THREE ESSAYS ON FRESHWATER SUPPLY, FRACKING USE AND AGRICULTURAL TECHNOLOGICAL PROGRESS

A Dissertation

by

AURORA M VARGAS

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Chair of Committee,	Bruce A. McCarl
Committee Members,	Efstratios N. Pistikopoulos
	Anastasia Shcherbakova
	Ximing Wu
Head of Department,	Mark Waller

May 2020

Major Subject: Agricultural Economics

ABSTRACT

Water efficiency and a productive agriculture are key factors in our ability to meet future water and food demands under population growth and climate stressors. This study investigates freshwater supply, water use in hydraulic fracturing and forces driving agricultural technical progress.

The research involves three studies. In the first study, cost and GHG emissions estimates were constructed on a mobile solar powered nanofiltration unit designed to provide safe water to communities in South Texas. The second study looks at water usage and its cost in the Texas hydraulic fracturing industry along with cases where the cost of recycling produced water is competitive with the cost of traditional input water. In the final study, an analysis will be done on the effects of agricultural research funding and climate change on technical progress for US crop yields.

The major findings are as follows: 1) Within a case study in South Texas colonias, while tap water is the most cost efficient water delivery system, a mobile solar powered unit provides a next best, cost efficient alternative with low GHG emissions; 2) Water usage in the Texas Eagle Ford shale hydraulic fracturing industry is increasing and increasingly costly due to the transportation of the water; 3) Recycling and reusing produced water in hydraulic fracturing industry is cost competitive if raw freshwater needs to be transported more than 314 miles; 4) Total research and development funding increases crop yields for cotton and sorghum but in recent times at a decreasing rate; 5) Climate change, in the form of increased temperatures, appears to be diminishing yield

growth rates with decreased precipitation negatively effecting hay, sorghum, winter wheat and spring wheat. 6) Low temperatures have both a positive and negative effect on crops and high temperatures have consistently negative effects on all crop yields; 7) Agricultural funding of research and development and funding towards adaptation are key factors in adapting to climate change to compensate for decreasing crop yields and increasing global demand.

DEDICATION

I would like to dedicate this dissertation to my mother Maria Vargas who sacrificed so much, including her own doctoral degree, to push me and my sisters to work hard and be strong and independent women. I would also like to dedicate this work to my father Gabriel Vargas who worked without stop to ensure we had everything we needed to focus on our academic and career pursuits. I love you both very much. Thank you.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. McCarl, and my committee members, Dr. Pistikopoulos, Dr. Shcherbakova and Dr. Wu for their guidance and support throughout the course of this research. They have seen me grow and learn throughout my career at Texas A&M University and I cannot thank them enough for their acceptance and shared wisdom over the years.

Thanks also go to Katelyn Keller and Andrea Gurney for making my time at Texas A&M University a bearable experience. A graduate degree is no walk in the park but together we kept it as bright as possible.

Finally, I would like to thank Justin Katz for his solidarity, patience and love throughout this process. If it were not for you this would have been a rough five years, but together we made it through.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a dissertation committee consisting of Professors Bruce A. McCarl, Anastasia Shcherbakova and Ximing Wu of the Department of Agricultural Economics and Professor Efstratios N. Pistikopoulos of the Department of Chemical Engineering.

The water analyses depicted in Chapter 2 were conducted in part by Bilal Abada of the Department of Civil and Environmental Engineering. All other work conducted for the dissertation was completed by the student independently and under the advisement of Dr. McCarl.

Funding Sources

This graduate study was supported by the three sources 1) a Sloan Pem fellowship from the College of Agriculture and Life Sciences of Texas A&M University; 2) a National Science Foundation (NSF) INFEWS project under Grant Number [1739977] and 3) the Texas A&M University Water Seed Grant Initiative.

NOMENCLATURE

AF	Acre Feet
API	American Petroleum Institute
ATRI	American Transportation Research Institute
CHIPS	Colonias Health, Infrastructure and Platting Status tool
DOE	Department of Energy
EDAP	Economically Distressed Areas Program
EIA	Energy Information Administration
FEW	Food- Energy- Water
GHG	Greenhouse Gas
HWT	Household-level Water purification Technologies
IEA	International Energy Agency
IPCC	International Panel on Climate Change
LCA	Life Cycle Analysis
NF	Nanofiltration
NG	National Geographic
TEA	Techno Economic Analysis
TSOS	Texas Secretary of State
TWDB	Texas Water Development Board
UN	United Nations

USC	United States Code
USGS	United States Geological Survey
UNDESA	United Nations Department of Economic and Social Affairs
WCID	Water Control and Improvement Districts

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

Page

1. INTRODUCTION

Many regions of the world are currently either facing water scarcity or are about to with the situation exacerbated by increased population growth, aquifer depletion and climate change effects. By 2050 global demand for water is projected to increase by 30% - 85% (United Nations Foundation 2006), and global food demand is projected to increase by approximately 70% (FAO 2009a). Simultaneously, many areas are experiencing dwindling groundwater supplies (Russo and Lall 2017; USGS 2013), lower rates of technical progress (Kapilakanchana 2016) and projections of hotter and, in places, drier conditions due to climate change (Knutti and Sedlacek 2013). A large number of areas around the world will be substantially affected (Freyman 2014). Addressing water scarcity and food productivity involves numerous challenges regarding supply of and demand for freshwater resources, research investments and effects of climate change.

1.1. Threats to freshwater supply

Freshwater supplies are fundamentally limited in availability. Although approximately 71% of the Earth's surface is covered with water, only 2.5% of that water is freshwater and most of that (60%) is captured in glaciers or icecaps (USGS 2016). The remaining freshwater can be categorized as surface water in rivers and lakes, and groundwater in aquifers. Furthermore, there are a number of relevant threats involving freshwater supply and demand.

One such threat to surface and ground water supply is climate change (Figure 1.1). Namely, climate change is projected to increase global temperature and in turn cause alterations in the hydrological cycle (Knutti and Sedlácek 2013). For some regions, warmer air leads to greater evaporation of surface water and stronger storms with more precipitation while other regions are expected to experience drier air, with accompanying drought and low groundwater recharge (Chen et al. 2001; Seager et al. 2009; Cook et al. 2007). In both cases, the increasingly warmer temperatures are expected to increase vegetative water demand for evapotranspiration.

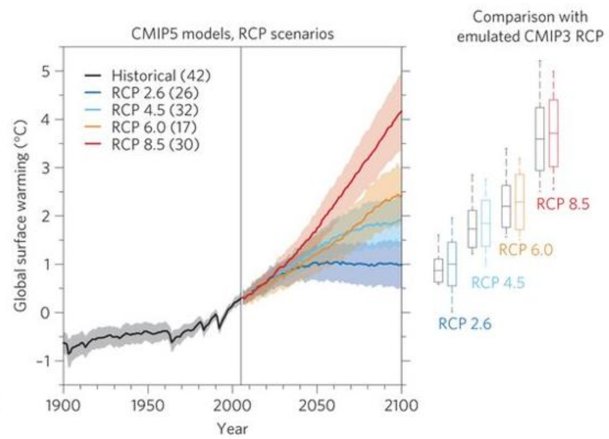

Figure 1.1: Global temperature change projection (Knutti and Sedlacek, 2013)

There is also the reality of climate change induced increases in precipitation intensity with greater proportion of the rainfall occurring in a shorter number of days and a greater number of dry days throughout the year (Pendergass and Knutti 2018). This increased rainfall intensity tends to lead to a greater incidence of floods and less ability for the water to be retained as reservoir capacities are reached and aquifers cannot recharge quickly enough to take advantage of the precipitation. As a result, there are greater river flows and inflows to the ocean with a lower proportion of freshwater being usable for basic water supply. Additionally, greater intervals between rainfall increase dependence on irrigation. Finally, certain areas including the US southwest are expected to face a drier future (Seager et al. 2009; Cook et al. 2007) and more globally there are projections of drier conditions in many world regions (IPCC, 2013).

Another threat involves groundwater depletion. Globally, groundwater storage is declining with many aquifers depleting due to pumping rates surpassing recharge rates. Total water storage in aquifers is being diminished by approximately 1-2% per year (IEA 2016).

1.2. Threats to agricultural technical progress

Climate stressors that harm water supply are also negatively affecting agricultural technological progress (Villavicencio et al. 2013; Andersen et al. 2018). Technological progress focuses on raising agricultural production primarily through intensification. Intensification supports yield enhancements over a diverse range of farmer adaptations and is essential in future agricultural production (Fei and McCarl, 2020). Unfortunately, rates of technological progress increase are falling. In other words, crop yields are still benefiting from technological progress, but they are benefiting at a decreasing rate across all regions of the United States (Kapilakanchana 2016).

1.3. Demand alterations

On the demand side, there are increasing freshwater and food demands due to a growing population and the water demand increasing effects of climate change. The Food and Agriculture Organization (FAO) estimates the global sum of water withdrawals to be approximately 3,900 cubic kilometers (km3) per year or 3,160 million-acre feet (AF) (FAO 2016). The largest water user is the agricultural sector which has an estimated 70% share of global water withdrawals, the industrial sector is estimated to have a 19% share, and the municipal sector is estimated to have an 11% of the freshwater withdrawals **Figure 1.2**.

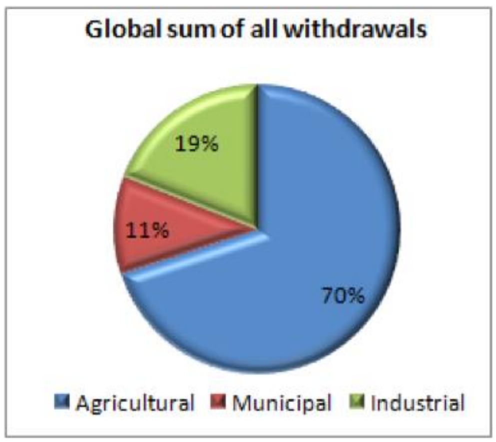

Figure 1.2: AQUASTAT (FAO 2016)

Agriculture is the largest water user across the globe. However, the diversion amount is not constant across time. Rather, agricultural water withdrawal differs from year to year with the variability caused by many factors including regional climate, percentage of the population in agriculture, whether or not the land is irrigated, irrigation techniques, technology employed for crop management, soil management and crop mixes.

With global population projected to increase to 9.1 billion by 2050 (UNDESA 2009) there is a growing demand for agricultural food production. Agricultural food demand is dependent on many variables, one of which is economic growth (FAO 2018). When a country's economic growth increases, the desire for meat products also increases. This requires both a direct demand increase in meat products and an indirect demand of cereal grains and feed products to sustain the meat demand. FAO projects an increase of cereal production from 2.2 billion tons to 3 billion tons by 2050. Meat demand is also projected to increase from approximately 200 million tons to 470 million tons (FAO 2009b).

In turn, for an increase in farm productivity there is likely to be an increase in agricultural water demand along with water demand from growing urban areas (FAO 2018). The increase in population increases demand for municipal and industrial water use. Freshwater is used in multiple facets of daily life be it through consumption, cleaning, cooking, waste management, showering, as well as in the support of employment opportunities. This will put further strain on freshwater water supplies. Another challenge to consider is the location of water. Water is often not located where you want it to be and is heavy and costly to move. This means that water must often be transported via expensive means to the people in municipalities and to the industrial sector.

All sectors will now more than ever need to find innovative ways to efficiently manage freshwater withdrawals and consumption and we have a need for agricultural productivity expansion. Interdisciplinary studies will aid in thorough understanding, holistic analysis and realistic implementation of the overlapping sectors' goal of efficient freshwater use.

1.4. Objectives and plan of dissertation

This dissertation aims to examine economic issues regarding the efficient procurement of water in water scarce regions plus address factors driving agricultural technical progress across the United States. This will be done in three essays:

- The first essay will consider the case of providing water supplies to now unserved colonias on the Texas-Mexico border. The essay will investigate the cost of supplying safe potable water via a mobile solar powered nanofiltration unit versus alternative water delivery systems. This will be examined under case study conditions using data for several colonias. There will also be a life cycle analysis to determine which system uses the least amount of energy as well as which produces the lowest greenhouse gas emissions.

- The second essay will forecast the volume of freshwater used in hydraulic fracturing in the Eagle Ford Shale via ordinary least squares. Following the forecast, a breakeven analysis of the cost of switching to recycling water infrastructure is analyzed as well as the breakeven number of miles for freshwater transportation during the hydraulic fracturing process.

- The final essay focusses on how climate change and agricultural research and development funding affects crop yields in the United States using data from the period from 1975-2015. A fixed effects, county level model is implemented and key variables are identified that influence the growth rates of crop yields.

1.5. References

Andersen, M. A., J. M. Alston, P. G. Pardey, and A. Smith. 2018. "A Century of U.S. Farm Productivity Growth: A Surge Then a Slowdown." *American Journal of Agricultural Economics* 100**:**1072–1090.

Chen, C., D. Gillig, and B. McCarl. 2001. "Effects of Climate Change on Water Dependent Regional Economy: A Study of the Texas Edwards Aquifer." *Climate Change* 49:397-409.

Chengcheng, F. J. and B. A. McCarl. 2019. "Agricultural Technical Progress as a Climate Change Adaptation Strategy: Challenges." Working paper, Department of Agricultural Economics, Texas A&M University.

Cook E.R., R. Seager, M.A. Cane, and D.W. Stahle. 2007. "North American drought: reconstructions, causes and consequences." *Earth Science Review* 81:93-134.

Freyman, M. 2014. *Hydraulic Fracturing & Water Stress: Water Demand by the Numbers.* https://core.ac.uk/download/pdf/71364916.pdf (accessed November 20th, 2018).

International Energy Agency (IEA). 2016. *Water Energy Nexus.* https://www.iea.org/publications/freepublications/publication/WorldEnergyOutlook2016ExcerptWaterEnergyNexus.pdf (accessed November 20, 2018).

Kapilakanchana, M. 2016. “The effect of Technological Progress, Demand, and Energy Policy on Agricultural and Bioenergy Markets.” PhD dissertation, Department of Agricultural Economics, Texas A&M University.

Knutti, R., J. Sedlacek. 2013. “Robustness and uncertainties in the new CMIP5 climate model projections.” *Nature Climate Change* 3:369-373.

Pendergrass, A. G. and R. Knutti. 2018. “The Uneven Nature of Daily Precipitation and its Change.” *Geophysical Research Letters* 45(21):11,980-11,988.

Russo, T. and U. Lall. 2017. “Depletion and response of deep groundwater to climate-induced pumping variability”. *Nature Geoscience* 10:105-108.

Seager, R., A. Tzanova, and J. Nakamura. 2009. Drought in the Southeastern United States: Causes, Variability over the Last Millennium, and the Potential for Future Hydroclimate Change. *Journal Climate* 22:5021-5045.

United Nations Foundation (UN). 2006. *What Will Life on Earth be like in 2050?* https://unfoundation.org/media/what-will-life-on-earth-be-like-in-2050/ (accessed on November 10, 2018).

United Nations, Department of Economic and Social Affairs (UNDESA). 2009. *World Population Prospects, The 2008 Revision – Executive Summary*. New York.

United Nations, Food and Agriculture Organization (FAO). 2009a. *Global Agriculture Towards 2050.*

http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf (accessed on November 18, 2019)

United Nations, Food and Agriculture Organization (FAO). 2009b. *2050: A Third More Mouths to Feed*. http://www.fao.org/news/story/en/item/35571/icode/ (accessed on November 19, 2019)

United Nations, Food and Agriculture Organization (FAO). 2016. *AQUASTAT: Water Uses.* http://www.fao.org/nr/water/aquastat/water_use/index.stm (accessed on November 7, 2018).

United Nations, Food and Agriculture Organization (FAO). 2018. The Future of Food and Agriculture: Alternative Pathways to 2050. http://www.fao.org/3/I8429EN/i8429en.pdf (accessed on November 19, 2019).

U.S. Geological Survey (USGS). 2013. *Groundwater Depletion in the United States (1900-2008).* https://pubs.usgs.gov/sir/2013/5079/SIR2013-5079.pdf (accessed on November 10, 2018).

U.S. Geological Survey (USGS). 2016. *How much water is there on, in, and above the Earth?* https://water.usgs.gov/edu/earthhowmuch.html (accessed on November 4, 2018).

Villavicencio, X., B. A. McCarl, X. M.Wu, and W. E. Huffman. 2013. "Climate change influences on agricultural research productivity". *Climatic Change*. 119: 815–824.

