP 8.5 climate than an RCP 4.5 climate. This is likely explained by dryland production practices performing relatively better than irrigated due to imposed adaptations. Similar to scenarios RCP 4.5 and RCP 8.5, more cattle are expected in the northern study area (District 1), than the southern (District 2) although there is more variation in expected cattle production among adaptation scenarios in District 2 than District 1.

Table 3.5: Estimated cattle in the Texas High Plains as land transitions from irrigated and dryland cropping to rangeland production at 2030, 2050, and 2080 under the all scenarios.

	2030	2050	2080
base	483,498	483,498	469,370
D4	520,168	557,844	622,777
D8	535,635	560,145	603,389
DH4	520,168	557,844	622,777
DH8	535,635	560,145	587,832
RCP 8.5	535,635	560,145	587,832
RCP 4.5	520,168	557,844	617,105
H4	520,168	557,844	622,777
H8	535,635	560,145	594,329
HY4	520,168	557,844	622,777
HY8	535,635	560,145	603,389
L4	520,168	557,844	622,777

Table 3.5 Continued

	2030	2050	2080
L8	535,635	560,145	603,389
S4	520,168	557,844	622,777
S8	535,635	560,145	603,389

Income

Agricultural income is expected to change over the study period with the greatest income expected under the base scenario (Table 3.6). Income is expected to increase over the study period under the base and RCP 4.5 scenarios but decline under RCP 8.5. At 2030, income is greatest under the base but lowest under RCP 4.5. At 2050, income is greater under RCP 4.5 compared to the base or RCP 8.5 but by 2080, income is again highest under the base scenario. Income on a district level changes based on the scenario and study year. In District 1, income is lower at 2050 than at 2080 for all scenarios. Income is always higher in District 2 compared to District 1 but these differences are largely due to existing agricultural land.

Table 3.6: Yearly agricultural income from irrigated and dryland crops, and rangeland in the Texas High Plains at 2030, 2050, and 2080 under the base, RCP 4.5 and RCP 8.5 scenarios (in $1000).

		2030	2050	2080
Base	D1	$ 804,621	$ 964,919	$ 1,279,217
	D2	$ 2,034,573	$ 1,928,086	$ 1,970,143
	D3	$ 44,732	$ 44,578	$ 44,577
	D6	$ 231,601	$ 229,319	$ 225,600
	Total	$ 3,115,527	$ 3,166,902	$ 3,519,536
RCP 4.5	D1	$ 772,477	$ 1,079,461	$ 1,204,717
	D2	$ 1,575,459	$ 1,876,934	$ 2,040,153
	D3	$ 31,270	$ 46,467	$ 49,359
	D6	$ 174,442	$ 203,240	$ 205,507

Table 3.6 Continued

		2030	2050	2080
	Total	$ 2,553,647	$ 3,206,103	$ 3,499,736
RCP 8.5	D1	$ 883,274	$ 763,875	$ 907,631
	D2	$ 1,927,383	$ 1,425,716	$ 1,108,920
	D3	$ 39,911	$ 33,364	$ 26,974
	D6	$ 221,600	$ 170,501	$ 115,333
	Total	$ 3,072,167	$ 2,393,456	$ 2,158,858

Over the study period, most income is generated without the use of water or in the surface zone (Table 3.7). Little difference exists between income generated between the base, RCP 4.5 and RCP 8.5 scenarios. Most of the expected differences in income generated between zones can be attributed to existing agricultural land use; however, income generated from areas of low saturated thickness falls substantially between 2030 and 2080. Income generated in the base is lower at 2050 compared to 2030 except for the low lift/high saturated thickness and high lift/high saturated thickness. Under RCP 4.5, a similar pattern is present. Conversely, under RCP 8.5, all hydrologic zones are predicted to have a lower income at 2050 than 2030.

Table 3.7: Yearly agricultural income from irrigated and dryland crops, and rangeland in the Texas High Plains at 2030, 2050, and 2080 by hydrologic zone under the base, RCP 4.5 and RCP 8.5 scenarios (in $1000).

	base			RCP 4.5			RCP 8.5		
	2030	2050	2080	2030	2050	2080	2030	2050	2080
lhs[1]	601	795	1,002	798	1,047	,239	818	692	416
hlls	1,922	652	167	2,159	748	51	2,184	545	271
hlms	1,853	1,545	2,049	2,259	1,648	1,778	2,220	1,165	686
llhs	93	113	127	71	36	40	51	21	26