2. COST AND LIFE CYCLE ACCOUNTING OF ONSITE SOLAR POWERED WATER SUPPLY VERSUS CONVENTIONAL ALTERNATIVES

2.1. Introduction

Many low-income communities on the Texas- Mexico border, called colonias, have poor to no infrastructure for potable water, electricity, drainage, and/or sewage. There are an estimated 2,294 total colonias in Texas with an approximate total population of 500,000 people (Barton et al. 2015). Despite significant federal and state efforts to improve the well-being of colonia residents (Lambert 2016), approximately 15% of these communities do not have systems providing potable water, wastewater disposal or reliable electricity (Barton et al. 2015).

Water supply is a difficult issue for many colonias as they are in rural, often arid, areas that are distant from available water supply infrastructure. Approximately 40% of colonia residents are below the poverty line with another 20% falling just above it (Barton et al. 2015). Furthermore, under emergency situations such as hurricanes (which are expected to occur with increased severity under climate change), potable water access is decreased further.

Another colonia water supply issue, is the quality of water supplies in the area. Much of the groundwater in the regions where the colonias are located (along the Texas-Mexico border) exhibits high salinity that makes the water inappropriate for drinking and difficult for irrigation. Some supplies are contaminated with compounds like arsenic. In those cases one alternative water supply solution is water purification including desalination. However, such purification is costly (Shannon et al. 2009). To obtain potable water many colonia residents currently depend on bottled or vended water for drinking and cooking which is also expensive (Jepson 2014).

Because of colonias' reliance on bottled water, the communities use large volumes of plastic water bottles. This is not only costly but is also environmentally unfavorable in terms of pollution and greenhouse gas emissions. The manufacture of single use water bottles and larger 5-gallon jugs emits harmful carbon dioxide and are commonly improperly disposed of causing environmental pollution. Given the carbon dioxide links to climate change and the desire for a clean environment this may not be the most appropriate long-term solution. With the colonias' current use of water conveyance, they are unwittingly worsening the climate damages they face where low income communities potentially disproportionately feel the effects and costs of climate change relative to other communities but have limited adaptation options.

2.2. Objective

This study investigates the economic cost and greenhouse gas emission consequences of supplying colonias with potable water via a mobile solar powered nanofiltration desalination unit in comparison with alternative means of water supply. Conditions faced by three select colonias near the Texas-Mexico border will be used in a case study analysis to develop both cost and GHG life cycle assessments consequences.

2.3. Literature Review

The majority of colonias in Texas are near the Texas-Mexico border. **Figure 2.1** shows where colonias are located in Texas and gives an idea on their concentration.

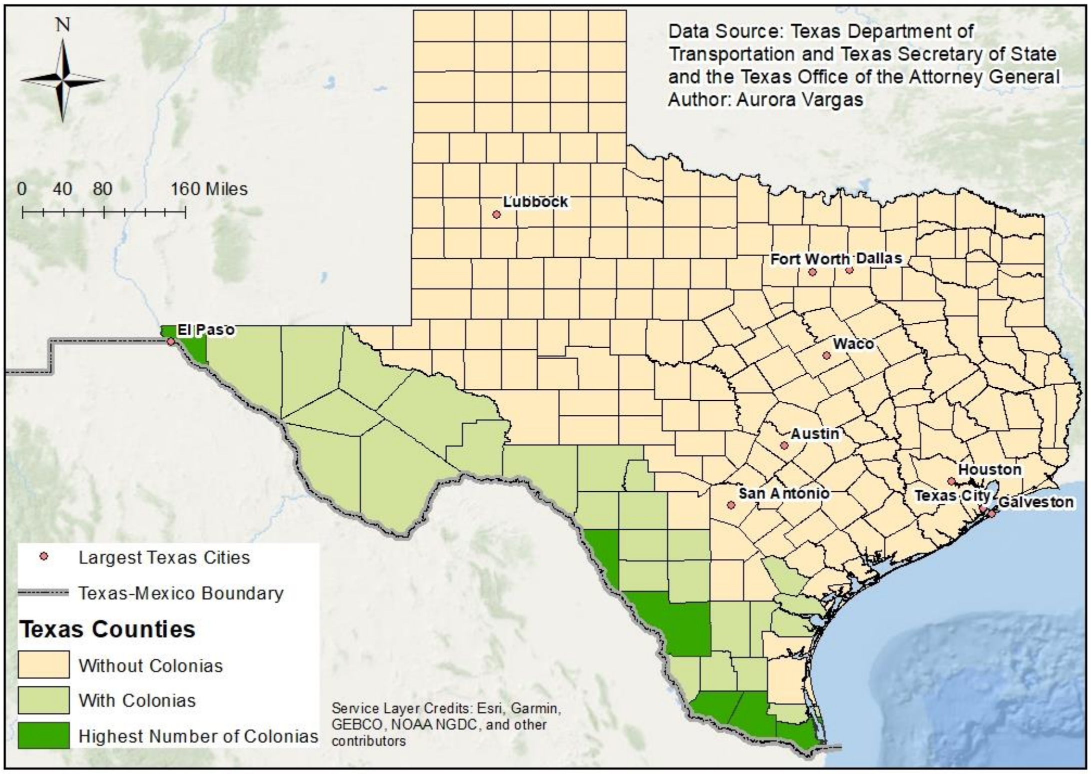

Figure 2.1: Texas counties with colonias

Using the Colonias Health, Infrastructure and Platting Status tool (CHIPS-Parcher and Humberson 2009) we can investigate general characteristics regarding colonias' access to potable water, sewage disposal systems and paved roads. The database classifies colonias into four groups.

The first group of colonias are called green colonias. These are colonias that have full access to potable water, wastewater disposal systems and paved roads. The second or yellow group has functioning water systems and water disposal but lack paved roads. Third group lacks infrastructure for potable water, wastewater disposal and platted land

and are classified as red colonias. The fourth and final colonias group is an unknown category which contains those which have an unknown status with respect to potable water, wastewater disposal systems, paved roads, etc. Approximately 73,000 residents are in registered red colonias that are without access to safe potable water for everyday use (Barton et al. 2015). Jepson (2016) also identified that colonia households with mixed citizenship status were 4.2 times more likely to be in the red category and water insecure.

To provide water security through access and quality, Texas legislature allocated $250 million to south Texas counties through the Economically Distressed Areas Program (EDAP) with the money directed toward provision of adequate water and wastewater infrastructure on public property. Later, Mroz et al. (1996) estimated that a further $250 million would be needed to make improvements in the water supply to all colonias as well as $500 million for sewage treatment. In response, another $250 million was approved in 2007, which broadened the EDAP program to the entire state, not just border counties, and also allowed use of funds for private-home water and wastewater connections in the areas served (Lambert 2016). Also, federal funding of $300 million was provided to the Colonia Wastewater Treatment Assistance Program (CWTAP) to complement state initiatives in the colonias.

Along with funding, an additional factor to complete water access is the provision of oversight and accountability of the service providers constructing the water and sewage systems for the colonias (Carter and Ortolano 2004). Thus, further legislative oversight and incentives must be put in place to ensure that EDAP funding is used efficiently and water access can be ensured.

A third factor is the water development preference of the area in terms of focus on irrigation (Jepson 2014). In much of the region, the Water Control and Improvement Districts (WCID) are farmer controlled and in the past have excluded colonia residents from voting for WCID board candidates, generally defining colonias as “urban property” and outside their districts. This denial left colonia residents without power to change the districts’ operations from irrigation to domestic water supply (Jepson 2012).

With legislature and construction slow moving, water vending businesses have made drinking water available for colonia residents. At approximately $0.25 a gallon, residents may fill gallon or 5-gallon jugs with guaranteed drinking quality water. However, many vending stations are distant and water is heavy, making vended water a difficult supply to access without costly transportation (Jepson 2014a). With this in mind, funding was put toward household-level water purification technologies (HWT) so that residents would not need to travel for water but instead could purify water in the household. Unfortunately, only 63% of surveyed colonia residents stated a willingness to adopt HWT if it was free and approximately 25% were willing to pay $10-$100 for HWTs (Jepson 2015). Even if the technology were to be given for free, the education required for technology installation and upkeep may be outside the ability of the residents. Water quality tests would also be left to the residents and poor water quality could easily manifest itself with the improper installation and maintenance of the HWT.

A solution outside of public infrastructure was suggested by Olmestead (2004), where the recommendation was to establish a low cost, small scale, water treatment system by providing an appropriate subsidy that was sufficient to incentivize a distant water provider to extend service to the rural area. One way of accomplishing Olmstead's suggestion is provision of an efficient mobile water treatment unit for rural colonias as will be studied here.

2.4. Regional Water Analysis

One of the first steps in examining this issue was to obtain regional water samples and examine their water quality attributes. Water samples were collected in cooperation with Dr. Juan Landivar and Dr. Juan Enciso from the Texas A&M Agrilife Research and Extension program in McAllen Texas. These were drawn from:

- A well in the colonia Campacuas
- An unnamed canal that runs by the colonia Wes-Mer in Hidalgo County.
- A well in the colonia San Isidro in Starr County.

All three of these are in South Texas near the United States-Mexico border as seen in **Figure 2.2**. These sources were chosen because of the proximity to high concentrations of colonias (Barton et al. 2015). Additionally, a past study in Hidalgo County described 55% of colonia households as water insecure (Jepson 2014b). This is area was judged to be a location with potentially suitable sites for mobile water treatment systems.

The water samples were received in plastic containers and stored immediately in 4 ℃ refrigerators until analysis. Analysis showed high salinity in all samples and a high arsenic concentration that fell above EPA standards in the case of the Canal Wes-Mer.

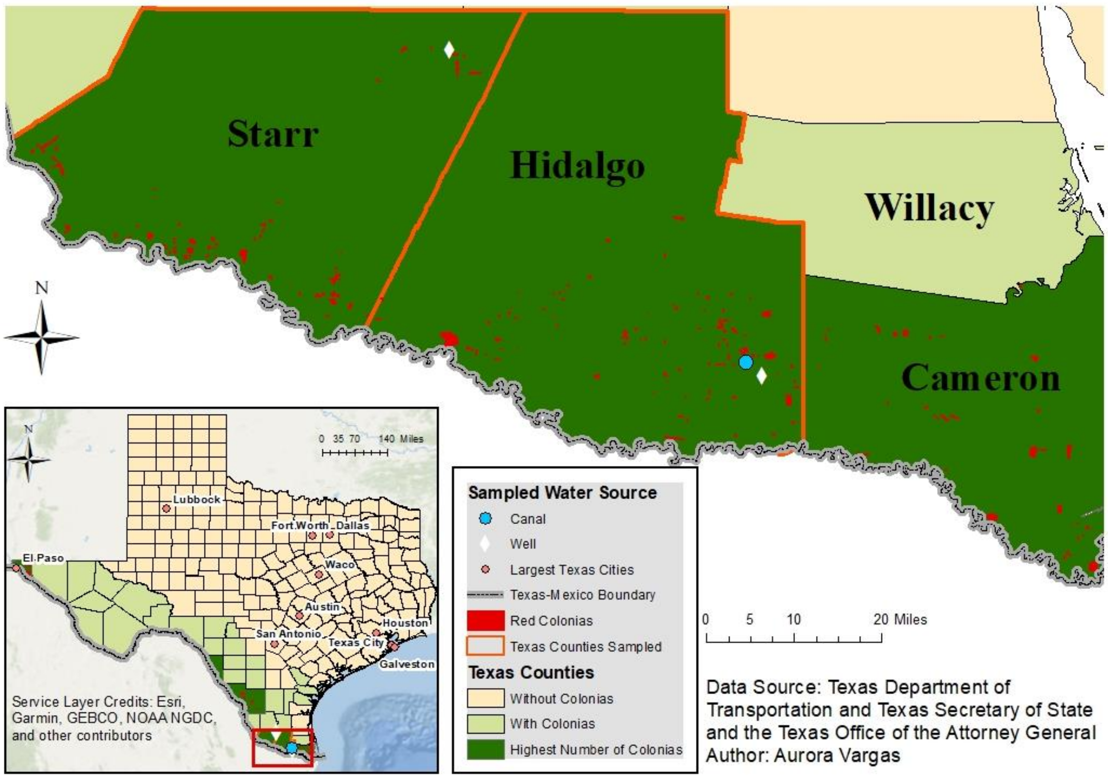

Figure 2.2: Sampled Texas counties' wells and canal

In a parallel study (Mordearsi et al 2019) nanofiltration (NF) membranes were chosen over conventional reverse osmosis membranes based on the filtration needs of the water samples. In particular Mordearsi et al 2019 found that NF membranes can efficiently filter the brackish waters found in association with the sample colonias at a lower energy requirement.

2.5. Cost Analysis

To do a cost analysis for the mobile solar powered water filtration units, estimations were needed for the costs of acquisition, construction, installment and operation. The unit studied was the one designed in the parallel study by Mordearsi et al 2019, and consisted of an immobile set of water storage, distribution, site infrastructure, charging stations and solar panels along with a mobile water treatment system (**Figure 2.3**).

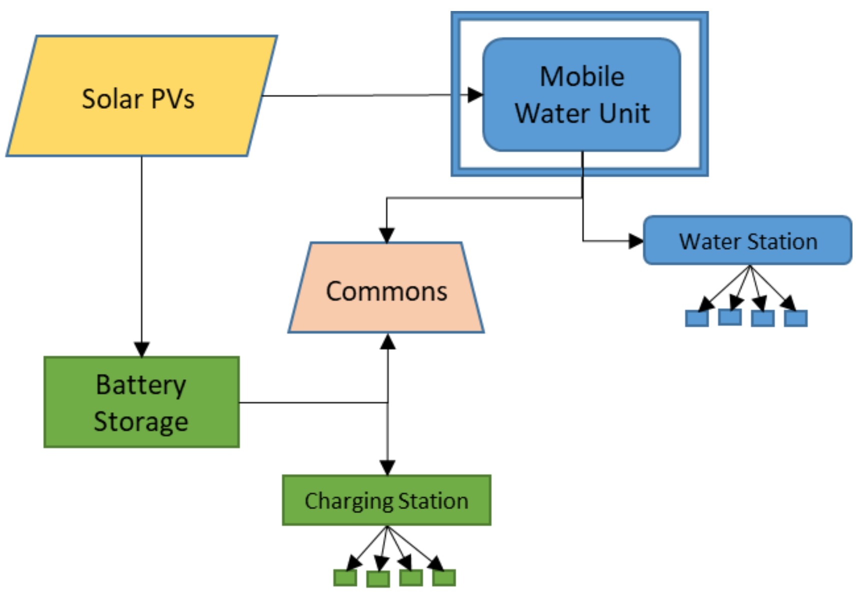

Figure 2.3: Proposed mobile solar powered water filtration unit layout

The immobile parts of the proposed unit are composed of a) a battery storage/charging station, b) a water station, c) solar panels and d) linking infrastructure in a common area. The solar panels are assumed to be installed on a flat plat of land. From there, wires would be connected to a battery nearby for storage with a charging station available for residents to charge personal small batteries when solar electricity is not being used for the filtration process. The linking commons area is a place where pipes and pumps link the water to storage and the panels to a small grid. Finally, the water station will be composed of large water tanks that will be filled by the mobile water filtration unit. The filtration unit will connect to the solar panel grid and consume solar electricity to power the filtration process.

The mobile unit will be stationed at a colonia for approximately six days and will filter 84,000L of water. This amount, assuming 200 colonia residents, provides a supply over two weeks of 30L per person per day for drinking and cooking. At the end of the six-day period the mobile unit will be transported an average of 10 miles to a sister red colonia where it will remain the next 6 days and then will return to the first colonia. In this case both colonias will have their own fixed equipment in the form of solar panels, water storage, linking infrastructure and a charging station.

2.5.1. Cost of Immobile Inputs

The immobile inputs for the proposed unit include all water storage tanks, pumps, solar panels and battery banks that would be located permanently at each red colonia that was in the program.

For storage, a tank with capacity to store 1,700 gallons would be needed to store the water feed that will go into the water filtration unit and ensure continuous filtration. Following filtration, one tank of 525 gallons is needed to collect permeate before transfer to the long-term storage tanks. The long-term storage tanks for treated water supply will be six tanks of 5,000 gallons, which will be used for distribution over the two weeks.

Regarding pumps, two are needed for the process. The first pump will be used to pump water from the source to the feed tank. The second pump is needed to pump water from the 525-gallon tank to the 5,000-gallon distribution tanks.

For electricity creation, solar panels will be installed on flat land in four rows of five panels with 19 panels in each colonia. The electricity generated will be stored in a battery bank for water filtration and, if excess generation, for colonia resident use.

Given the tanks, battery and solar panel/installation requirements, the area of land needed for the immobile section of the proposed unit totals 262 m^2 per colonia. **Table 2.1** outlines the immobile part requirements over a 20-year lifespan, their cost estimation source, cost estimation per unit and total cost estimation.

Table 2.1: Cost of immobile inputs and source

Product	*Source*	*# of Units*	*Cost per Unit*	*Price*
Solar Panels	Silfab Solar	19	$228.00	$4,332.00
Solar Panel Installation	Silfab Solar	1	$8,448.00	$8,448.00
Tank (525)	Norwesco	2	$679.00	$1,358.00
Tank (5,000)	Norwesco	12	$2,400.00	$28,800.00
Tank (1,700)	Chem-Trainer	2	$1,284.00	$2,568.00
Utility Pump	AquaPro	40	$162.00	$6,480.00
Battery Bank	Discover	2	$28,932	$57,864.00
Plat (sq meter)	Texas Farm Bureau	262	$0.63	$165.35

2.5.2. Cost Mobile Inputs

The mobile section of the proposed unit is the water filtration unit itself. The filtration unit is a desalination unit that will be transported on a trailer pulled by truck between two colonias. For every two colonias, one filtration unit will be required. The filtration unit uses nanofiltration membranes to process the water and the unit holds three membranes. **Table 2.2** outlines the cost estimation of each mobile part over a 20-year lifespan.

Table 2.2: Cost of mobile inputs and source

Product	*Source*	*# of Units*	*Cost per Unit*	*Price*
Desalination Unit	FilmTec	1	$13,310.00	$13,310.00
NF membranes	Lenntech	21	$317.00	$6,657.00

2.5.3. Cost of Transportation

The cost of transportation of the mobile unit to each colonia is considered in this section. We assume the mobile unit will be transported via truck to and from the colonias. To determine the cost of transportation, estimates from an American Transportation Research Institute (ATRI) annual report were used to estimate the marginal costs of transport. The marginal costs include both vehicle-based (fuel, truck/trailer lease or purchase, repair and maintenance, truck insurance premiums, etc.) and driver-based costs (wages and benefits) (Hooper and Murray 2018). In 2017, the average marginal cost per mile driven was $1.691. This price was used for the distance between red colonias, which is approximately 10 miles with the cost of transport estimated over a 20-year life span (**Table 2.3**).

Table 2.3: Cost of transportation and source estimation

Product	***Source***	***# of Units***	***Cost per Unit***	***Price***
Transportation (miles)	ATRI	10,400	$1.691	$17,586.40

2.5.4. Summary cost evaluation

The summary of costs for the proposed unit can be seen in **Table 2.4**. Considering a historical inflation rate of 3.00% and a 20-year life span, the annual amortized costs of infrastructure (immobile inputs and transportation) necessary in each red colonia is approximately $144,286 with $288,571 being the total cost for two colonias. In addition to that cost, two colonias will share a water filtration unit along with the required NF membranes. Thus, the total cost of the project is $310,705 for two colonias of approximately 200 residents each and a bi-monthly supply of 84,000L per colonia.

Table 2.4: Annualized Cost of Proposed Unit over a 20-year life

Individual Infrastructure	***Price***
Solar Panels	$4,332
Solar Panel Installation	$4,116
Tank (525)	$1,592
Tank (5,000)	$33,752
Tank (1,700)	$3,010
Utility Pump	$4,289
Battery Bank	$67,814
Plat	$165
Avg Trucking Cost	$25,216
Cost per Colonia	**$144,286**
Subtotal for two Colonias	**$288,572**
Shared Infrastructure	
Water Filtration Unit	$13,310
NF Membranes	$8,823
Total for two Colonias	**$310,705**

This equates to approximately 44 million filtered liters available to the residents of each of the two red colonias during all of the next 20 years. To determine the amortized cost of a single liter of water, the project cost is divided by the total number of liters filtered during that time. The cost of a single liter of water filtered through this process is $0.004 or $38.84 per person for a full year of 30 liters of water a day.

Now let us compare this cost to three traditional alternatives: single use water bottles, 5-gallon jugs and tap water. The results of the alternatives are given in **Table 2.5** and only describes the cost of water filtration in each system.

Table 2.5: Cost per Liter of Proposed versus Traditional Sources

Product	***Cost ($)/L***	***Source***
Filtration Unit	$0.0036	-
Tap Water	$0.0021	TML (2019)
Bottled Water	$0.2906	IBWA (2016)
Vended Water	$0.1057	PRIMO (2019)

The lowest cost option is tap water at $0.0021 per liter. This rate was pulled from the Texas Municipal League as the average water rate in Texas for residential water. As residential water comes from a utility, this cost is not a marginal cost of water and does not reflect the current marginal cost of building the municipal water filtration systems. In the case of the colonias, municipal tap water infrastructure is likely not a feasible option. Thus, the proposed filtration unit at $0.0036/L is cost-effective compared to the cost of water per liter of bottled water ($0.29) and vended water ($0.11).

If red colonias account for 15% of total colonias in Texas, approximately 344 communities could benefit from this mobile water filtration unit at a total cost of approximately $53.5 million dollars over 20 years or $2.7 million dollars per year for all red colonias. On an average per resident basis, it would cost $39.00 per person per year to receive water from the filtration unit.

2.6. Life Cycle Assessment

2.6.1. LCA Overview

Life cycle assessment in a greenhouse gas context is an environmental management process that considers all the emissions associated with a product or service throughout its lifecycle, from cradle to grave. To standardize the process of LCA, the International Organization of Standardization (ISO) outlines a framework of four key requirements in an LCA. They are as follows:

1. Goal and Scope Definition: reasoning, application and audience of the study as well as the product system and function
2. Life Cycle Inventory (LCI): identification of lifecycle inputs and outputs and associated data collection
3. Life Cycle Impact Assessment (LCIA): characterization, classification and valuation of the emission impacts of the inputs and outputs listed in the LCI
4. Interpretation: evaluate the results of the LCIA and service/product recommendations to decision makers

I implement those steps below.

2.6.2. Goal and Scope Definition

2.6.2.1. Goal

The goal of the mobile unit is to provide red Hispanic colonias in South Texas with access to safe drinking water that is more convenient than obtaining water from other sources. This study will apply the LCA methodology compare the energy consumption and carbon dioxide emissions of 4 alternative systems of obtaining water supply via, 1) single use 500mL water bottles (SUB), 2) vended 5 gallon water jugs (VW), 3) the proposed mobile water filtration unit (MF) and 4) municipal tap water (TW).

2.6.2.2. Scope

The four systems considered are broken down into 6 life cycle stages. The first stage is the resin and container production stage. This is the stage where resin for plastic is created and formed into containers for single use water bottles and reusable 5-gallon jugs. The second stage is the water filtration stage which is where water is filtered at the water bottling plant. The third stage is the bottling of the water for distribution. Next, we consider the transportation of the water to the market and also the transportation of water to the household. The final stage is the disposal of the water supply container.

2.6.2.3. Function and Functional Unit

The system function is the conveyance of a two-week water supply to red colonia households by the four different systems mentioned (MF, SUB, VW and TW). The functional unit, the unit of performance for the output, is liters of water supplied to the colonia households. This functional unit is scaled up to the reference flow, the amount of product to fulfill the function, of 84,000L of water supplied to a colonia every two weeks.

2.6.2.4. Key Assumptions

Many assumptions are made throughout the LCA. The first is that the reference flow of 84,000L per colonia every two weeks adequately supplies drinking and cooking water needs for a single colonia of 200 residents. The second assumption is that during the resin & production and disposal stages, the containers are not recycled. This is because many of the colonia residents do not have access to infrastructure for recycling. The third assumption is that the resin and production stage does not take into account any secondary packaging such as corrugated boxes or polyethylene wrap. The fourth assumption is that upstream costs and considerations are not taken into account. The final assumption is that the analysis will only be looking at the operating costs of each system of all alternatives and not the costs of inputs outside of plastic bottle use. For example, I will not be considering fabrication costs of solar PV panels or nanofiltration membranes and the cost of energy and emissions needed to create these inputs.

2.6.3. Life Cycle Inventory (LCI)

The system stages are dependent on the product system being considered. The following subsections break down the stages and assumptions for each individual system.

2.6.3.1. Data Categories

This section outlines the types of data used throughout the analysis.

2.6.3.1.1. Energy Data

The energy data used for the analysis was collected from many sources and converted to kilowatt hours of electricity. **Table 2.6** identifies sources of energy data used for each stage and system.

Table 2.6: Energy Use Data Collection References

	PET	***PCV***	***PCU***	***TAP***
Resin and Container Production	GREET (2019)	GREET (2019)	GREET (2019)	-
Water Filtration	Dettore (2009)	Dettore (2009)	Dettore (2009)	Modarresi et al. (2019)
Water Bottling	Dettore (2009)	Dettore (2009)	-	-
Transportation to Market	DOE (2018)	DOE (2018)	-	-
Transportation to Household	MotorTrend (2019)	MotorTrend (2019)	SDTruck-Springs (2019)	Dettore (2009)
Disposal	Dettore (2009)	Dettore (2009)	Dettore (2009)	-

2.6.3.1.2. Emissions Data

The kilowatt hours of electricity from the previous section are converted to CO_2 grams equivalent per 84,000L using the European Commission (EC) Joint Research Center publication (Steen 2000) that gives the grams of CO_2 emissions per kilowatt hour of coal, natural gas and solar energy. Additionally, the Environmental Protection Agency

(EPA) provided the CO_2 equivalent emissions from gasoline and diesel use per mile (EPA 2014).

2.6.3.2. Single Use Bottle System Overview

The system stages of the first product, single use bottles (SUB), are demonstrated in **Figure 2.4**.

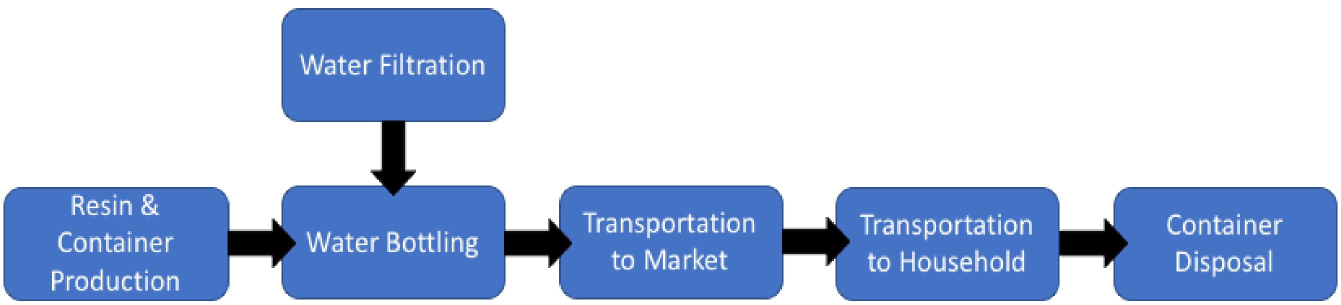

Figure 2.4: SUB System Life Cycle Stages

The cycle begins with the creation of the polyethylene terephthalate (PET) which is used to make the plastic of the SUB as well as the actual production of the bottle. Next, the water is filtered at the municipal level through reverse osmosis and microfiltration and again at the bottling plant where ozone treatment and UV disinfection further treats the water (Dettore 2009). The bottling plant is assumed to pack 500mL bottles in cases of 24 bottles each. To meet the water demand level of 84,000L per colonia every two weeks will require 168,000 bottles. In other words, 7,000 cases of SUBs are needed every two weeks to provide the reference flow of water or 18 water bottles a day per resident. Next, the water bottles are transported to the market where they can be purchased and then transported to the colonia household. Regional distribution to the market is approximated to involve a travel distance of 120 miles (Dettore 2009) in a diesel class 8 truck with a mileage of 5.29 (EPA 2018). Transportation to the household is assumed to involve approximately 40 miles round trip because colonias are considered to be in food deserts, such that the residents must drive 20 or more miles to reach a grocery store (Bailey 2010). The assumed miles per gallon is 24.7 which is the United States national average. The final stage is the disposal of the PET bottle to a landfill.

2.6.3.3. Vended Water Jug (VW) System Overview

The system stages for the second system, vended water jug, are outlined in **Figure 2.5**.

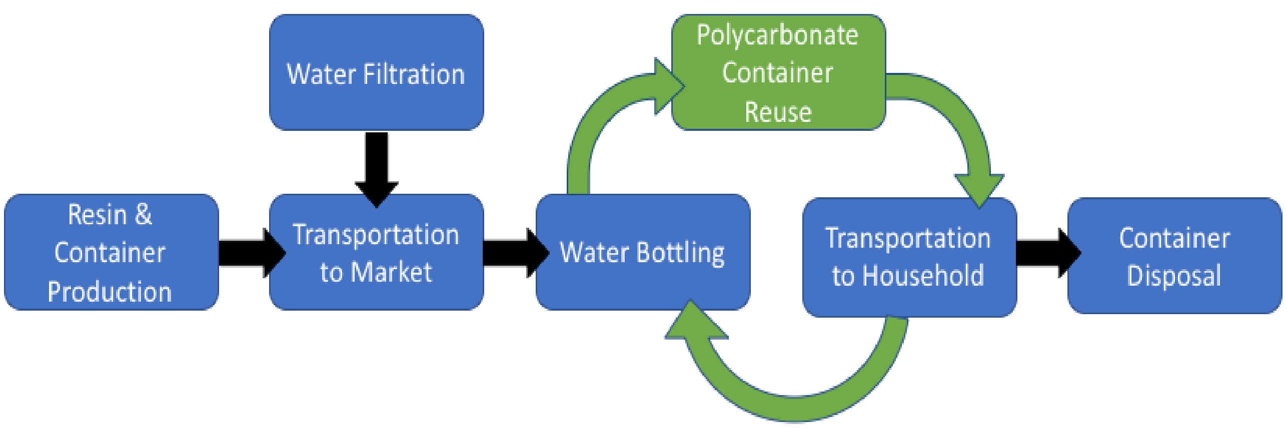

Figure 2.5: VW System Life Cycle Stages

The VW stages are similar to the SUB except for the occurrence of reuse. First the polycarbonate (PC) resin is created and then used to produce a 5-gallon PC jug; because of the structure of PC the bottle is more durable than PET and can be reused multiple times (Hamilton 2001). Water filtration and transportation to market follow the same assumption as used above in the SUB analysis. However, we assume the water bottling is done manually at the water vending machine. Then the PC bottles are transported to the household following SUB assumptions. Once the water has been consumed the cycle reenters the previous stages of bottling and transportation to household. We assume that colonia residents travel the distance to the vending machine twice in two weeks. After 50 reuses of the PC bottles, they enter the disposal stage and then the cycle begins again at resin and container production. To provide the colonias with the demanded reference flow of 84,000L, 4,438 bottles must be filled and assuming 50 reuses, they 89 bottles are needed to be manufactured and disposed of per year.

2.6.3.4. Mobile Water Filtration Unit (MF) System Overview

The system stages for PC unit filtered system are shown in **Figure 2.6**.

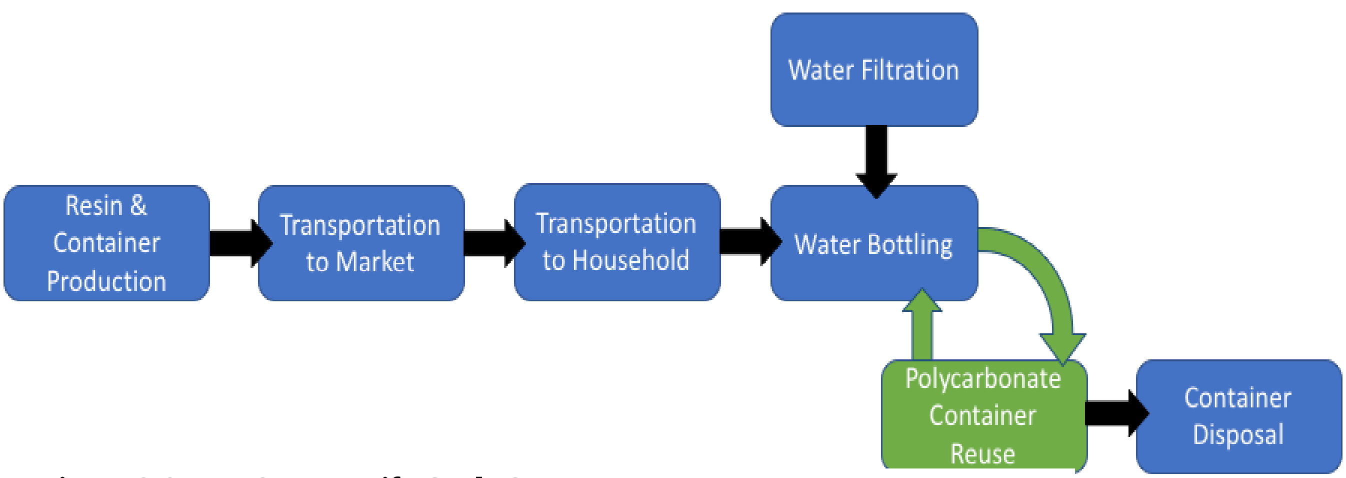

Figure 2.6: MF System Life Cycle Stages

The third system stages are similar to the second because they both use PC jugs as containers. The differences lie in where the water filtration is taking place. Here we start with the production of the PC resin along with the production of the PC container. Then the empty jug is transported to the market, the consumer transports the jug to the household and once there will manually pump the filtered water into the jugs. The water filtration in this system is done by a mobile solar powered NF unit and will travel to approximately 10 miles to the colonia once every two weeks. The energy and emissions costs of transporting the unit to the colonia is included in the transportation to household stage. The PC jug is reused up to 50 times after which it is disposed in a landfill. To provide the colonias with the demanded reference flow of 84,000L, 4,438 bottles must be filled and assuming 50 reuses, thus 89 bottles are needed to be manufactured and disposed of per year.