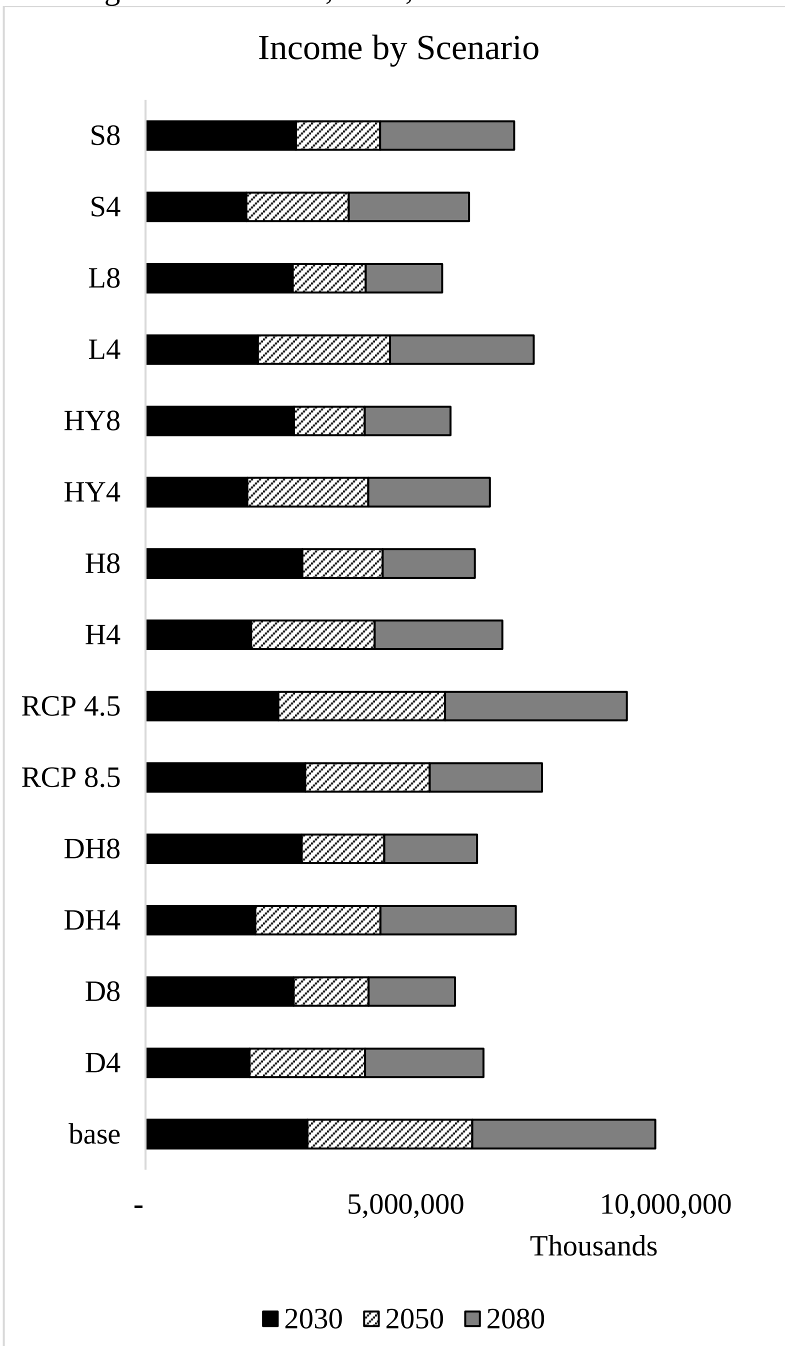
Table 3.7 Continued

	base			RCP 4.5			RCP 8.5		
	2030	2050	2080	2030	2050	2080	2030	2050	2080
llls	8,949	2,111	664	8,501	1,959	662	8,590	1,710	466
llms	1,452	739	625	1,337	465	334	1,337	410	243
mlhs	383	282	1,192	195	361	952	180	89	146
mlls	6,996	622	222	6,827	602	308	7,218	465	137
mlms	4,059	2,575	2,645	3,254	2,286	2,483	3,246	1,391	1,109
surface	49,484	62,598	71,665	38,904	64,153	11,736	49,488	47,755	44,579

[1] Aquifer zones characterized by low lift/low saturated thickness (LL/LS), low lift/medium saturated thickness (LL/MS), and medium lift/medium saturated thickness (ML/MS).

Analysis of agricultural income across all scenarios shows mixed results with no adaptation strategy consistently projecting a higher income across the entire study period and assumed climate conditions (Figure 3.7). The base and RCP 4.5 show higher levels of projected income in 2050 and 2080. Generally, expected incomes are higher when climate conditions of RCP 4.5 are assumed compared to 8.5 for each adaptation scenario.

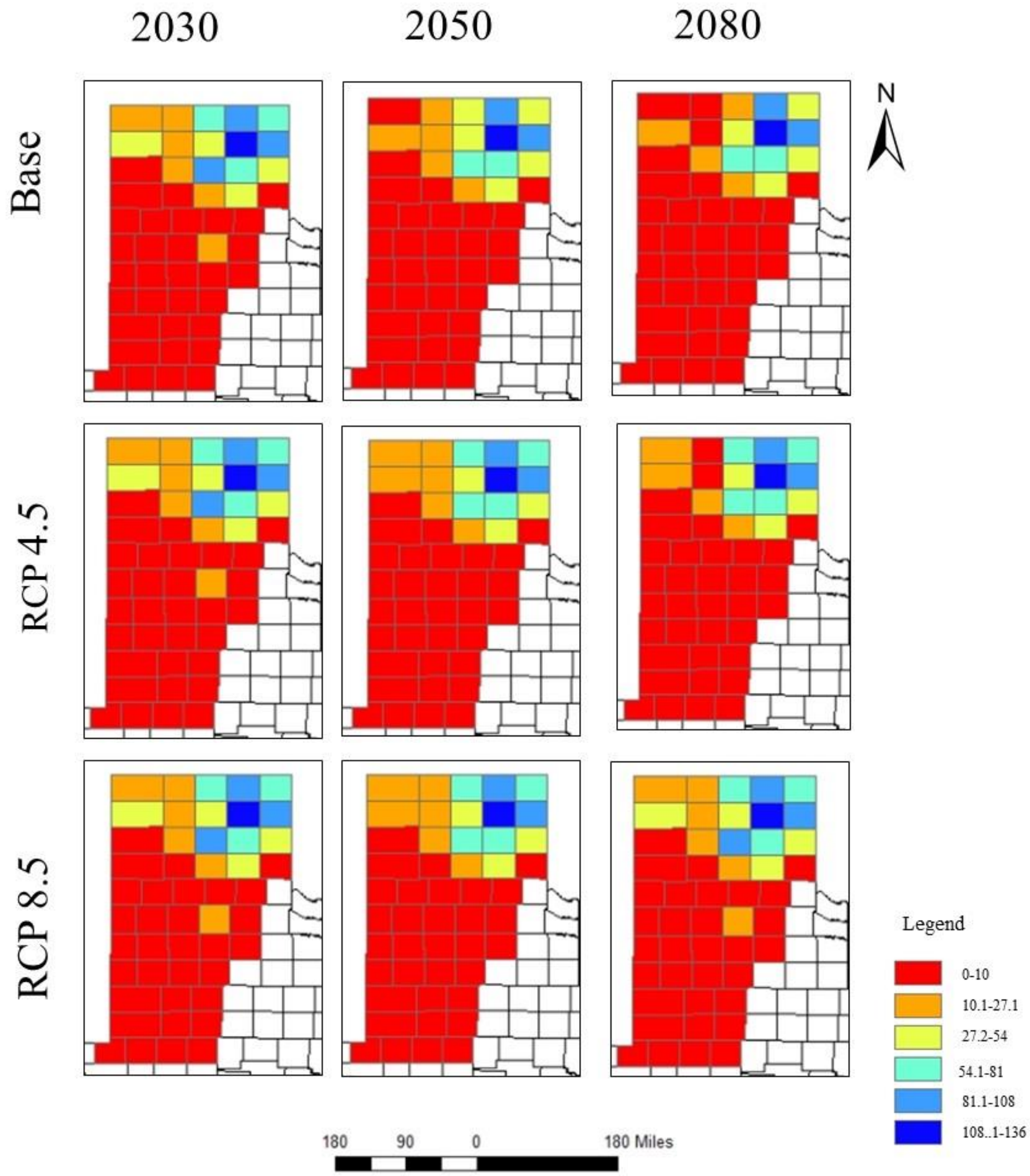
Figure 3.7: Yearly agricultural income from irrigated and dryland crops, and rangeland in the Texas High Plains at 2030, 2050, and 2080 under all scenarios.



Hydrology

In response to agricultural activity, saturated thickness declines (Figure 3.8) and pumping lift increases over the study period. Average saturated thickness by county falls across all scenarios but shows little variation across scenarios. At 2030, there was a maximum difference of 5 feet of saturated thickness among scenarios. More water is expected to be pumped under the base and RCP 4.5 compared to RCP 8.5. Through 2080, more water is used under the base compared to RCP 8.5. Counties in the northern part of the study region used more water and retained greater saturated thickness throughout the study period. This can largely be explained by greater water at the start of the study. Conversely, saturated thickness is expected to decline 87% or more in each zone in District 2.

Figure 3.8: Average saturated thickness in the Ogallala aquifer by county in the Texas High Plains in 2030, 2050, and 2080 under the base, RCP 4.5 and RCP 8.5 scenarios.



Irrigation water demand lowers saturated thickness and increases pumping lift which impacts water irrigation costs. While saturated thickness and pumping lift are inversely related, due to existing agricultural land distribution, some trends develop with respect to the aquifer zones that experience the greatest changes to saturated thickness and pumping lift. In District 1, more water is available at the start of the study as demonstrated by a greater number of zones observed. This leads to more water used in District 1 and greater increases in pumping lift compared to the other districts.

Water use does not vary greatly among scenarios until later in the study period (Table 3.8). More water is used in the base than in the other scenarios. Average saturated thickness across all scenarios is relatively consistent through 2050. DH8 is an exception and uses less water by 2030 and 2050 compared to other scenarios. At 2080, more water is conserved if climate conditions are assumed follow RCP 8.5 with the most water remaining in the aquifer under S8, L8, HY8, and D8. This is due to dryland crop yields performing favorably compared to their irrigated counterparts. Similar to previous comparisons across districts, more water remains in District 1 compared to District 2. In all scenarios, average saturated thickness across District 2 falls over 90% by 2050 compared to 18-25% declines in District 1 in the same time period.

Table 3.8: Average saturated thickness in the Ogallala aquifer by county in the Texas High Plains in 2030, 2050, and 2080 under all scenarios.

	2016	2030	2050	2080
base	24.840	20.073	16.479	14.250
D4	24.840	20.296	17.611	15.981
D8	24.840	20.318	17.699	17.506
DH4	24.840	20.219	17.184	15.335
DH8	25.354	20.631	17.556	16.321
RCP 8.5	24.840	20.332	17.478	15.649
RCP 4.5	24.840	20.274	17.338	15.405
H4	24.840	20.212	17.156	15.288
H8	24.840	20.213	17.193	15.996
HY4	24.840	20.283	17.493	15.785
HY8	24.840	20.275	17.546	17.299

Table 3.8 Continued

	2016	2030	2050	2080
L4	24.840	20.203	17.188	15.342
L8	24.840	20.337	17.734	17.483
S4	24.840	20.315	17.683	16.147
S8	24.840	20.298	17.783	17.694

The marginal value of an inch of water declines over the study period (Table 3.9). There is no difference in the shadow price of water across scenarios. Shadow prices for low lift/low saturated thickness are slightly higher in District 2 after 2030 compared to the other districts across all years of the study period. Relatively less water and greater agricultural acreage at the start of the model generates a higher shadow price for District 2. Overall, high shadow prices for water can be seen in District 1 across all three zone types (low lift/low saturated thickness, low lift/medium saturated thickness, and medium lift/medium saturated thickness) with the highest price corresponding to medium lift, medium saturated thickness.

Table 3.9: Shadow price of water under the base, RCP 4.5 and 8.5 scenarios at 2016, 2030, 2050, and 2080 by hydrologic zone.

		2016			2030			2050			2080		
	District	llls[1]	llms	mlms	llls	llms	mlms	llls	llms	mlms	llls	llms	mlms
base	D1	12.781	12.781	19.733	3.400	3.392	5.21	0.513	0.51	0.777	0.03	0.03	0.045
	D2	12.781			4.281			0.644			0.037		
	D6	1.566			0.412			0.061			0.004		
RCP 4.5	D1	12.781	12.781	19.733	3.400	3.392	5.21	0.513	0.51	0.777	0.03	0.03	0.045
	D2	12.781			4.281			0.644			0.037		
	D6	1.566			0.412			0.061			0.004		
RCP 8.5	D1	12.781	12.781	19.733	3.400	3.392	5.21	0.513	0.51	0.777	0.03	0.03	0.045
	D2	12.781			4.281			0.644			0.037		
	D6	1.566			0.412			0.061			0.004		

[1] Aquifer zones characterized by low lift/low saturated thickness (LL/LS), low lift/medium saturated thickness (LL/MS), and medium lift/medium saturated thickness (ML/MS).

Conclusions and Future Work

Since the 1960s, there have been substantial concerns about the future of irrigation from the Ogallala aquifer. This has stimulated a number of researchers to study potential future agricultural activity based on the known levels of water remaining and the likely rate of depletion. Here, we extend that work to consider the whole region, heterogeneous characteristics in terms of pumping lift and saturated thickness, the dynamic evolution of the aquifer over the next 60 or so years, and the complicating effects of climate change as well as possible climate change adaptation responses.

Our study leads to a number of findings. First, under the business-as-usual case without climate change, we find that inevitably declining aquifer levels will cause agriculture to move from irrigated cropland to dryland production and into grazing base land uses. We also initially find a range of crop mix and irrigation strategy responses with lower water using crops employed along with deficit irrigation. We find that over time, agricultural incomes decline.

When we factor in the effects of climate change in the form of higher temperatures and lower precipitation, we find this stimulates an increase in crop water needs. In turn, we find that the climate change effect increases the rate at which the aquifer water levels decline. However, we find this effect can be offset for crops by the use of adaptation scenarios like drought tolerance and heat tolerance, and changing maturity dates. This finding is consistent with the evidence reported by Hornbeck and Keskin (2014) who found that producers employed drought resistant agricultural strategies in counties with similar characteristics but limited water access and geographic proximity to those over the Ogallala developed drought resistant agriculture. They also found that those counties possessed a less productive agriculture and a lower valued agricultural economy.

Future work on the issue would do well to include a wider variety of dryland production and rangeland grass/cattle adaptations. In the current specification, rangeland cattle adaptations like species shifts as found important and Zhang et al. (2013) were not considered. Further analysis could also consider the northern migration of crop mixes as found important in Fei, McCarl and Thayer (2017) and Aisabokhae, McCarl and Zhang (2012). Finally, aquifer depletion concern induced limits to pumping as suggested by Amosson et al. (2009) would slow aquifer depletion and change model outcomes.

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CHAPTER IV

TEXAS HIGH PLAINS REGIONAL ECONOIMC EFFECTS OF CLIMATE CHANGE AND DECLINING OGALLALA AQUIFER LEVELS

Introduction

Water is a valuable input to agricultural production. Irrigated cropland yield and profit generally surpasses its dryland counterpart. Through irrigation technology, farmers are usually able to provide adequate moisture throughout the growing season when yearly rainfall falls below plant requirements. This, in turn, removes some of the risk related to weather conditions.

Since the end of the Dust Bowl, agriculture has relied on irrigation in arid areas. Today, over 50% of the irrigated acres in the United States (US) in the arid regions within the states of Nebraska, California, Arkansas, Texas, and Idaho (Irrigation and Water Use, 2018). The source of the water for this irrigation varies greatly among states with some utilizing surface water (Idaho, Arkansas) but others relying on groundwater, some of which is depleting. Large areas in Texas and Nebraska pump water from the depletable Ogallala aquifer. In the Texas High Plains (THP) irrigation supports the production of corn, cotton, wheat, and sorghum. The resultant irrigated yields and consequent levels of regional agricultural production are higher than are those in other areas of the state. It was estimated that in 2012, the value of production for all crops produced in the region totaled over $1.6 billion (Amosson et al., 2012).