2.6.3.5. Municipal Tap Water System Overview

The stages of the final system, municipal tap water, are outlined in **Figure 2.7.**

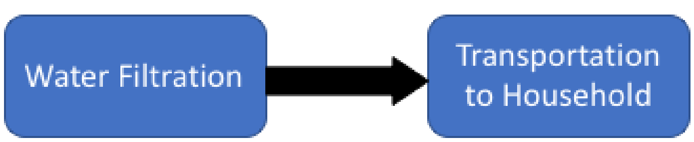

Figure 2.7: TW System Life Cycle Stages

The municipal tap water system is the simplest because it does not consider plastic container production and the only transportation considered is the distribution of the tap water to the household. First, the water is treated as previously mentioned. Second, the water is distributed via intricate pipelines to households for consumption.

2.6.3.6. Energy Use Across System

The four systems are evaluated against each other and the energy requirements in kilowatts per hour per 84,000L (kWh/84,000L) are computed for each stage.

Table 2.7: Energy use across systems and stages in kWh/84,000L

	Bottle Single Use	***Jugs Multiple Use***	***Mobile Unit***	***Tap Water***
Resin and Container Production	2620	65.0	65.0	-
Water Filtration	579	513	55.4	55.4
Water Bottling	387	-	-	-
Transportation to Market	758	758	-	-
Transportation to Household	676	676	52.5	7.79
Disposal	164	370	3.7	-
Total kWh/84,000L	**5190**	**2020**	**177**	**63.2**

As **Table 2.7** shows, the four systems have vastly different energy requirements. The system with the greatest energy requirements is the single use bottle system at 5190 kWh/84,000L. This is not surprising as the plastic bottles are not reused and thus energy necessary for PET production is large (**Figure 2.8**). The system with the second largest energy requirement is the multiple use jug system at 2020 kWh/84,000L. The multiple use jug stage that uses the most energy is the transportation of the PC container to the market. The system with the third largest energy requirements was the mobile system at 177 kWh/84,000L. Finally, the system with the lowest energy requirement is the tap water system at 63.2 kWh/84,000L. The difference between the two lowest energy values is a whole order of magnitude less, with approximately a 113.8 kWh/84,000L difference.

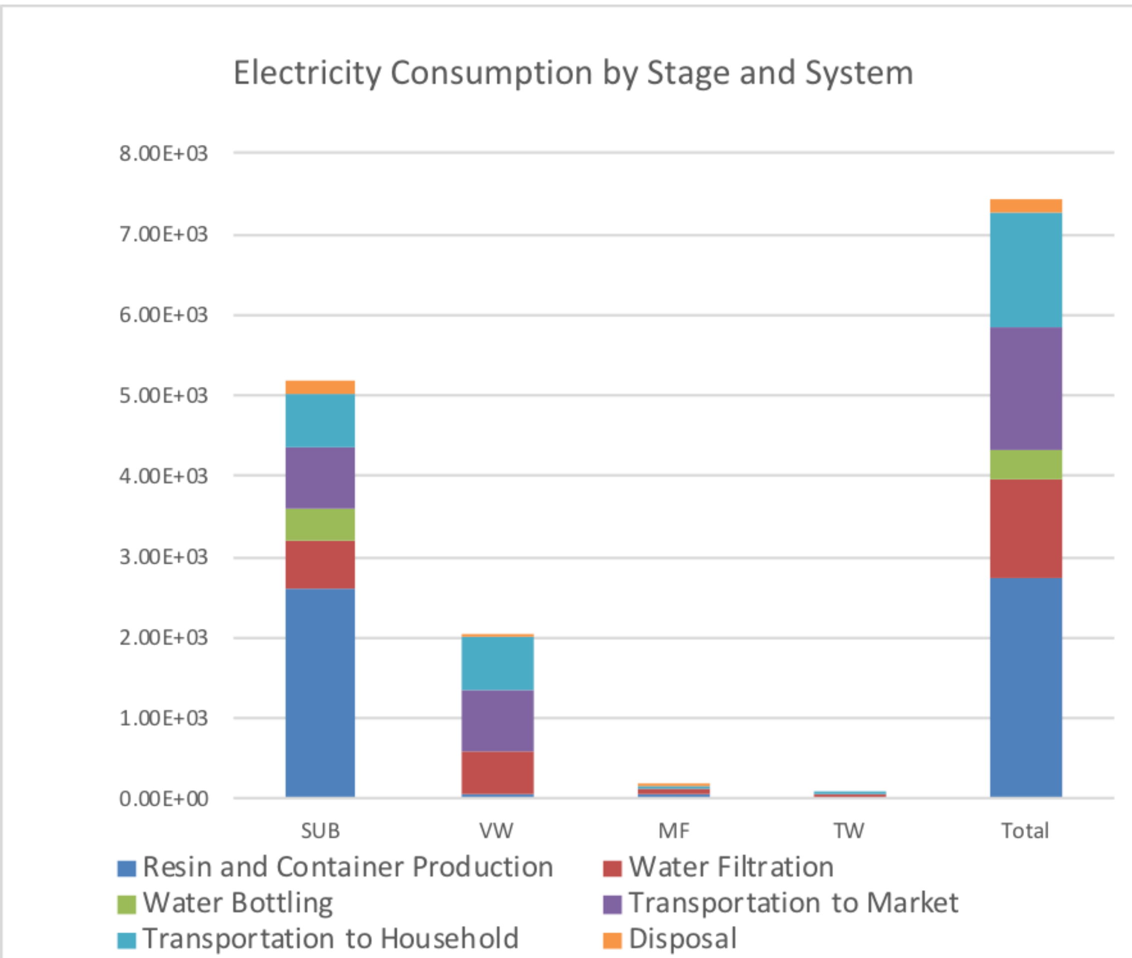

Figure 2.8: Electricity Consumption of each System and their Stages

2.6.4. Life Cycle Analysis (LCA)

The energy requirements reviewed in the previous section are used here to determine the grams of carbon dioxide (CO_2) equivalent that are emitted through each stage of the four different systems. **Table 2.8** shows the CO_2 emissions in grams per 84,000L for each product system and stage.

Table 2.8: CO_2 emissions in grams across systems

	Bottle Single Use	***Jugs Multiple Use***	***Mobile Unit***	***Tap Water***
Resin and Container Production	7.39E+03	3.20E+02	3.20E+02	-
Water Filtration	5.21E+05	4.62E+05	5.54E+01	5.54E+01
Bottling	3.49E+05	-	-	-
Transportation to Market	5.99E+05	5.99E+05	-	-
Transportation to Household	1.80E+05	1.80E+05	1.40E+04	7.02E+03
Disposal	5.95E+02	1.86E+01	1.86E+01	-
Total g CO_2/84,000L	**1.66E+06**	**1.24E+06**	**2.26E+04**	**7.07E+03**

The table illustrates the CO2eq emissions of each of the four systems. The system with the greatest emissions is the single use bottle system at 1.66e+06 g CO_2/84,000L where transportation to market has the largest share of emissions in the system (**Figure 2.9).** The next largest net emission system is the multiple use jugs with 1.24e+06 g CO_2/84,000L where again transportation to market holds the highest emission share. Next is the considerably lower emitting mobile system at 2.26e+04 g CO_2/84,000L. Because the mobile system does not include transportation of water to the market, the stage with the largest share of emissions is the transportation of the mobile unit to the colonia's households. Finally, the least emitting system is tap water with g CO_2/84,000L of 7.07e+03. Of the two stages in the system, distribution of water to the household carries the largest emission share.

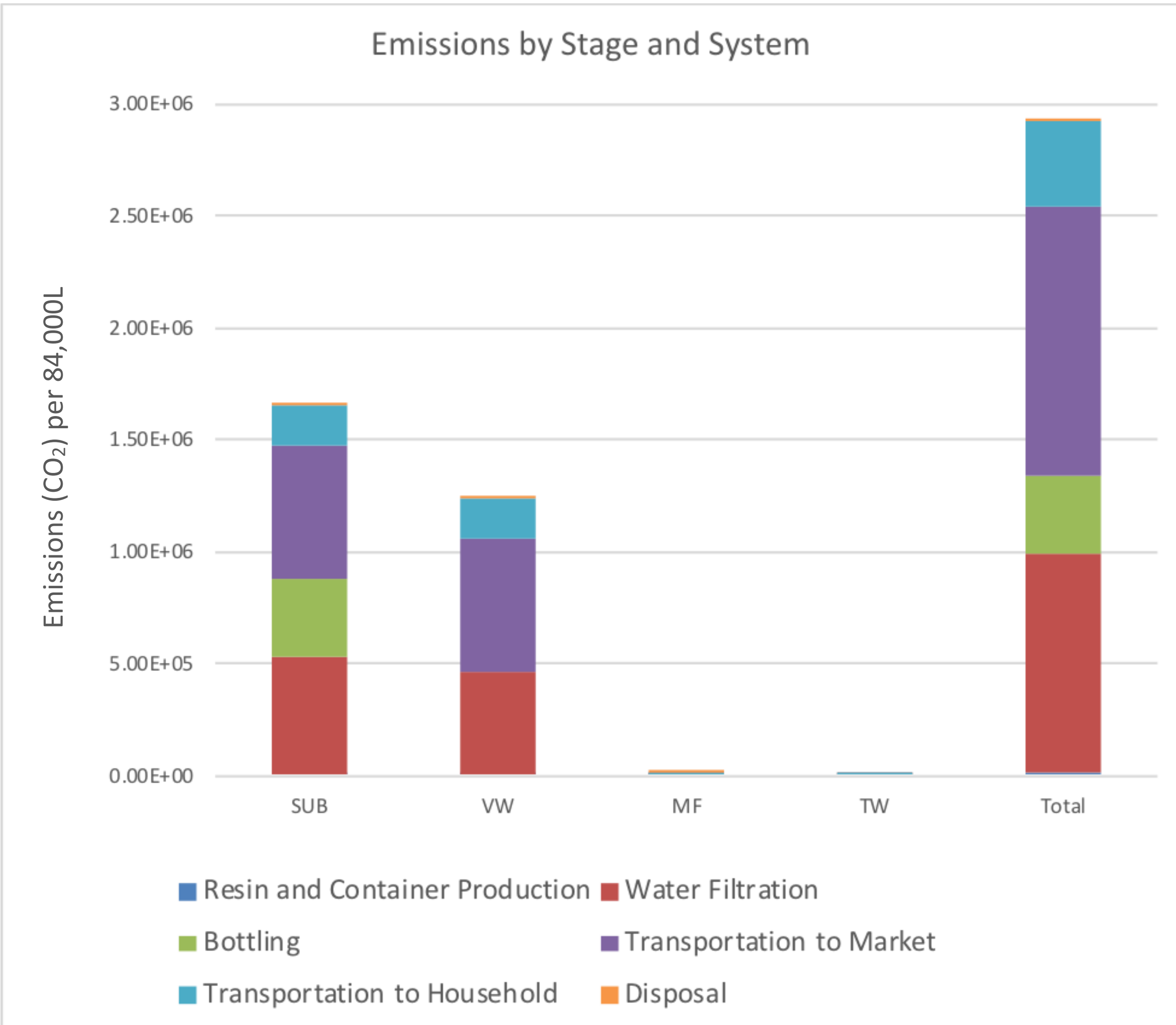

Figure 2.9: Carbon Dioxide Emissions by stage and system

2.6.5. Interpretation

Considering the energy and emission results the system that uses the lowest amount of energy and lowest CO_2 emissions is the municipal tap water system. The next best alternative to municipal tap water is the mobile system. The case study being looked at in this analysis does not have the option of municipal tap water because there is no infrastructure in the area, and it is not forthcoming. Thus, the least emitting practical system is the mobile one. One of the main reasons the mobile system is lower emitting is because the electricity used in the water filtration stage is provided by low emitting solar energy which has much less emissions compared to coal powered electricity. Another benefit of the mobile system is that the water filtration system is mobile and shared between two nearby colonias. This means that there is great emissions savings with respect to transportation.

2.7. Conclusion

Colonias are water stressed communities on the Texas-Mexico border a number of which do not have potable water access and also face poor quality potential ground and surface water supplies. As a possible source of potable water supply, a mobile solar powered water filtration unit that could purify diminished quality water is evaluated. The results show the mobile system is lower cost and lower GHG emitting relative to currently used bottled water and large jug water from vending machines. The study estimates that the shared mobile unit would cost approximately $39 per person per year, or $2.7 million per year for all of the colonias in Texas that are classified as without water (called red colonias). The per liter cost of this alternative is \$0.0036 which is 81% lower than current small bottle supplied and 29% less than large bottle supplies.

A life cycle analysis was done comparing emissions across alternative water supply means. The results show that a tap water system has the lowest emissions and costs per liter, but that the proposed mobile water filtration unit is the next best of those alternatives in terms of cost, energy use and carbon dioxide emissions.

2.8. References

Barton, J., E. R. Perlmeter, E. Sobel-Blum, and R. Marquez. 2015. *Las Colonias in the 21st Century: Progress Along the Texas–Mexico Border.* Monograph, Federal Reserve Bank of Dallas, number 00002.

Freyman, M. 2014. Hydraulic Fracturing & Water Stress: Water Demand by the Numbers. https://core.ac.uk/download/pdf/71364916.pdf (accessed November 20th, 2018).

Chen, C., D. Gillig, and B. A. McCarl. 2001. "Effects of Climatic Change on a Water Dependent Regional Economy: A Study of the Texas Edwards Aquifer". *Climatic Change* 49(4):397-409.

Davidhizar, R. and G.A. Bechtel. 1999. “Health and quality of life within *colonias* settlements along the United States and Mexico border.” *Public Health Nursing* 16(4): 301–306.

Dettore, C. G. 2009. *Comparative life-cycle assessment of bottled vs. tap water systems*. Report no. CSS09-11. Ann Arbor, MI, USA: Center for Sustainable Systems, School of Natural Resources and Environment, University of Michigan.

Freyman, Monika. 2014. Hydraulic Fracturing & Water Stress: Water Demand by the Numbers. https://core.ac.uk/download/pdf/71364916.pdf (accessed November 20th, 2018).

Hamilton, D. 2001. "Closing the Loop on Material Selection". *Water and Wastes Digest.* June. Web. Accessed 18 October 2019.

Hooper, A. and M., Dan. 2018. *An Analysis of the Operational Costs of Trucking: 2018 Update.* American Transportation Research Institute.

International Energy Agency (IEA). 2012. *Water for Energy: Is Energy Becoming a Thirstier Resource?* https://www.iea.org/media/publications/weo/WEO_2012_Water_Excerpt.pdf (accessed November 20, 2018).

Jepson, W. 2012. "Claiming Space, Claiming Water: Contested Legal Geographies of Water in South Texas." *Annals of the Association of American Geographers* 102(3):614-631.

Jepson, W. and H. L. Brown. 2014a. "'If no gasoline, no water': privatizing drinking water quality in South Texas colonias." *Environmental and Planning A* 46:1032-1048.

Jepson, W. 2014b. “Measuring ‘no-win’ waterscapes: Experience-based scales and classification approaches to assess household water security in colonias on the US–Mexico border.” *Geoforum* 51:107-120.

Jepson, W and E. Vandewalle. 2016. “Household Water Insecurity in the Global North: A Study of Rural and Periurban Settlements on the Texas–Mexico Border.” *The Professional Geographer* 68(1): 66-81.