Despite increasing irrigation efficiency, water withdrawals from the Ogallala aquifer in Texas are unsustainable since current and anticipated pumping rates are well in excess of levels of recharge. It was estimated that 13.2 million acre-feet of water disappeared from the Ogallala aquifer in Texas from 2011-2013 with water levels dropping on average 41.2 feet from 1950-2013 and 3.5 feet from 2011-2013 (McGuire, 2014). Although declining water levels increases irrigation pumping costs, in many areas of the Ogallala aquifer, eventual depletion of the water remains likely. Declining aquifer levels and increasing irrigation costs are expected to cause land-use conversions from irrigated to dryland production. That case is anticipated to arise across much of the THP region (Colaizzi et al., 2009).

In addition to declining water availability, climate change is anticipated contribute to the issue by increasing temperature, decreasing precipitation and more frequent extreme events lowering yields, thereby raising per acre crop water demands, and stimulating faster aquifer depletion (What Climate Change Means for Texas, 2016). This suggests that regional agricultural production is uncertain as agricultural productivity it is likely to decline (McCarl et al., 2016). Therefore, as local climate conditions change over the coming decades, regional agricultural production is expected to fall. An indicator for the magnitude of such effects can be seen from production observations under the 2011 drought which caused an estimated $7.62 million in total agricultural losses across the state (Guerrero, 2011).

The regional THP economy is to a large extent driven by the health of the agricultural production sector (Terrell, Johnson, and Segarra, 2002). Future changes to agricultural output due to diminished yields, increasing pumping costs and land conversion from irrigated to dryland practices are expected. This work investigates the future impact of climate change and aquifer depletion induced alterations in future agricultural output as it affects the regional THP economy. This will be done using the results from the previous essay regarding both outcomes under business-as-usual and outcomes under different degrees of climate change. In particular, using input-output analysis and region-specific cost coefficients, this work projects potential regional economic impacts due to changing agricultural output due to alterations in crop mix, reductions in yields, increases in pumping cost and land use changes to dryland cropping and grazing lands. Results on the regional future economic impacts are likely to be useful to regional planners to help anticipate changes to the regional economy.

Literature Review

Water scarcity and the movement or transfer of water between users and time horizons has regional economic impacts (Terrell, Johnson, and Segarra, 2002). Previous research shows that as water becomes scarce--supply and availability are altered (Leones et al., 1997; Hornbeck and Keskin, 2015) --shifts in production and economic activity are expected. Due to heterogeneous soil and water characteristics, even if overall, economic surplus or benefits remain constant, some users benefit from scarcity while others lose (Howe, Lazo and Weber, 1990). When considering the potential economic impact of changes to water use, the influence of the regional economy's structure cannot be ignored (Howitt et al., 2015).

Changes to water use in terms of quantity and location can be spurred by market creation, administrative, governmental policies, changes in supply, depletion and shifting climates. In such cases, there is growing concern that declining water use for agricultural production will have a negative impact on the rural agricultural economy and future food security (Howe and Goemans, 2003; Rosegrant and Ringler, 2000). Parallels exist between loss of water due to economic markets and loss of water due to physical resource constraints. If it is assumed that water is used by the most productive users and users who sell their rights would be compensated, overall economic benefits could be expected (McMahon and Smith, 2013). However, under most case studies, the effects of water rights transfers from agricultural use to other user groups leads to losses to rural and agricultural users (Howe, Lazo and Weber, 1990). Secondary impacts as a result of efficiency gains or additional protections for specific groups (agriculture) remain in discussion as water use patterns shift (Meinzen-Dick and Ringler, 2008; Livingston, 1995; McCarl et al., 1999).

Within Texas specifically, a number of studies attempt to show the regional impacts of changing water use in agricultural production using IMPLAN. Whited (2010) shows the potential impacts of the transition from irrigated to dryland agriculture for Uvalde County, Texas. This analysis suggest substantial regional impacts as irrigated agriculture disappears from production including the loss of 750 jobs and $34 million from agricultural inputs (Whited, 2010). Using a similar approach, Dudensing (2017) estimates the impacts of water market trading in Burleson and Hale Counties, Texas. Under these scenarios, water market trading is shown to benefit agricultural water lease holders through transfer payments but the overall impact to the regional economy is negative and exceeds any benefits from the lease or sale payments. This suggests that in these communities, declining agricultural production is harmful for the regional economy (Dudensing, 2017). These findings are echoed by Terrell, Johnson, and Segarra (2002) who use output from a regional agricultural model to predict future cropland changes as a result of declining aquifer levels in the southern high plains (SHP) and link this to a regional economic impact analysis. They find that as agricultural land shifts to dryland cotton production, the regional economic activity from agriculture declines.

While useful to show the importance of water use for the regional economy, these studies were done on a small geographic scale which may not capture the full effects of the output changes. In addition to water use and depletion, climate change is an important driver of future agricultural production and was ignored in the above referenced studies. Modeling future climate impacts on agricultural production is difficult as effects vary by crop, region, and climate model (Chen, McCarl and Thayer, 2017). Further, many studies utilize a mathematical programming or econometric approach to analyze impacts which assumes factor substitution over time which differs greatly from the Leontief isoquant, static outlook imposed through IMPLAN. Studies on the response of crops to warmer, drier, and more varied climate conditions suggest that crop mix will shifts towards more heat tolerant cotton, rice, sorghum, and winter wheat when conditions are drier (Cho and McCarl, 2017). Further, in crop studies regional crop yields are expected to suffer in areas with projected drier and warmer climates (Adams et al., 1990; Reilly et al., 2002). These studies estimate the direct impacts of climate change on agricultural output and do not consider the broader regional effects. Once these effects are included through an IMPLAN analysis the effects of climate change on the regional economy are expected to be larger than previously estimated. The proposed analysis will provide a regional analysis that extends the expected economic impacts beyond agricultural output to show the potential effects on the regional economy.

Conceptual Framework

This work that will be reported on in this essay is based on input-output (I-O) analysis as described in the early 20th century by Leonteif (1936) and is an effort to show the movement and impact of spending throughout an economy. A number of variants of the basic techniques have been developed including expansions to include multiple regions, environmental issues such as pollution (Leontief, 1970) and specific sectors to show the economic impact of shifts in agricultural products such as livestock (Goldmsith and Wang, 2011). Specific to this research, a number of studies have used I-O modeling to show the impact of changing irrigated acreage or practices on a regional economy (Guerrero et al., 2010). Following Dudensing (2017) and Guerrero et al., (2010), the I-O framework used herein seeks to identify the value of water and current climate in agricultural production.

Similar to Dudensing (2017), we assume that agricultural producers are profit maximizing agents. Water and climate are inputs to agricultural production following the theory in Heady and Dillon (1972):

$$Y = f(X_L, X_K, X_{T,} \dots X_{m,}, \ X_{climate}, X_{water}) \quad (4.1)$$

Under this specification, Y is an agricultural output and $X_L, X_K, X_T \dots X_m$ are inputs such as labor, capital, land, fertilizer, etc., $X_{climate}$ are local climate conditions and X_{water} is the input of water. Farmers are maximizing profits according to:

$$Max \ \prod = \ YP_Y - \ w_m X_m \quad (4.2)$$

Whereby $\prod$ is farm profits arising from production of Y using inputs X_m where P_Y is the price of the output and w_m the costs of inputs. Profit is assumed to be greater if farmers in a given county have access to the input X_{water} and change based on optimal climate conditions.

Fundamentally, I-O analyses utilize a regional specific transaction table, technical coefficients and multipliers. Notation and theoretical background are based on Miernyk (1965) and (Shaffer, 1999). The transaction table describes the regional economy and the usage of factors of production from other sectors (j) when producing in a specific sector (i). Technical coefficients giving the amount of factor i used when producing one unit of output j (a_{ij}) can be derived from the transaction table by dividing through by total output. Using the technical coefficients from the transaction table, a final formula which relates total output to final demand and technical coefficients develops to form the multiplier matrix or the Leontief inverse ($(I - A)^{-1}$) and show the output as a function of final demand.

$$X = (I - A)^{-1} Y \qquad (4.3)$$

Using this formula, analysis can show the expected changes to the regional economy as a function of changes to final demand. The multiplier approach and I-O analysis establishes three classifications for expected impacts: direct, indirect, and induced. The total impact of the economy to a change in final demand can be shown by adding these separate components. Direct effects are the immediate change to the industry. In I-O analysis, direct effects are the effect of changing agricultural output as a result of changes to changing crop production practices and yields. Indirect effects are impacts to related industries (agricultural inputs and other related industries). Induced effects represent the next level of impacts as a result of the direct and indirect effects. Induced effects can be thought of as the third-level impacts that happen as a result of the direct and induced effects that are not captured directly by observing those changes but are the result of changed behavior and spending patterns. The three types of effects demonstrate the incidence of direct, intermediate and induced impacts on output among sectors and how much changes in output affect the regional economy. The magnitude and effected sectors at each of the effect levels can be traced back using the transaction tables and technical coefficients.

Methodology and Data

Regional Economic Modeling Approach

IMPLAN is the IO tool that will be used to assess the regional economic effects of future changes to agricultural output (IMPLAN, 2014). Reductions to agricultural production as a result of less irrigation water and shifts to production practices that require fewer inputs are expected to be reflected in lower total economic activity. In particular, acreage shifts from irrigated to dryland are expected to require fewer inputs, produce less output, and subsequently lower product sales. The effect can be large as Texas A&M Agrilife Extension crop budgets for cotton in 2016 in the study area shows dryland revenue of $254.82/acre and variable cost of $289.14/acre as compared to $909.84/acre and $760.98 for irrigated cotton. In addition, irrigated production practices include water pumping, additional labor and energy inputs, additional fertilizer, and more of other variable and fixed compared to likely dryland replacements which could impact the regional economy.

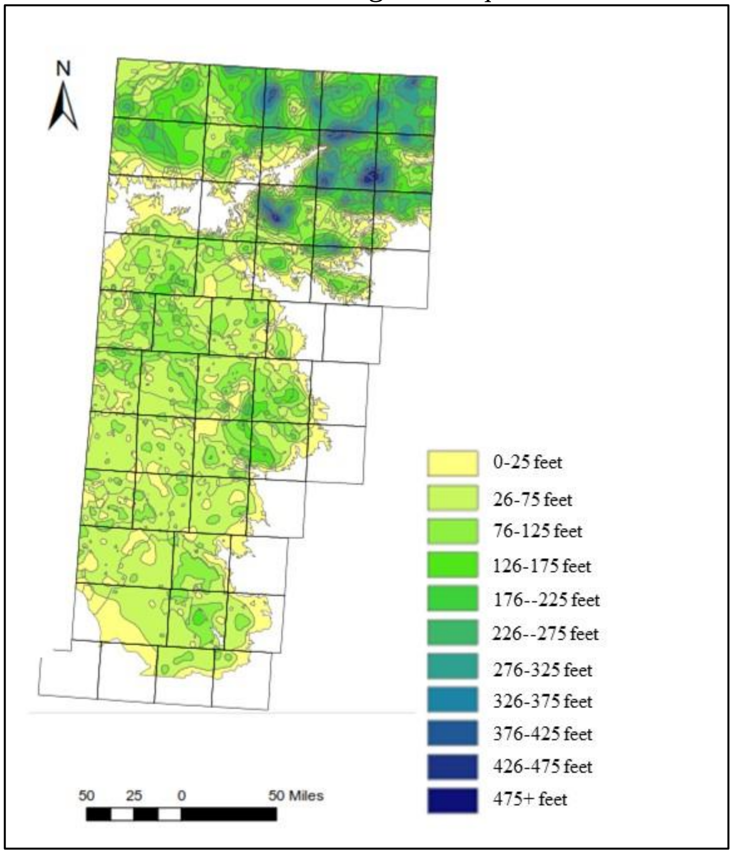
In order to accurately reflect the effect of changing crop mix and yields on the regional economy, IMPLAN coefficients were altered based on differences between crops chosen by the model in the previous essay. The changes were developed based on region specific crop budgets from Texas A&M Agrilife Extension (Texas A&M Agrlife Extension, 2016). This approach deviates from the analysis-by-parts (Whited, 2010) and follows Dudensing and Falconer (2009) and Dudensing, Robinson, and Hanselka (2016). By altering IMPLAN coefficients to reflect a regional production function for each crop and production practice, estimates of the effect will deviate from IMPLAN generated production functions and consequently better reflect production practices in this region of Texas. Altering IMPLAN coefficients also relaxes the Leonteif isoquants assumption. In this approach, the per-acre-expenditures were converted to per-sales-dollar expenditures for the value-added coefficients including employee compensation, proprietor's income, and other property income were altered as well as absorption coefficients for expenditures. Absorption coefficients dictate the distribution of expenditures by sector for a given activity. All crop budget categories were successfully matched to IMPLAN sectors. In order to complete this transformation, value-added coefficients were first modified and the IMPLAN model run to reflect changes. Then, industry coefficients were altered based on extension budget data and all coefficients were re-balanced to reflect these changes. This allowed the model to reflect the regional coefficients and take advantage of IMPLAN's default industry coefficients that are not captured in the more simplified crop budget.

In total, eight different IMPLAN models were specified: cotton irrigated, cotton dryland, corn irrigated, corn dryland, wheat irrigated, wheat dryland, sorghum irrigated, and sorghum dryland. These four crops, specified under irrigated and dryland production practices, were selected due to their current prevalence in the region and are expected to remain dominant crops under future growing and market conditions.