Keplinger, K., B. A. McCarl, M. Chowdhury, and R. Lacewell. 1998. Economic and Hydrology Implications of Suspending Irrigation in Dry Years. *Journal of Agricultural and Resource Economics* 23(1): 191-205.

Knutti, R., J. Sedlacek. 2013. “Robustness and uncertainties in the new CMIP5 climate model projections.” *Nature Climate Change* 3:369-373.

Lambert, T. 2016. *Economically Distressed Areas Program (EDAP).* Texas Legislative Budget Board (LBB).

Mroz, R. C, L. L. Morales, and J. Van Derslice. 1996. “Health and hygiene in the Colonias: Water and disease.” *Family and Community Health* 19(1): 49-58.

Nicot, J. P., R. Reed, R. Costley, and Y. Huang. 2012. *Oil and Gas Water Use in Texas: Update to the 2011 Mining Water Use Report.* Texas Water Development Board. http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830939_2012Update_MiningWaterUse.pdf (accessed October 12, 2018).

Olmstead, S. M. 2004. “Thirsty *colonias*: Rate regulation and the provision of water service.” *Land Economics* 80:36-150.

Organisation for Economic Cooperation and Development (OECD). 2012. *Environmental Outlook to 2050: The Consequences of Inaction.* http://www.oecd.org/environment/indicators-modelling-outlooks/49844953.pdf (accessed November 20, 2018).

Parcher J. W. and D. G. Humberson. 2007. *CHIPS: A New Way to Monitor Colonias Along the United States-Mexico Border.* United States Geological Survey. Open-File Report 2007-1230.

Rassenfoss, S. 2011. “From Flowback to Fracturing: Water Recycling Grows in the Marcellus Shale.” *Journal of Petroleum Technology* 63:48-51.

Steen, M. 2000. *Greenhouse Gas Emissions from Fossil Fuel Fired Power Generation Systems*. European Commission Report EUR 19754 EN (61 p.). Joint Research Centre, Institute for Advanced Materials.

StratoSolar. 2018. *World Primary Energy in 2050: Based on EIA Baseline Projection.* http://www.stratosolar.com/2050-world-energy-sankey-diagram.html (accessed November 18, 2018).

Thayer, A. 2018. “Climate, Water, Water Markets and Texas Agriculture: Three Essays.” PhD dissertation, Department of Agricultural Economics, Texas A&M University.

United Nations (UN). 2017. *The Future of the World's Population in 4 Charts.* https://blogs.worldbank.org/opendata/future-world-s-population-4-charts (accessed November 20, 2018).

U.S. Energy Information Administration (EIA). 2017. *EIA Projects 28% increase in World Energy Use by 2040.* https://www.eia.gov/todayinenergy/detail.php?id=32912 (accessed November 20, 2018)

U.S. Environmental Protection Agency (EPA). 2014. *Greenhouse Gas Emissions from a Typical Passenger Vehicle.* National Service Center for Environmental Publications (NSCEP). Pubnumber: 420F14040

U.S. Geological Survey (USGS). 2016. *How much water is there on, in, and above the Earth?* https://water.usgs.gov/edu/earthhowmuch.html (accessed on November 4, 2018).

U.S. Geological Survey (USGS). 2013. *Groundwater Depletion in the United States (1900-2008).* https://pubs.usgs.gov/sir/2013/5079/SIR2013-5079.pdf (accessed on November 10, 2018).

3. FORECASTED WATER USE IN THE TEXAS FRACKING INDUSTRY AND INNOVATIVE WATER ALTERNATIVES

3.1. Introduction

In a world with increasing water scarcity there are possible reallocations to high value users from lower valued user. The increased prevalence of hydraulic fracturing is adding a new source of high valued water demand. Globally, estimates indicate approximately 52 cubic kilometers (km^3) or 42 million-acre feet (AF) of freshwater is consumed annually by the energy sector (Spang et al. 2014). Hydraulic fracturing, within energy production, is a significant and growing user in Texas using an estimated 81.5 thousand acre feet in 2011 (Nicot et al 2018).

Hydraulic fracturing or 'fracking' is the act of extracting oil and natural gas by forcing a liquid at high pressure against a target rock formation until it cracks or fractures (USGS 2018). While the concept of fracking has been known for a century, modern fracking as we know it was implemented in the early 1940's and became more successful with the 1990's marriage of hydraulic fracturing and horizontal drilling (Business Insider 2015). With horizontal drilling, typically when the target rock unit is reached, the drill follows a horizontal path through the target rock. Then when this is integrated with fracking, water, chemicals and sand are injected to fracture oil or natural gas bearing rock formations thus releasing the natural gas and oil facilitating flow to a production well.

The largest and most productive natural gas shale plays are in Pennsylvania and Texas, but freshwater usage in the fracking process varies greatly between the two. In the Marcellus Shale in Pennsylvania, the fracking industry recycles 97% of their produced water while the Eagle Ford Shale in Texas is principally using freshwater.

3.2. Objective

The objective of this study is to review evidence on freshwater usage in shale formations, forecast the expected volume of water needed in the Eagle Ford Shale, estimate the cost of water delivered to fracking sites and explore conditions when it is cost efficient to employ produced water recycling.

3.3. Literature Review

Here we will discuss studies on the Marcellus shale play in Pennsylvania and the Eagle Ford shale play in Texas. These two shale plays were chosen because of their substantial contribution to United States natural gas production. We will also discuss the water and energy demands in Texas.

3.3.1. Marcellus Shale

In 2010 a study on fracking in Pennsylvania's Marcellus Shale showed that 96% of the produced water was reused (Rassenfoss 2011). When modern fracking was in its infancy, Pennsylvania used freshwater in their fracking process. However, after the fracture, oil is recovered along with a portion of the fracking water and that water is called produced water. Produced water must be treated and properly disposed or reused. Beginning in 2001, three produced water treatment/disposal practices arose: 1) use of municipal water treatment facilities, 2) use of industrial water treatment facilities and 3) use of underground injection. However, in 2011 municipal and industrial water treatment facilities were required to a halt produced water treatment due to high total dissolvable solids discharged into the Monongahela River basin. At the same time, Ohio was experiencing greater earthquakes due to underground disposal injection wells and that later resulted in stricter disposal regulations (Rabe and Borick 2013). With the injection restrictions and the high cost of transportation to available injection wells, the industry turned to recycling produced water on or near site. Economically recycling produced water was the industry's lowest cost option and more efficient than hauling to distant disposal sites while using freshwater.

3.3.2. Eagle Ford Shale

The Eagle Ford Shale in South Central Texas used approximately 24 thousand AF of water in 2011 (Nicot et al. 2012). About 5% of produced water is recycled in the Eagle Ford shale. This low percentage of recycled water is due to relative cost of treatment and the cost of produced water transport and disposal versus the cost of procuring and transporting freshwater. However, if freshwater demand is expected to increase in the Eagle Ford shale, causing greater scarcity or stricter regulations on treatment and disposal, recycling may become more attractive.

3.3.3. Texas Water Demand

The population of Texas is the second largest in the United States and Texas is the fastest growing state (U.S Census Bureau, 2011, 2014). Currently the population is 28.3

million but is projected to increase to 51 million by 2070 (**Figure 3.1**). With the increase in population one would expect to see a demand for freshwater to match. However, the

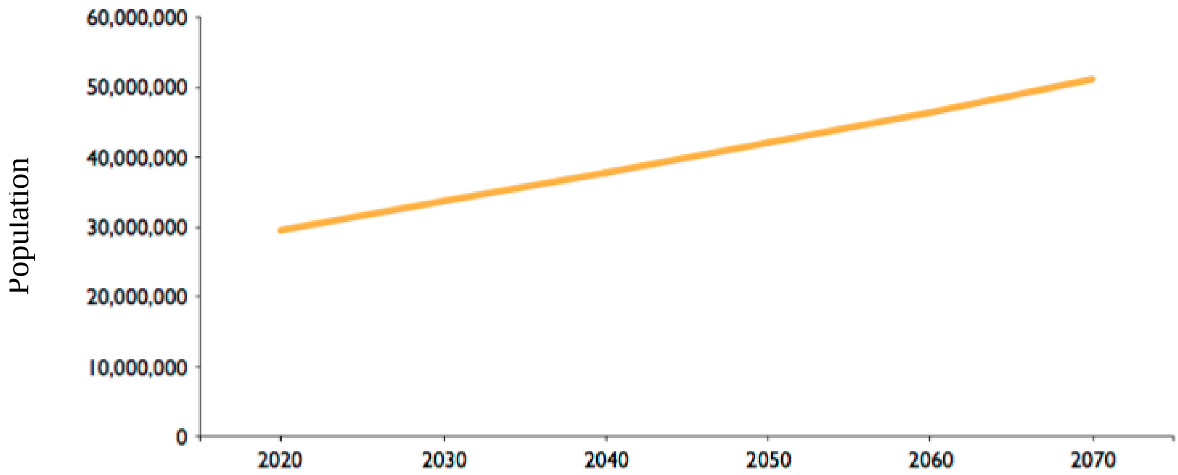

Figure 3.1: Projected population in Texas (TWDB 2017)

Texas Water Development Board (TWDB) projection of water demand to 2070 shows it only increasing by 17% from current levels (**Figure 3.2**). This is because there are multiple sectors competing for water (**Figure 3.3**) and each sector is projected to make technological advancements in water use efficiency at different rates plus large increases in water supplies are not expected to occur. Municipal freshwater demand is projected as the fastest growing demand component in Texas. With consideration of the planet's limited freshwater supply, in **Figure 3.3** we can see that the water needed to fulfill municipal needs will most likely be traded off from the decrease in water used within the agricultural sector.

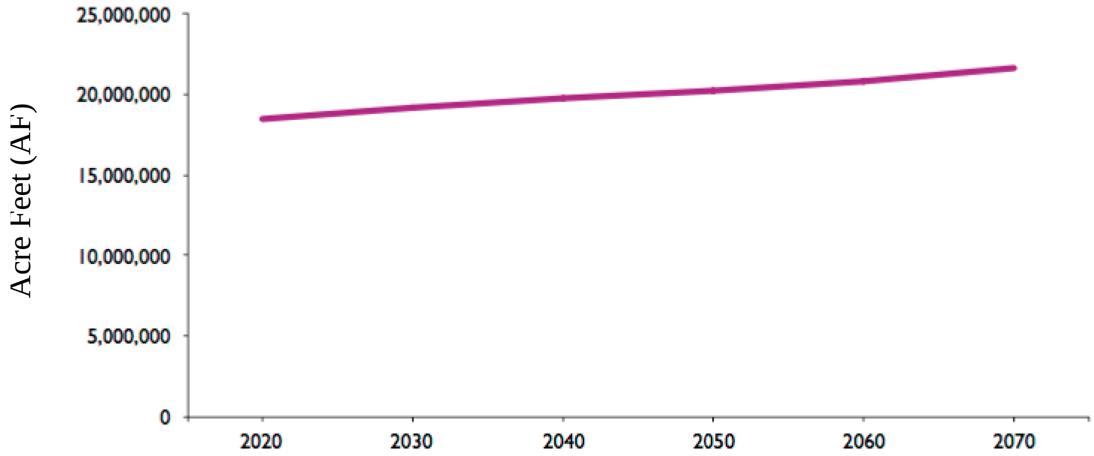

Figure 3.2: Projected annual water demand in Texas in AF (TWDB 2017)

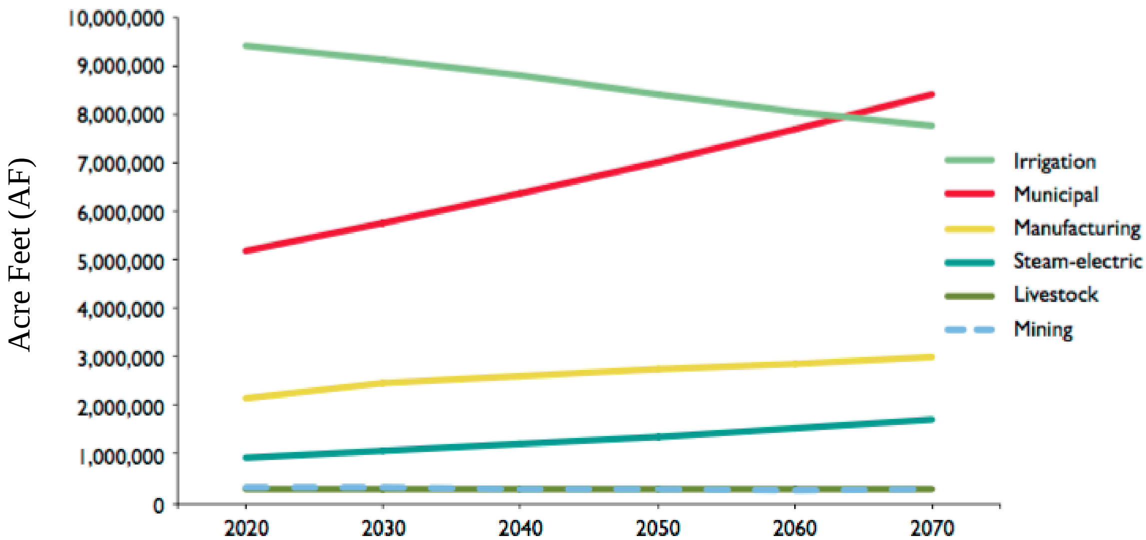

Figure 3.3: Projected annual water demand by water use category in AF (TWDB 2017)

Fracking in Texas uses only 1% of the freshwater demanded throughout the state or 184,070 acre feet (AF) of freshwater (TWDB 2017). However, as freshwater is increasingly becoming more valuable such that the low percentage should not dissuade the industry from innovating and using less freshwater, especially as a majority of well plays are in regions that are water stressed (**Figure 3.4**: Freyman 2014).

Another consideration is the cost of hauling and transporting freshwater to the well play. The cost of the water itself is low, however the cost of transporting the water to its final destination is high. As water stress intensifies with climate change and municipal water demand increases, pumping freshwater and transporting the water to the well play will become increasingly more expensive.

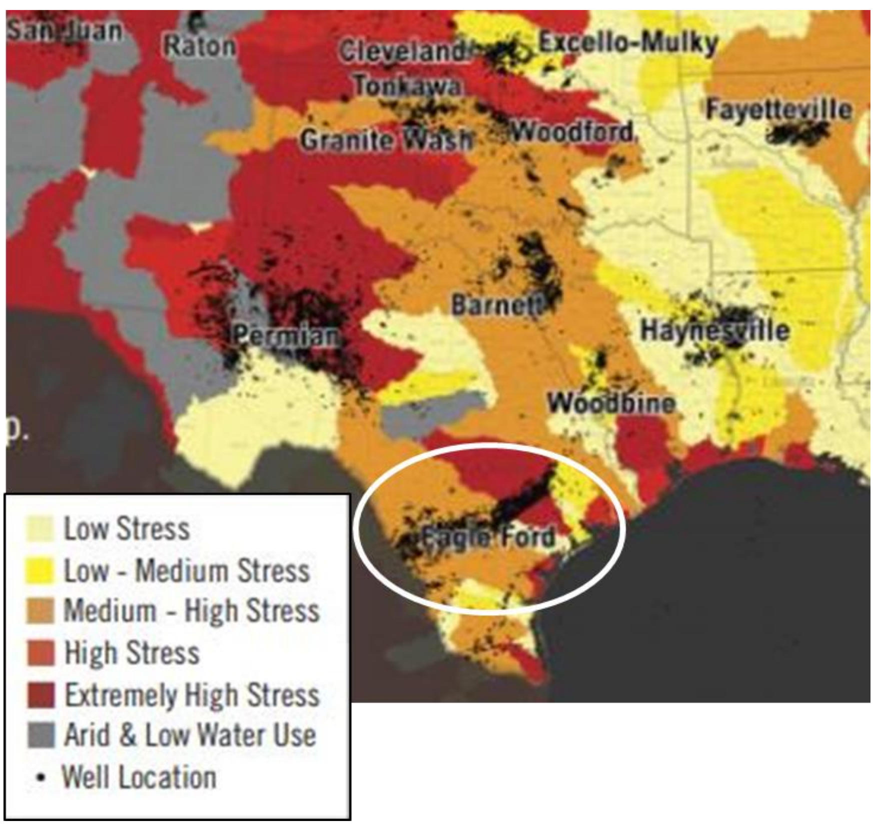

Figure 3.4: Level of water stress and oil and gas wells in Texas (Freyman 2014)

3.3.4. Texas Energy Demand

In 2018, Texas consumers used approximately 376 terawatt-hours (TWh) of energy (ERCOT 2019). The Texas long-term load forecast shows an increase of approximately 28% from 2019 to 2029 (**Figure 3.5**). Of the energy consumed, 38% or 144 TWh were generated from natural gas. Natural gas is the largest used source of generation energy in Texas with coal a close second at 25% or 93 TWh. The third largest source is wind energy at 19% or 70 TWh and is likely to overtake coal in the coming years as wind investments continue (ERCOT 2018).

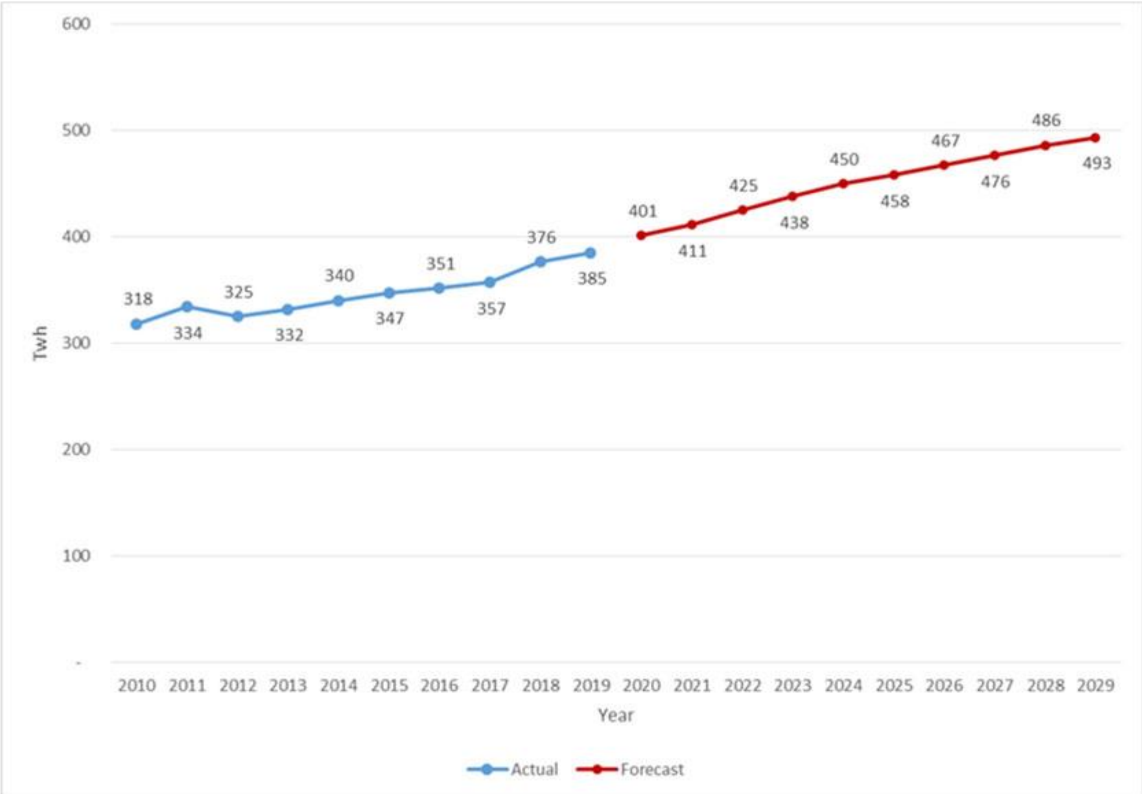

Figure 3.5: Projected annual energy demand in terawatt hours in Texas to 2029 (ERCOT 2019)

3.4. Data

3.4.1. Forecasting Eagle Ford Activity

Here I would like to forecast the water volume used in each county that is a part of the Eagle Ford shale to determine future demand. To do this I will be using monthly fracking data from 2011 to 2017 from FracFocus. Each of the 29 Texas counties that are within the in the Eagle Ford shale are considered: 1) Attacosa, 2) Bastrop, 3) Bee, 4) Brazos, 5) Burleson, 6) DeWitt, 7) Dimmit, 8) Duval, 9) Fayette, 10) Frio, 11) Goliad, 12) Gonzales, 13) Grimes, 14) Karnes, 15) La Salle, 16) Lavaca, 17) Lee, 18) Leon, 19) Live Oak, 20) Madison, 21) Maverick, 22) McMullen, 23) Milam, 24) Robertson, 25) Walker, 26) Washington, 27) Webb, 28) Wilson and 29) Zavala. After the implementation of the Texas Hydraulic Fracturing Disclosure Rule all oil and gas operators are required to disclose the total volume of water used and the chemical ingredients used in their fracking treatments (TAC 2012). Operators can also voluntarily provide additional information, including total recycled water used. Needless to say, firms are profit maximizers who keep their operational practices confidential and thus do not report or disclose much of the information that this study would find useful.

3.4.2. Water Cost Data

One exercise done herein is estimation of the cost of water delivered to well heads. The cost data used for this estimation is from Baker Hughes (Sharr 2014), who breaks down the typical range of the costs of raw Eagle Ford Shale water into eight categories: 1) freshwater sourcing, 2) freshwater transfer, 3) freshwater storage, 4) freshwater treatment, 5) freshwater transfer, 6) produced water storage, 7) produced water transport and 8) produced water treatment. The first five components include the costs associated with supplying the freshwater (FW) to the well head and the last three components are the costs associated for treating the produced water (PW). From the cost ranges provided by Baker Hughes we obtained low, mean and high cost scenarios for each component and kept those costs not pertaining to transportation fixed (**Table 3.1**). By observing **Table 3.1** we can see that the sum of water transportation costs (FW transport, FW transfer and PW transport) is greater than the cost of freshwater and produced water treatment. This is further testament to the significant amount of cost that goes into water transportation and motivates how freshwater alternatives that allow for recycle and reuse at or near the well play can benefit the producer.

Table 3.1: Baker Hughes Water Cost Decomposition

$/bbl	*FW Sourcing*	*FW Transport*	*FW Storage*	*FW Treatment*	*FW Transfer*	*PW Storage*	*PW Transport*	*PW Treatment*	*Total FW Cost/bbl*
Low	0.30	1.00	1.00	0.10	0.60	1.00	2.00	1.00	$ 7.00
Mean	0.55	2.50	2.50	0.30	0.80	1.50	4.00	5.50	$ 17.65
High	0.8	4.00	4.00	0.50	1.00	2.00	6.00	10.00	$ 28.30

The components pertaining to transportation (2), (5) and (7) were decomposed further into cost of trucking the water and the distance in miles of transportation. The cost of trucking was pulled from the American Transportation Research Institute annual report (ATRI 2018) where there are estimates on the average marginal cost per mile. The cost includes both vehicle-based costs (fuel costs, truck/trailer lease, repair and maintenance, insurance, tires, etc.) and driver-based costs (driver wages and driver benefits). The average number of gallons in a water tanker truck was drawn from British Columbia Tap Water Association (BCTWA 2010). The cost of transporting 1 barrel of water 1 mile was computed by dividing the cost of trucking per mile by the number of barrels carried in the water truck.

Table 3.2: Key Assumptions and Conversions

Trucking Assumptions	
Cost of Trucking per Mile (2017) (ATRI)	$ 1.69
Gallons carried in Truck (BCTWA)	6,250
Gallons per barrel (bbl)	42
Barrels Carried in Truck	149
Cost of Transportation (bbl/mile)	$ 0.011
Low Cost of Transporting FW	$3.60
Mean Cost of Transporting FW	$7.30
High Cost of Transporting FW	$11.00

3.4.3. Recycled Water Data

Next we proceeded to estimate the cost of recycled water. Data on recycling infrastructure was drawn from the Approach Resources (Haines 2018). Using the Baker Hughes cost scenarios for cost of recycling water per barrel, we arrive at the cost estimates in **Table 3.3**. Unfortunately, we do not know cost components included in the recycled water total cost estimate. We will assume that the cost covers treatment, transfer and storage of the recycled water prior to reuse.

Table 3.3: Cost Savings

Cost Savings from recycling infrastructure	
Low Savings from Recycling (AR)	$ 3.20
Mean Savings from Recycling (AR)	$ 3.85
High Savings from Recycling (AR)	$ 4.20
Low Total Recycled water cost	$3.80
Mean Total Recycled water cost	$13.80
High Total Recycled water cost	$24.10

To determine the funds that can be allocated to transport, we subtract the cost of sourcing, storing, treatment of any freshwater and produced water from **Table 3.1** from the total recycled water cost in **Table 3.3.** This cost will cover transportation of produced water from the well to storage, treatment, storage and back to the well for reuse.

Table 3.4: Total Cost of Transporting Recycled Water

Total Cost of Transporting Recycled Water	
Low Cost to Transport Recycled Water	$ 0.40
Mean Cost to Transport Recycled Water	$ 3.45
High Cost to Transport Recycled Water	$ 6.80

3.5. Eagle Ford Shale Water Forecast

3.5.1. Forecast Methodology

Now we turn to forecasting the water needs for Eagle Ford shale fracking. To do this county level data is used in a linear regression model (Wooldridge 2010):

$$\boldsymbol{y = x\beta + u} \quad \textbf{(1)}$$

where $\boldsymbol{y}$ is the dependent variable, $\boldsymbol{x}$ is a set of independent variables**,** $\boldsymbol{\beta}$ is the coefficient for the independent variables and $\boldsymbol{u}$ is the error term. The linear regression will fit a line to the available data and use the slope to forecast future values. In this case we have forecasts of total water use for the 29 counties that are a part of the Eagle Ford shale:

$$\boldsymbol{FutureWaterUse_1 = PastWaterUse_1\beta + u} \quad \textbf{(2)}$$

$$\boldsymbol{FutureWaterUse_2 = PastWaterUse_2\beta + u} \quad \textbf{(3)}$$

$$\boldsymbol{FutureWaterUse_3 = PastWaterUse_3\beta + u} \quad \textbf{(4)}$$

$$\boldsymbol{\dots}$$

$$\boldsymbol{FutureWaterUse_{27} = PastWaterUse_{27}\beta + u} \quad \textbf{(28)}$$

$$\boldsymbol{FutureWaterUse_{28} = PastWaterUse_{28}\beta + u} \quad \textbf{(29)}$$

$$\boldsymbol{FutureWaterUse_{29} = PastWaterUse_{29}\beta + u} \quad \textbf{(30)}$$

such that

FutureWaterUse $_{1}$ **-*FutureWaterUse*** $_{29}$ are the forecasted values of water use from the seventh month of 2017 to the twelfth month of 2025.

$PastWaterUse_1$-$PastWaterUse_{29}$	are the available data on water volumes from the first month of 2011 to the sixth month of 2017.
β	is the coefficient on ***PastWaterUse.***
u	is the error term.

3.5.2. Forecast Results

Table 3.5 gives the results of the regression equations **(2)-(30)**.

Table 3.5: Forecast Regression Results

		Date Month	t-statistic	Constant	t-statistic	N	R-sq	adj. R-sq
1) Attacosa	Total Water	742107.0**	(2.65)	-411342301.5*	(-2.26)	77	0.086	0.073
2) Bastrop	Total Water	758.1	(0.13)	-367915.2	(-0.10)	77	0	-0.013
3) Bee	Total Water	-27217.6*	(-2.51)	18703002.3**	(2.66)	77	0.078	0.065
4) Brazos	Total Water	284698.2	(1.97)	-162029714.7	(-1.72)	77	0.049	0.036
5) Burleson	Total Water	655015.6***	(4.38)	-403049821.3***	(-4.14)	77	0.203	0.193
6) DeWitt	Total Water	1066199.0**	(3.15)	-587733162.2**	(-2.67)	77	0.117	0.105
7) Dimmit	Total Water	-169153.7	(-0.30)	318544029.5	(0.87)	77	0.001	-0.012
8) Duval	Total Water	-31.86	(-0.20)	30397.5	(0.3)	77	0.001	-0.013
9) Fayette	Total Water	38478.1	(0.8)	-19245676.1	(-0.61)	77	0.008	-0.005
10) Frio	Total Water	286241.2**	(2.95)	-164480807.6*	(-2.60)	77	0.104	0.092
11) Goliad	Total Water	490.3*	(2.11)	-308576.3*	(-2.05)	77	0.056	0.044
12) Gonzales	Total Water	524706.5*	(2.24)	-248217045.1	(-1.63)	77	0.063	0.05
13) Grimes	Total Water	-7276.6	(-0.34)	6643508.9	(0.48)	77	0.002	-0.012
14) Karnes	Total Water	2250235.2***	(4.9)	-1.27645e+09***	(-4.27)	77	0.242	0.232
15) La Salle	Total Water	1031518.5	(1.63)	-451437243.5	(-1.10)	77	0.034	0.021
16) Lavaca	Total Water	189499.9	(1.94)	-106679093.6	(-1.68)	77	0.048	0.035
17) Lee	Total Water	43056	(1.00)	-24796514.1	(-0.89)	77	0.013	0
18) Leon	Total Water	-93997.2*	(-2.62)	65890372.0**	(2.83)	77	0.084	0.072
19) Live Oak	Total Water	-258318.2	(-1.58)	203393530.5	(1.91)	77	0.032	0.019
20) Madison	Total Water	2225	(0.04)	7695190.3	(0.21)	77	0	-0.013
21) Maverick	Total Water	-70948.8*	(-2.41)	48434376.7*	(2.53)	77	0.072	0.06
22) McMullen	Total Water	454337.2	(1.07)	-163171004.4	(-0.59)	77	0.015	0.002
23) Milam	Total Water	-11123.1	(-1.80)	7709897	(1.91)	77	0.041	0.028
24) Robertson	Total Water	-40600.1	(-1.01)	31808263.8	(1.22)	77	0.014	0
25) Walker	Total Water	-1313.4	(-0.09)	1786818.5	(0.18)	77	0	-0.013
26) Washington	Total Water	-10191.1	(-1.11)	7423984.5	(1.24)	77	0.016	0.003
27) Webb	Total Water	722739	(1.91)	-331685054.5	(-1.35)	77	0.047	0.034
28) Wilson	Total Water	-159022.2**	(-3.33)	110479631.4***	(3.55)	77	0.129	0.117
29) Zavala	Total Water	-6383.1	(-0.07)	21299973.4	(0.37)	77	0	-0.013

Note: 1) t-statistics are in parentheses
2) * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

We can see that approximately half of the counties do not contribute greatly to the fracking water demand of the Eagle Ford shale. However, counties such as Atascosa, Bee, Burleson, DeWitt, Frio, Goliad, Gonzales, Karnes, Leon, Maverick, and Wilson all have significant water volumes (Total Water) with respect to time (Date Month). The statistical measure R_2, represents the amount of variance in the dependent variable that is explained by the independent variables in a regression model, in other words, a goodness of fit measure. The adjusted R_2, is similar to R_2 except that it adjusts for the number of independent variables added to the model. The R_2 values are low in this case as we fitted a line to the rising and falling, nonlinear fracking water use volume data.

Though the results show a significant forecasted increase in water volume used in the Eagle Ford shale, the fracking industry as a whole is still in its infancy. As such, with the industry newly established it is difficult to determine if the upward trend of water volume is likely to unfold or if it will plummet as it did in early 2016 (Macrotrends 2019) when the oil price dropped.

Figure 3.6 shows the resultant forecasted water demand in the Eagle ford shale counties.