Study Region

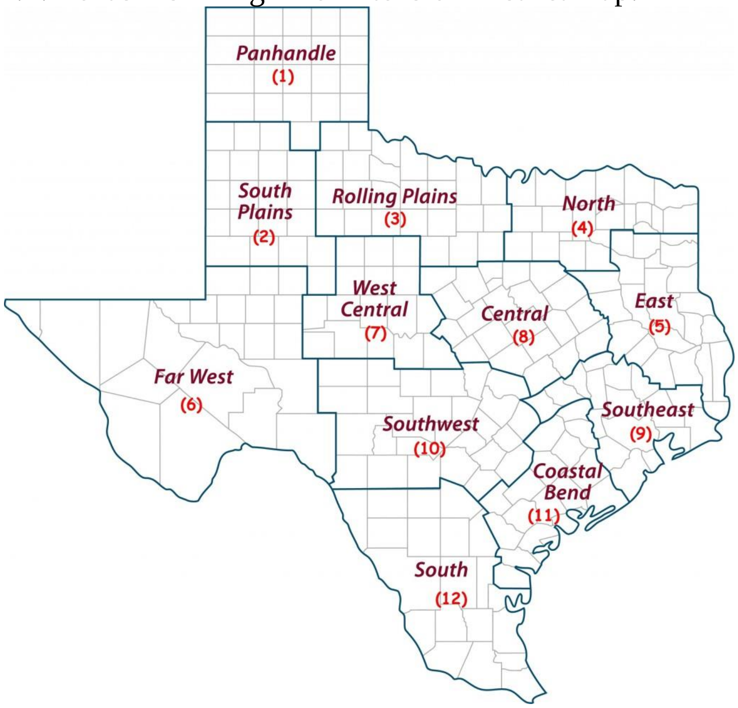
For the purposes of the regional agricultural model (described in Chapter 3), the study region encompasses the entire 49-county region over the Ogallala aquifer in Texas (Figure 4.1).

Figure 4.1: Saturated thickness of Ogallala aquifer in Texas.



However, for the purposes of this study, only the southern portion of the Ogallala aquifer which is defined as Texas A&M Agrilife Extension District 2 (Figure 4.2) will be included in the IMPLAN analysis. The study region will be called the southern high plains (SHP). District 2, or the south plains district, includes 20 counties and the city of Lubbock.

Figure 4.2: Texas A&M Agrilife Extension District map.



Model Input and Regional Agricultural Model

A dynamic nonlinear program was used to estimate the expected future changes to agricultural production under decreasing water availability and climate change effects. In the model, regional agricultural profits are maximized on a county-level through the production of irrigated or dryland corn, cotton, wheat, or sorghum. Rangeland cattle production are also possible production possibilities. The model is constrained by land and water availability. Crop yields are a function of water use and climate change effects. Pumping cost to irrigate increases as aquifer levels decline. Production costs for each crop are based on current crop budget estimates from Texas A&M Agrilife Extension. The model maximizes agricultural profit over all 49 counties over the

Ogallala aquifer from 2016-2080. Only the results from 2030 and 2050 will be used in this analysis. More information can be found in Chapter 3 of this dissertation.

Using the model above, two climate scenarios and a baseline case are analyzed. The baseline assumes that current climate is preserved into the future. The two climate scenarios represent different radiative forcing levels and subsequently two trajectories for climate variability (IPCC for Policy Makers). Climate in Extension District 2 under RCP 4.5 scenario is expected to be moderately warmer and drier with average precipitation levels decreasing 2 inches each year and average temperature increasing 5 degrees compared to climate from 1950-2015. A similar trend is observed under RCP 8.5 with climate for Extension District 2 expected to be warmer and drier with average precipitation levels decreasing 2 inches each year and average temperature increasing 7 degrees compared to climate from 1950-2015. The range of climate scenarios creates a range of expected responses from agricultural output that will inform subsequent regional economic activity.

Results from the regional agricultural model are used to forecast agricultural output. Crop yields are represented for the base, RCP 4.5 and RCP 8.5 scenarios at 2016, 2030, and 2050. Crop yields are multiplied by 2016 crop prices from the Texas A&M Agrilife Extension crop budgets to generate agricultural income at each study year and scenario. A table of crop income by year and scenario is below (Table 4.1). Revenue from crops is expected to be lower under RCP 4.5 and RCP 8.5 compared to the base at 2016, 2030, and 2050. At 2030, income is higher under RCP 8.5 compared to RCP 4.5 while the opposite is expected at 2050. Cotton becomes more prevalent under all scenarios as it responds positively to CO_2 and the climate shifts. Under RCP 4.5, acreage is anticipated to move into dryland sorghum while under RCP 8.5, dryland wheat is expected. Expected income from agricultural crops listed below are used to construct events in IMPLAN to evaluate regional income.

Table 4.1: Expected income from agricultural crops for 2016, 2030, and 2050 under the base, RCP 4.5 and RCP 8.5 scenarios (in $1000).

		Base		
		2016	**2030**	**2050**
Dry	Corn	60,933	151,803	337,328
	Cotton	1,543,162	2,658,415	3,260,905
	Wheat	23,166	46,887	34,221
	Sorghum	70,797	109,362	80,815
Irrigated	Corn	166,965	65,154	1,403
	Cotton	4,091,019	1,514,366	123,415
	Wheat	36,569	14,851	660
	Sorghum	31,559	10,4267	89
Total		6,024,169	4,571,265	3,838,837
		RCP 4.5		
		2016	**2030**	**2050**
Dry	Corn	60,933	29,002	28,176
	Cotton	1,543,162	2,293,058	3,505,909
	Wheat	23,166	153,801	37,847
	Sorghum	70,797	9,593	81,944
Irrigated	Corn	166,931	50,110	1,130
	Cotton	4,091,019	1,552,641	122,345
	Wheat	36,411	19,303	666
	Sorghum	31,563	8,401	86
Total		6,023,981	4,115,909	3,778,104
		RCP 8.5		
		2016	**2030**	**2050**
Dry	Corn	60,933	174,594	13,632
	Cotton	1,543,162	2,509,819	3,013,551
	Wheat	23,166	45,375	140,521
	Sorghum	70,797	113,593	8,584
Irrigated	Corn	166,965	54,453	963
	Cotton	4,091,019	1,535,771	121,822
	Wheat	36,537	16,639	664

Table 4.1 Continued

		RRP 8.5		
		2016	2030	2050
	Sorghum	31,553	9,349	82
Total		6,024,131	4,459,593	3,299,819

Data Analysis

As land is converted from irrigated to dryland, income to producers is expected to decline as yields are smaller under dryland production and the total regional economic effects decrease (Table 4.2). Analysis of output, value-added, and employment across the direct, indirect, and induced effects shows that the economic impact of crop production in the SHP declining from 2016-2050 under all three scenarios. This can be seen in the total effect of agricultural crop production output estimated at $11,694,495 (in $1000, 2018 dollars) compared to $8,914,464,170 at 2030 and $7,448,018 at 2050. Expected declines to output, value-added and employment can be attributed to converting land from irrigated to dryland production.