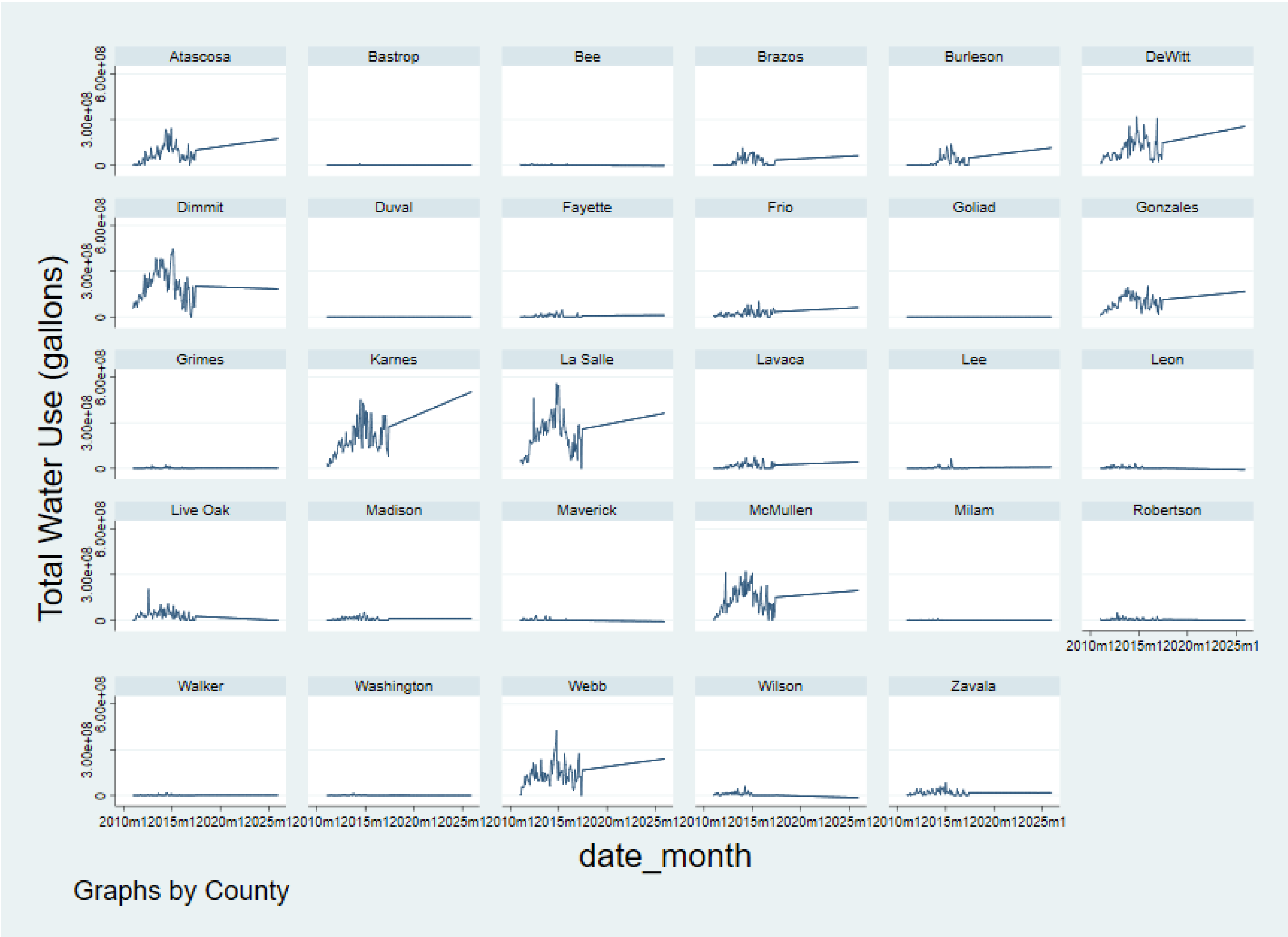

Figure 3.6: Forecasted water use in the Eagle Ford shale to 2025

3.6. Eagle Ford Shale Breakeven Analysis

Water supplies can be distant from fracking sites and is typically trucked into the site. To better understand the cost of water and how much the industry could invest in recycling produced water we compute the breakeven number of miles that water can be transported until it is better to recycle.

3.6.1. Breakeven Methodology

In a traditional breakeven analysis, one typically finds the point where fixed costs and variable returns are equal. In this study, the costs we will be equating are the cost of transporting freshwater and the cost of recycling and delivering produced water. Due to the nature of the recycled water cost, we will keep the cost of delivered recycled water fixed with three scenarios for its transport cost component. Then we will decompose the cost of transporting freshwater into the cost per mile of transport and the number of miles traveled. This will be done for each delivered recycled produced water scenario; low, mean and high:

$$\mathrm{RW_L = FW = FWTransport{*}Distance_L} \quad \textbf{(1)}$$

$$\mathrm{RW_M = FW = FWTransport{*}Distance_M} \quad \textbf{(2)}$$

$$\mathrm{RW_H = FW = FWTransport{*}Distance_H} \quad \textbf{(3)}$$

such that

RW_L – RW_H	are the fixed recycled water transportation costs at low, mean and high scenarios from **Table 3.4**.
FW	is the total cost of transporting freshwater.
FW Transport	is the cost of transporting one barrel of freshwater for one mile from **Table 3.2.**

Distance$_L$* – *Distance$_H$ the breakeven number of miles that can be travelled given the total costs of transportation.

The parameters of interest here are ***Distance$_L$* – *Distance$_H$*.** If we change equations (1)-(3) to focus on the parameter of interest, we have:

$$\text{Distance}_L = \frac{RW_L}{FWTransport} \quad \textbf{(4)}$$

$$\text{Distance}_M = \frac{RW_M}{FWTransport} \quad \textbf{(5)}$$

$$\text{Distance}_H = \frac{RW_H}{FWTransport} \quad \textbf{(6)}$$

Such that all variables are as described above.

3.6.2. Breakeven Results

The breakeven analysis determined the breakeven number of miles that equates the available cost of transporting recycled water to the cost of transportation and the distance traveled. **Table 3.5** gives the results of the analysis.

Table 3.6: Breakeven results for Eagle Ford Shale

Total Cost of Transporting Recycled Water	***Roundtrip (total)***	***One way***
Low Breakeven Miles	36.36	18.18
Mean Breakeven Miles	313.64	156.82
High Breakeven Miles	618.18	309.09

In a scenario where low costs are realized, the traditional freshwater system can only travel approximately 36 miles for total water transportation or 18 miles one way. In a scenario where mid-level costs are realized, we see an increase in travel miles where an estimated 314 miles is the total miles that can be allotted to the transportation of freshwater with 157 miles available for one way. Finally, at a high scenario produced water recycling cost a total of 618 miles can be travelled to transport freshwater to and within the well play with 309 miles allotted for one-way travel.

3.7. Discussion

Given the results from the forecast we see that demand for water is increasing in the Eagle Ford Shale along with increased municipal demand in all of Texas. As the Texas fracking increases production, water alternatives need to be considered. The breakeven analysis identifies conditions of where changes are in order. As the cost of transporting freshwater is the most expensive part of freshwater usage, the breakeven miles determine exactly how many miles traveled will equate to the cost of building recycled water infrastructure. When the producer needs to travel a distance larger than the ones stated in the breakeven analysis it is more cost efficient to invest in freshwater alternatives.

The breakeven analysis focusses on in house infrastructure to recycle and reuse water, but this may not be a viable option for certain oil and natural gas producers. If there is a medium to relatively small producer in the area without the capital to spend on in house recycled water infrastructure, other alternatives can be considered. Recently, producers in Odessa and Medina counties in Texas have reached out to the municipalities about altering their wastewater facilities to permit treatment of produced water and with the producers repurchasing that water for reuse (*Reclaimed Water Supply Agreement between the City of Odessa, Texas and Pioneer Natural Resources USA, Inc.*). Additionally, that reclaimed water while not being suitable for human consumption could be reused in certain agricultural and industrial processes. This type of agreement is beneficial for both producers and municipalities because producers can acquire water that is less expensive to transport to the well and municipalities get updated wastewater infrastructure as well as the potential for decreased strain on water supply in the area. **Table 3.6** outlines the costs of a barrel of water from each alternative, freshwater, recycled water and reclaimed water. The lowest cost estimate is the reclaimed water price, however, this does not take into account transportation from the municipal wastewater facility to the well pad. The reclaimed water price also does not take into account the maintenance and operations fee of $0.33 per 24 barrels of water and the prepayment of 3 million dollars to Odessa county to update their wastewater facility.

Table 3.7: Raw Cost of Available Water Alternatives per barrel

Cost of water by alternatives	***Cost ($/bbl)***	***Source***
Fresh Groundwater	*$0.55*	*Sharr (2014)*
Recycled Water	*$0.65*	*Haines (2018)*
Reclaimed Water	*$0.50*	*Reclaimed (2014)*

The same can be said for the fresh groundwater price. The price of the water does not include transportation from the water well to the well pad. Finally, though the recycled water price does include the treatment and transportation of the water within the well system, it does not take into account the initial cost of building the recycled water infrastructure and assumes it is already in place.

3.8. Conclusions

Water demand in Texas is increasing for both municipalities and industry. Here we forecasted the water demand and estimated the water cost for hydraulic fracturing in the Eagle Ford shale in south central Texas in addition to examining cases where produced water recovered from wells is competitive when recycled for additional use in fracking. Our forecast results show that fracking water demand for use in the Eagle Ford shale is increasing. With the increase in water demand, raw water alternatives must be considered as the cost of water used in the process increases with the distance that must be traveled to procure it.

For freshwater transport it is likely that increasing water demand will involve more distant water and at some point, increasing distances may make recycling of produced water competitive. Specifically, we determined the breakeven miles or distance that can be travelled such that raw freshwater transported in just equaled the cost of recycling water with existing infrastructure. There we found the breakeven transport miles under low mean and high produced water reuse cost scenarios are 36, 314 and 618 miles respectively.

Finally, we discussed the value of pumped freshwater, recycled water and reclaimed water. The reclaimed water had the lowest cost $0.50 per barrel of water with pumped freshwater a close second ($0.55/bbl) and recycled water being the most expensive ($0.65/bbl). This was done in the context of an agreement with a municipality for water treatment to acceptable levels. Thus, with increased future fracking and increasing distances to freshwater, alternatives to freshwater pumping will become more common place.

3.9. References

16 Tex. Admin. Code (TAC) §3.29 (2012) (Railroad Commission of Texas, Hydraulic Fracturing Chemical Disclosure Requirements).

British Columbia Tap Water Association (BCTWA). 2010. *How many tanker trucks does it take to supply water to, and remove wastewater from, a horizontally drilled and hydrofracked wellsite?* http://www.bctwa.org/Frk-HowManyTankerTrucks.pdf (accessed August 20, 2019)

Business Insider. 2015. *The origin of fracking actually dates back to the Civil War.* https://www.businessinsider.com/the-history-of-fracking-2015-4 (accessed on November 11,2019).

Electric Reliability Council of Texas (ERCOT). 2018. *Fuel Mix Report.* http://www.ercot.com/content/wcm/lists/144927/Wind_One_Pager_FINAL.pdf (accessed December 10, 2019).

Electric Reliability Council of Texas (ERCOT). 2019. *Long-Term Load Forecast.* http://www.ercot.com/gridinfo/load/forecast (accessed December 10, 2019).

Freyman. 2014. *Hydraulic Fracturing & Water Stress: Water Demand by the Numbers.* https://core.ac.uk/download/pdf/71364916.pdf (accessed November 20th, 2018).

Haines, L. 2018. "Shaving Water Costs. Water Solutions." *Oil and Gas Investor.* May, pp. 69-72.

Hooper, A. and D. Murray. 2018. *An Analysis of the Operational Costs of Trucking: 2018 Update.* American Transportation Research Institute (ATRI). http://atri-online.org/wp-content/uploads/2018/10/ATRI-Operational-Costs-of-Trucking-2018.pdf (accessed October 10, 2018)

Macrotrends. 2019. *Crude Oil Prices-70 Year Historical Chart.* *https://www.macrotrends.net/1369/crude-oil-price-history-chart* (accessed December 10, 2019).

Nicot, J. P., R. Reed, R. Costley, and Y. Huang. 2012. *Oil and Gas Water Use in Texas: Update to the 2011 Mining Water Use Report.* Texas Water Development Board. http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/0904830939_2012Update_MiningWaterUse.pdf (accessed October 12, 2018).

Rabe, B. G. and C. Borick. 2013. "Conventional politics for unconventional drilling? Lessons from Pennsylvania's early move into fracking policy development." *Review of Policy Research* 30(3): 321-340.

Rassenfoss, S. 2011. “From Flowback to Fracturing: Water Recycling Grows in the Marcellus Shale.” *Journal of. Petroleum Technology* 63:48-51.

Reclaimed Water Supply Agreement between the City of Odessa, Texas and Pioneer Natural Resources USA, Inc.

Sharr, A. *Water Management Trends & The Eagle Ford.* Baker Hughes (November 2014): http://www.tamuk.edu/eagleford/pdf/Baker_Hughes_April%20Sharr.pdf (accessed August 15, 2019).

Spang, E. S., W. R. Moomaw, K. S. Gallagher, P. H. Kirshen and D. H. Marks. 2014. “The Water Consumption of Energy Production: An International Comparison.” *Environmental Research Letters* 9(10): 1-14.

Texas Water Development Board (TWDB). 2017. *2017 State Water Plan, Water for Texas Chapter 5: Future population and water demand.* https://www.twdb.texas.gov/waterplanning/swp/2017/chapters/05-SWP17-POPULATION-DEMAND.pdf (accessed on November 8, 2018).

U.S. Census Bureau. 2014. *State totals: Vintage 2014*. www.census.gov/popest/data/state/totals/2014 (accessed November 5, 2018)

U.S. Geological Survey (USGS). 2018. *Water Use in the United States: Total Water Use.* https://water.usgs.gov/watuse/wuto.html (accessed on October 30, 2018).

Wooldridge, J. M. 2010. *Econometric Analysis of Cross Section and Panel Data*. MIT Press Books, The MIT Press, edition 2, volume 1, number 0262232588.

4. AGRICULTURAL RESEARCH AND DEVELOPMENT AS CLIMATE CHANGE ADAPTATION IN AGRICULTURE

4.1. Introduction

The next 25 years we are in an era of committed climate change where it appears temperatures will rise by about one degree centigrade regardless of mitigation effort (IPCC 2014). This is a concerning realization as some estimate such warming will reduce global crop production by greater than 10% by 2050 (Tai, Martin, Heald 2014). Such reductions in crop production would threaten food supplies and the situation would worsen over time as the global population is projected to increase from 7.9 billion in 2019 to 9.8 billion by 2050 (UN 2017). Income growth is also projected with alterations toward meat consumption which also requires increased productivity of livestock feeds (FAO, 2009). These forces raise the question, “How are we going to feed the future?” With the increase in food demand and limited possibilities for land and water use expansion in many areas (Ehrlich and Harte 2015) as population grows, scientific advances increasing crop yields are vital.

Villavicencio et al. (2013) shows that increases in agricultural research and development (R&D) investment and total precipitation contribute to agriculture productivity growth, while temperature increases reduces productivity. Thus, investment in research is a good form of increasing future crop production to offset climate induced reduction, However, Alston, Babcock and Pardey (2010) warn that the peak effect of research is felt 24 years in the future. In other words, if we want to see results in the future we have to invest now because the effects of research and implementation take time. Unfortunately, we have seen U.S. Public Agricultural R&D investment fall from $3.7 billion in 2007 to $ 2.7 billion in 2015 (USDA CRIS 2017). As a result, crop yield growth rates have fallen in every U.S. region displaying a slowing of technological advancement (Kapilakanchana 2016).

4.2. Objective

This study examines crop yield growth and the influence of total agricultural research and development funding and shares of funding towards crop productivity and adaptation along with changes in climate and the passage of time using data on historic crop yields in the United States. This will be done using county level US data which allows for insight into possible adaptations in research investment to help bolster future crop production.

4.3. Literature Review

The classical approach to determining impacts of inputs on production of outputs is founded in the estimation of production functions. Additionally, Just and Pope (1979) extended the production function approach so it accounted for the way inputs affected the variability of production with Chen, McCarl and Schimmelpfennig (2004) and McCarl, Villavicencio and Wu (2008) extending this to look at climate as one of the inputs. Just and Pope (1979) conclude that a production function used in variability analysis must contain a component that explains the effect of inputs on expected outputs alongside a second component where the output variability is explained by the effects of inputs.

Additionally, Mendelson, Nordhaus and Shaw (1994) defined the Ricardian approach where they consider how climate effects farmland rent or value, as opposed to crop yields. The approach was conceived as an alternative to the production function approach that they indicated overestimates damage of climate effects as it does not allow for farmer recourse and crop mix or other forms of adaptation.

To account for omitted variable bias the literature is seen to prefer the use of a panel data approach (Deschenes and Greenstone 2007; Schlenker and Roberts 2009). Deschenes and Greenstone (2007) use panel data and fixed effects to remove time invariant differences but results do not have large signal and they do not account for the option of farmers to store their grain and wait for a higher price in the market. Also, they do not consider technological advancement which overestimates the loss of farmer profits due to climate change. Chen, McCarl and Schimmelfennig (2004) and McCarl, Villavicencio, and Wu (2008) used panel approaches and found climate change had regionally differentiated impacts on crop yields and crop yield variance. Schlenker and Roberts (2009) find that the national agricultural yields of corn, soybeans and cotton increase until they respectively meet temperatures above 84.2^{o} F, 86^{o} F and 89.6^{o} F where there is a sharp decrease in production. Burke and Emerick (2016) use panel data to study the long-term trends of climate change on agricultural outcomes and find that long run adaptation might be able to mitigate potentially half but more likely none of the short-term impacts of high temperatures on production.