Table 4.2: Total economic impact of expected agricultural production in the Texas southern high plains under decreased water availability and climate change.

Output (in $1000)					
Year	**Scenario**	**Direct Effect**	**Indirect Effect**	**Induced Effect**	**Total Effect**
2016	Base	6,103,399	4,203,593	1,387,502	11,694,495
2030	Base	4,631,387	3,214,800	1,068,277	8,914,464
	RCP 4.5	4,170,041	2,909,476	966,538	8,046,055
	RCP 8.5	4,518,245	3,128,588	1,040,388	8,687,221
2050	Base	3,865,183	2,688,022	894,813	7,448,018
	RCP 4.5	3,827,794	2,717,316	905,790	7,450,895

Table 4.2 Continued

Output (in $1000)					
Year	**Scenario**	**Direct Effect**	**Indirect Effect**	**Induced Effect**	**Total Effect**
	RCP 8.5	3,343,218	2,372,280	791,093	6,506,591
Value Added (in $1000)					
Year	**Scenario**	**Direct Effect**	**Indirect Effect**	**Induced Effect**	**Total Effect**
2016	Base	962,377	2,064,193	758,676	3,785,247
2030	Base	598,741	1,555,986	584,009	2,738,736
	RCP 4.5	545,984	1,409,612	528,404	2,484,001
	RCP 8.5	593,611	1,515,315	568,768	2,677,694
2050	Base	406,962	1,284,510	489,090	2,180,562
	RCP 4.5	367,646	1,298,003	495,087	2,160,737
	RCP 8.5	327,320	1,132,686	432,402	1,892,408
Employment					
Year	**Scenario**	**Direct Effect**	**Indirect Effect**	**Induced Effect**	**Total Effect**
2016	Base	26,307	32,353	10,557	69,216
2030	Base	19,694	25,197	8,118	53,010
	RCP 4.5	17,964	22,842	7,346	48,152
	RCP 8.5	19,147	24,481	7,907	51,535
2050	Base	16,117	21,303	6,793	44,213
	RCP 4.5	16,746	21,925	6,877	45,548
	RCP 8.5	14,538	19,083	6,006	39,627

As crop mix changes to better suit the regional climate conditions input usage patterns are altered, which impacts the regional economic indirect and induced effects from agricultural production. These changes can be seen in the differences between RCP

4.5 and RCP 8.5. For example, at 2030, expected total output induced is higher under RCP 8.5 ($8,687,221, 2018 dollars) compared to RCP 4.5 ($8,046,055, 2018 dollars). Conversely, at 2050, total output from crop production is expected to be higher under RCP 4.5 than RCP 8.5 indicating that the regional economic impacts from each scenario will change over time.

At 2050, agricultural induced income is expected to be greatest under the base scenario and then lower under RCP 4.5, with the smallest income under RCP 8.5. Conversely, the regional economic impact from indirect and induced effects is expected to be highest under RCP 4.5 and lower under the base scenario. Indirect and induced effects are still expected to be lowest at 2050 under RCP 8.5. The total effects are expected to be highest under RCP 4.5 for output, value-added, and employment. This can likely be explained by shifting crop mixes. Under the base scenario, dryland corn is prevalent while under RCP 4.5, cotton and sorghum acreage increases. These crops have different inputs to production that create more regional economic benefits despite lower agricultural income. This suggests that while total economic impacts are lower under the climate change scenarios, shifting crop mixes to cotton production may be more beneficial to the regional economic activity than shifts to other crops.

Compared to the base in 2016, total economic effect is expected to decline; however, the losses are not uniformly distributed across output, value-added, or employment. The total effect of value-added is expected to decline more than output or employment. For example, the total effect of output in 2050 under RCP 8.5 is expected to be 56% of the total effect for output under the base in 2016. Conversely, the total effect of value-added in 2050 under RCP 8.5 is expected to be 50% and employment is expected to be 57% compared to the base 2016. This indicates that while regional economic activity is expected to decline, losses to output and employment may not be as great in the value-added components of the economy.

Analysis of the impacted industries reveals similarities across output and value-added affected industries (Table 4.3 and Table 4.4). Generally, the most affected industries were consistent between output and value-added components of the economy except that petroleum refineries were affected by output and extraction of natural gas and crude petroleum and insurance carriers were affected by declines in value-added. Under both output and value-added, cotton farming and support activities for agriculture were most impacted. Other industries affected by declining output across all years and scenarios included: grain farming, insurance agencies, brokerage and related agencies, wholesale trade, maintenance and repair construction of nonresidential structures, and real estate. Similarly, lower contributions to the economy from value-added components is expected to affect: wholesale trade, insurance agencies, brokerages, and related activities, maintenance and repair construction of nonresidential structures, monetary authorities and depository credit intermediation, owner-occupied dwellings, real estate. Similarities can be seen across years and scenarios except that full-service restaurants and limited-service restaurants are expected to be affected under the base scenario in 2050.

Table 4.3: Output impacts for by top sectors affected by changes to agricultural output at 2016, 2030, and 2050 under the base, RCP 4.5 and RCP 8.5 scenarios (in $1000).

	2016	**2030**			**2050**		
Industry	**Base**	**Base**	**4.5**	**8.5**	**Base**	**4.5**	**8.5**
Commercial and industrial machinery and equipment repair and maintenance	13,712	15,009	8,978	15,847	19,631	4,994	5,199
Cotton farming	6,145,247	4,578,146	4,216,508	4,437,402	3,706,797	4,001,892	3,457,968
Electric power generation - Fossil fuel	9,955	3,853	3,320	3,424	94	82	74
Electric power transmission and distribution	278,568	103,553	104,534	103,763	6,395	7,770	7,718
Farm machinery and equipment manufacturing	155,237	118,135	105,434	115,819	99,013	93,157	82,343
Full-service restaurants					504		
Grain farming	406,736	416,104	283,337	432,433	477,538	155,302	172,659
Insurance agencies, brokerages, and related activities	398,329	375,615	336,572	363,113	360,599	370,454	325,125
Limited-service restaurants					778		
Local government electric utilities	9,536	3,690	3,180	3,280	90	78	71
Maintenance and repair construction of nonresidential structures	264,289	207,458	189,983	200,612	175,736	189,624	163,740
Monetary authorities and depository credit intermediation	160,573	134,233	118,536	131,400	124,268	116,845	102,255
Owner-occupied dwellings	180,939	141,335	127,987	137,820	117,412	121,554	106,160

Table 4.3 Continued

	2016	2030			2050		
Industry	**Base**	**Base**	**4.5**	**8.5**	**Base**	**4.5**	**8.5**
Petroleum refineries	50,686	88,225	74,494	84,392	106,740	109,583	95,296
Real estate	223,913	179,591	160,467	174,892	156,982	154,552	135,144
Support activities for agriculture and forestry	864,956	642,193	588,062	623,868	516,993	546,287	473,878
Wholesale trade	329,728	261,820	234,558	254,912	226,738	224,820	196,375

Table 4.4: Value-added impacts for by top sectors affected by changes to agricultural output at 2016, 2030, and 2050 under the base, RCP 4.5 and RCP 8.5 scenarios (in $1000).

	2016	**2030**			**2050**		
Industry	**Base**	**Base**	**4.5**	**8.5**	**Base**	**4.5**	**8.5**
Commercial and industrial machinery and equipment repair and maintenance	82,585	63,730	55,486	62,710	55,934	49,292	43,209
Cotton farming	949,809	551,874	524,316	541,810	332,430	360,401	313,052
Electric power generation - Fossil fuel	3,825	1,503	1,303	1,335	39	34	30
Electric power transmission and distribution	113,982	42,371	42,772	42,456	2,617	3,179	3,158
Extraction of natural gas and crude petroleum	16,417	28,222	24,597	26,760	33,028	36,351	31,680
Farm machinery and equipment manufacturing	2,590	4,202	2,827	4,494	5,649	2,040	2,300
Full-service restaurants					253		
Grain farming	80,519	90,201	62,153	94,400	105,142	37,220	40,992
Insurance agencies, brokerages, and related activities	149,518	142,172	127,500	137,549	137,271	141,026	123,771
Insurance carriers	485	1,208	231	1,389	2,684	224	108
Limited-service restaurants					433		
Local government electric utilities	2,375	927	713	775	20	16	14
Maintenance and repair construction of nonresidential structures	120,809	94,831	86,843	91,702	80,331	86,679	74,847

Table 4.4 Continued

	2016	2030			2050		
Industry	**Base**	**Base**	**4.5**	**8.5**	**Base**	**4.5**	**8.5**
Monetary authorities and depository credit intermediation	102,639	84,276	74,419	82,395	76,844	72,252	63,231
Owner-occupied dwellings	121,038	93,087	84,243	90,658	76,195	78,878	68,890
Real estate	128,736	103,254	92,258	100,552	90,255	88,858	77,699
Support activities for agriculture and forestry	658,377	488,817	447,614	474,868	393,518	415,816	360,700
Wholesale trade	216,388	171,822	153,931	167,289	148,799	147,541	128,873

Conclusion

Agriculture by its very nature has long adapted to local weather conditions and as continually adopted new innovations in production practices and crop/livestock varieties in an effort to further exploit the climate. Climate change and Ogallala aquifer depletion is expected to influence this dramatically reducing output while changing crop mix, land use and production practices in the THP. Decreasing agricultural output will not only impact agricultural producers but it will also have cascading impacts on the regional economy. The total value of economy, accounting for both the indirect and induced effects, will inevitably decline. Further, the assumed climate change scenario impacted results suggest that future climate developments could also negatively impact the THP agricultural economy.

These results suggest that aquifer depletion and climate change will jointly diminish the value of the regional agricultural economy. In particular our results show potential employment declines that amount to as much as 55% and potential losses of 40% within the revenues accruing to the farm machinery and equipment manufacturing industry.

Future work on this topic could address an expansion from the southern high plains only focus of this work this chapter to the full 49-county study area that is used in the second essay. Incorporating these additional counties would provide a more comprehensive overview of the expected impacts to the region. Finally, this analysis only includes economic impacts due to changes in crop production. Based on the results of Chapter 3 it is shown that rangeland cattle production is expected to increase. This gain in another sector of agricultural production should also be factored into the regional economic analysis. When included, total changes to agricultural production may not be severe as currently projected.

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CHAPTER V

CONCLUSIONS

This dissertation explores water issues in Texas in two domains: 1) the effects of water markets on agricultural producers and the supporting industries in the context of the Edwards Aquifer and 2) the effects of a declining aquifer in the context of the Texas High Plains (THP) with the complicating effects of climate change on agricultural production and the regional economy.

Across Texas, access to water resources has allowed communities to irrigate and in turn cultivate greater amounts of agricultural products and larger regional economies. As water demands other user groups have increased or as supplies have declined, alternative allocations and use patterns have evolved. Understanding the effects of such developments on agricultural output, producer income, and the regional economy is important and the essays composing this thesis address issues in that domain.

In Chapter 2, we examine the effects of a local water market that arose in the context of the Edwards aquifer on the associated on regional agricultural industry. Through an econometric analysis, we found that as the volume of water transfers in the water market increased, agricultural and related industry payroll declined. In terms of contribution, we believe this is the first study that to evaluate the regional agricultural industry effects in the context of the EA groundwater water market. The analysis also found that payroll of the oil industry, total regional payroll, and number of water market contracts were also important in explaining changes to agriculture and related industry payroll over time. Data availability prohibited a formal analysis of price effects within the water market and this would be a useful extension. Nevertheless, the finding on the negative effect of water market transfers on agriculture and related industry payroll suggests that in the interest of protecting regional vitality that perhaps it's appropriate to limit the extent of water trades as was done in the enabling legislation for the water market.

Analysis was also done in the context of the THP where we explored the effect of declining aquifer levels and climate change on future agricultural output, producer income, and the regional economy. Chapter 3 presents the results of a formal analysis on the future of THP irrigated agriculture in the face of a declining aquifer levels and climate change finding that the region inevitably will face the need to change crop mixes, adopt deficit irrigation practices, convert land from irrigation to dryland, and ultimately grassland grazing. In our climate change analysis, we found that climate change accelerates these developments but that adaptation like drought and heat resistant crop varieties lessened the extent of the decline.

In terms of contributions, compared to previous studies, this study was more regionally comprehensive. We included significantly more hydrological and agricultural land use change detail plus dealt with the emerging climate change issues in a fashion never before accomplished in that region. Geographically, the study encompassed all of the 49 counties in Texas that overlie the Ogallala aquifer. In terms of climate change, the study incorporated crop yield and stocking rate changes due to future climate change plus treated a number of possible adaptation scenarios. In terms of hydrological detail, it incorporated a much more comprehensive specification of the aquifer with the overlying land characterized by saturated thickness and depth to water. Finally, in terms of decision options, the model simultaneously included crop mix shifts to deficit irrigation, the discontinuation of irrigation with land moving to dryland cropping, and discontinuation of dryland crop production with land moving to cattle grazing.

To further extend the analysis in the THP, we show in Chapter 4 the potential future effects of changing agricultural output on the regional economy under the climate change scenarios addressed in chapter 3. Using input-output analysis, we project changes to total output, value-added, and employment. Findings show that climate change effects are likely to impact the regional economy and will have substantial impacts to many industry sectors.

Results from this dissertation could be used to: 1) assist in policy changes in the EA water market to maintain the agricultural industry or incentivize agricultural water rights holders to retain water rights, and 2) inform regional planning and producer decision making during the transition from irrigated to dryland agriculture in the THP.

Naturally this, like all studies, could be extended and as discussed in the individual chapters as important extensions would include adding price data to the water market study, adding more adaptation strategies and livestock species reactions to the High Plains aquifer study, and adding more analysis of the total economy to the effects of aquifer depletion on the regional economy study.