4.4. Panel Data

Panel data or cross-sectional approaches were used in this analysis. Panel data is data that has a number of observations (obs.) seen over time (t) on a number of cross-sectional individuals (i). In this study, we will have crop yields (obs.) by agricultural districts per state (i) over the course of 40 years (t).

4.4.1. Crop Data

Crop data was collected at the agricultural crop reporting district level per state from the United States Department of Agriculture National Agricultural Statistics Service (USDA NASS). Crops collected include corn, cotton, hay, sorghum, soybeans, winter wheat, and spring wheat from 1975-2015 (USDA NASS 2019). The states included are the 48 contiguous states (i.e. does not consider Alaska and Hawaii). The crop yields were calculated by dividing production by acres of land harvested. The share of acres that were irrigated for each crop was also considered.

Figures 4.1-4.7 present crop yields by state from 1975 to 2015 thus visualizing changes in yield growth rates over time. For states that have relatively low yields, the growth appears linear. However, states with high yields show an exponential growth in yields.

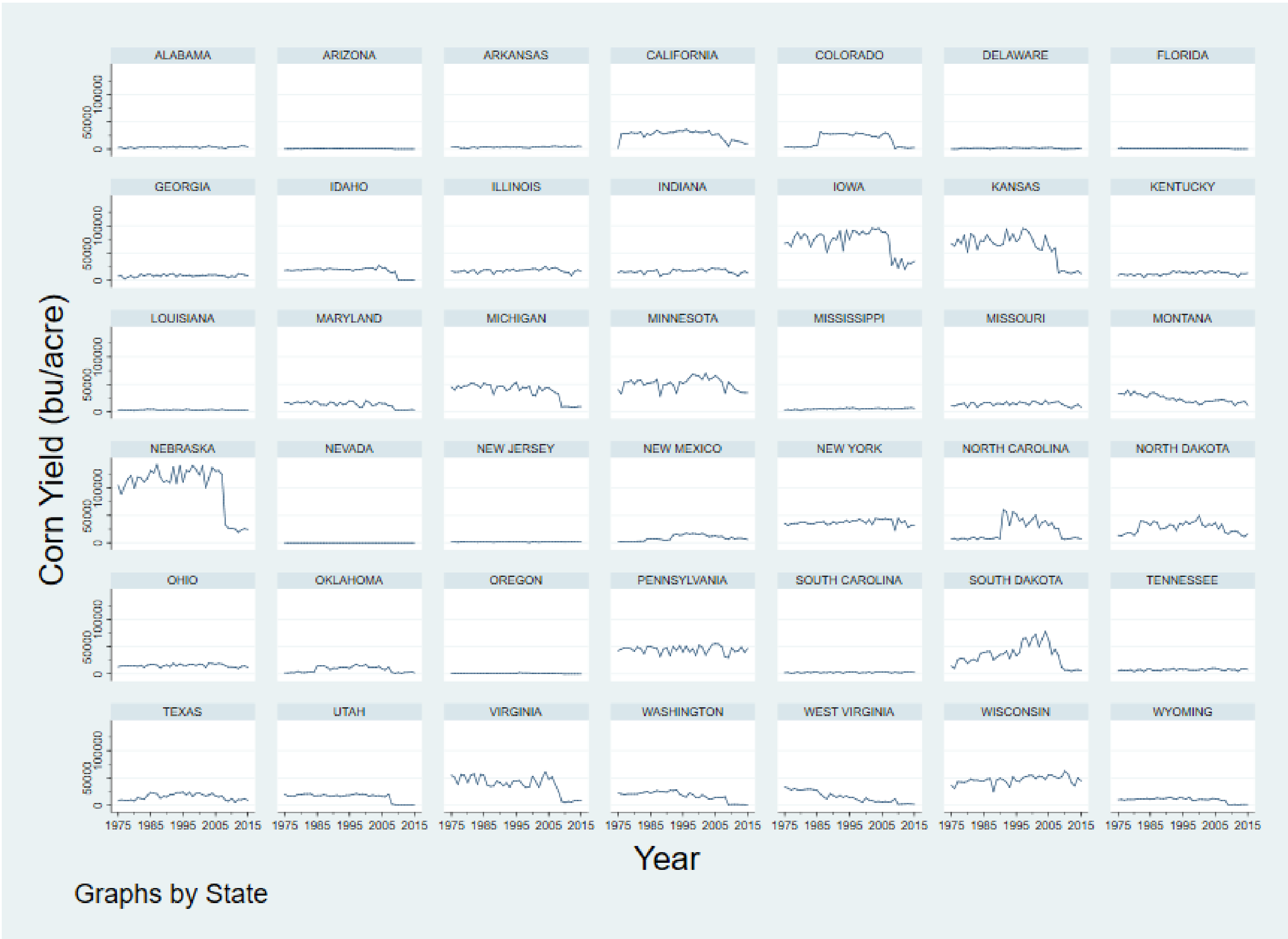

Figure 4.1: Historical corn yields in the United States from 1975 to 2015

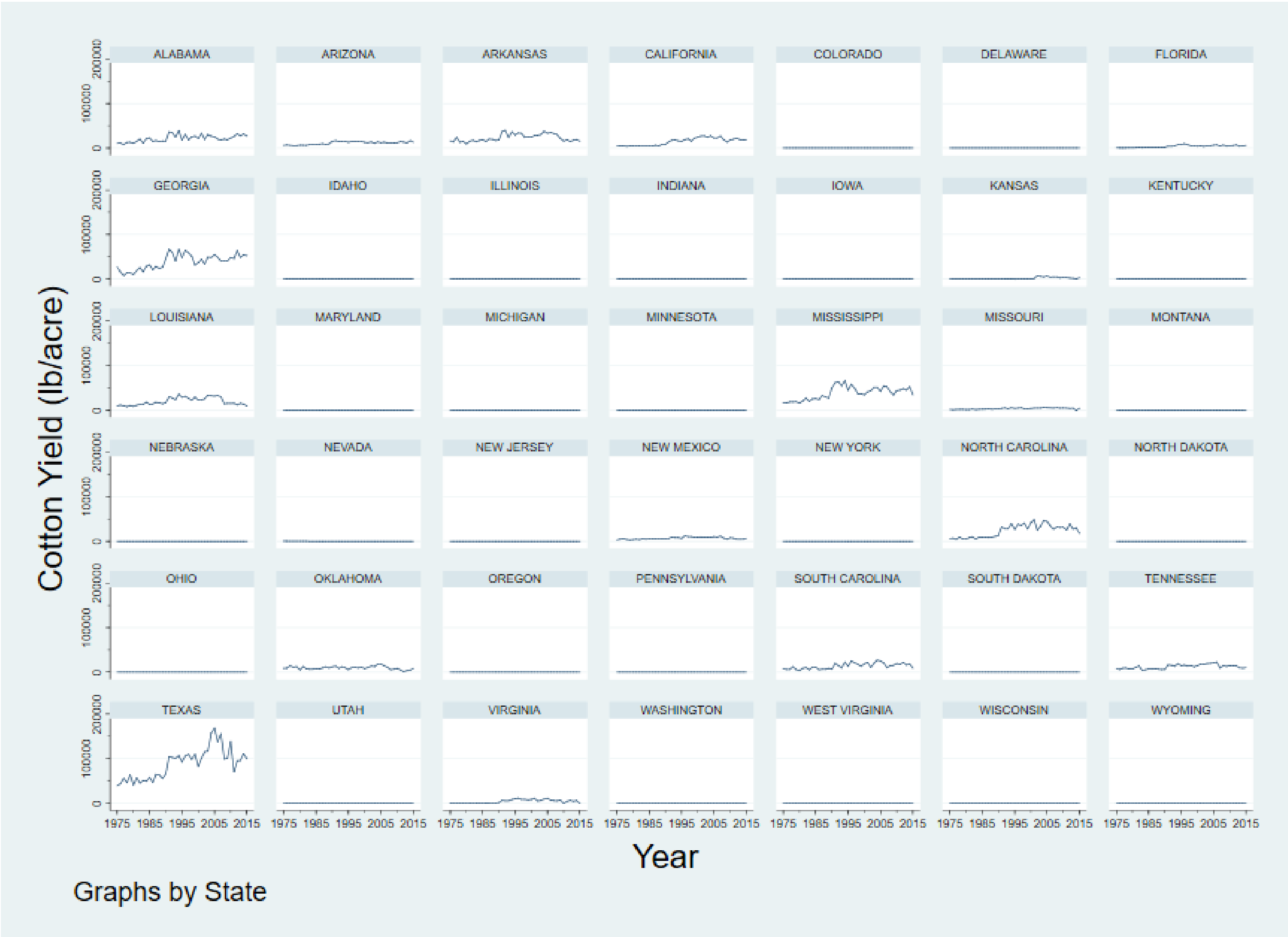

Figure 4.2: Historical cotton yields in the United States from 1975 to 2015

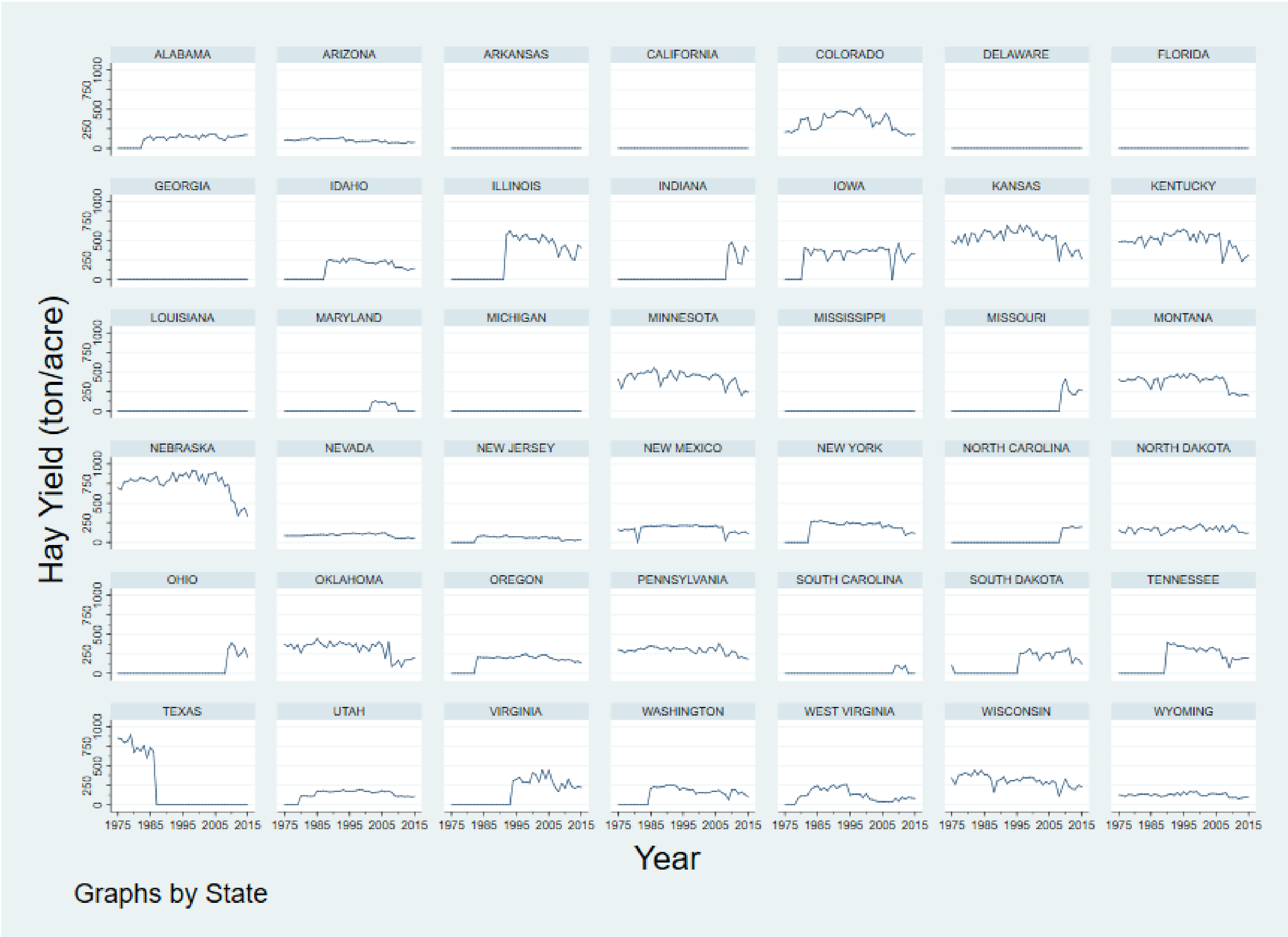

Figure 4.3: Historical hay yields in the United States from 1975 to 2015

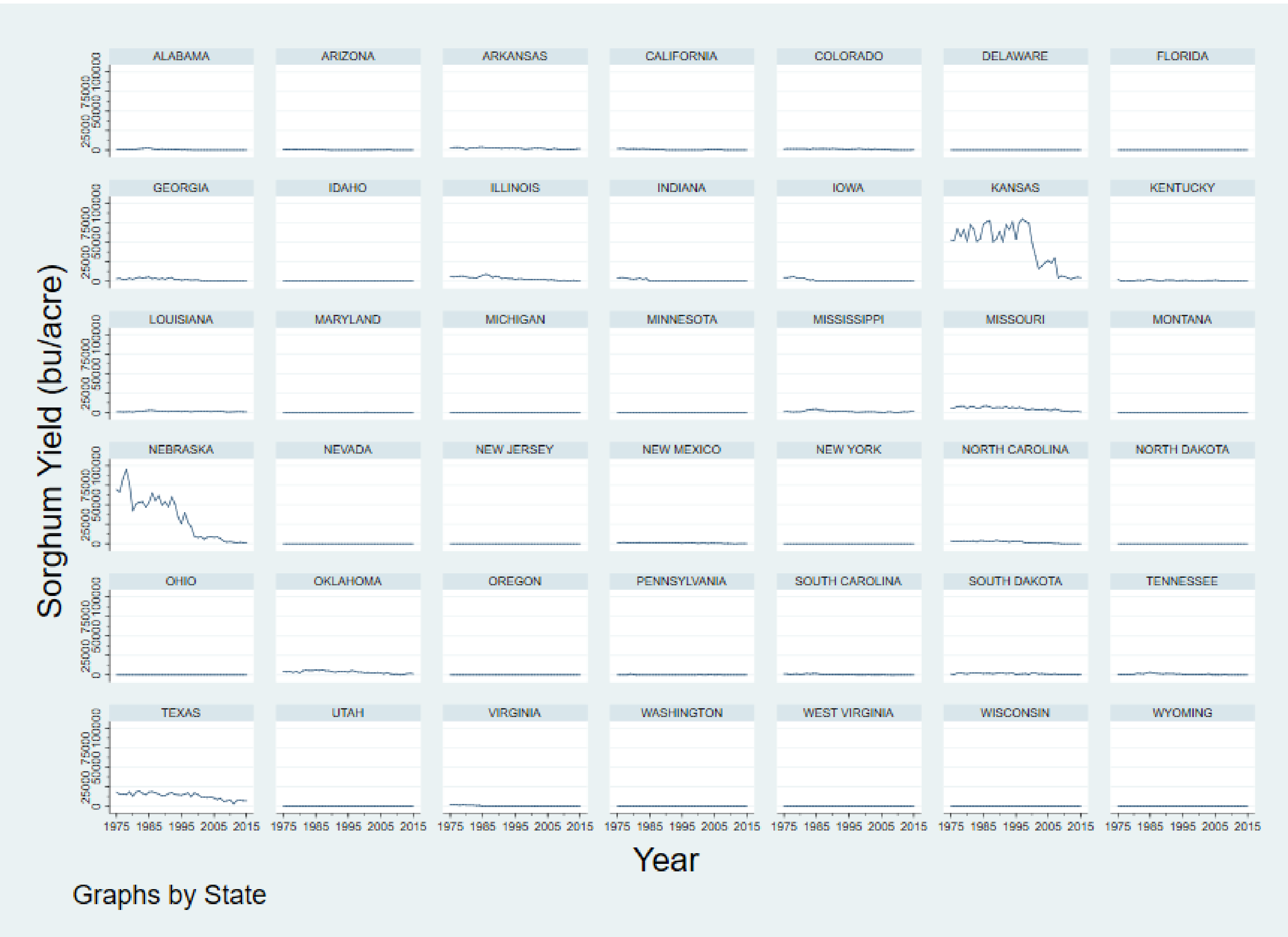

Figure 4.4: Historical sorghum yields in the United States from 1975 to 2015

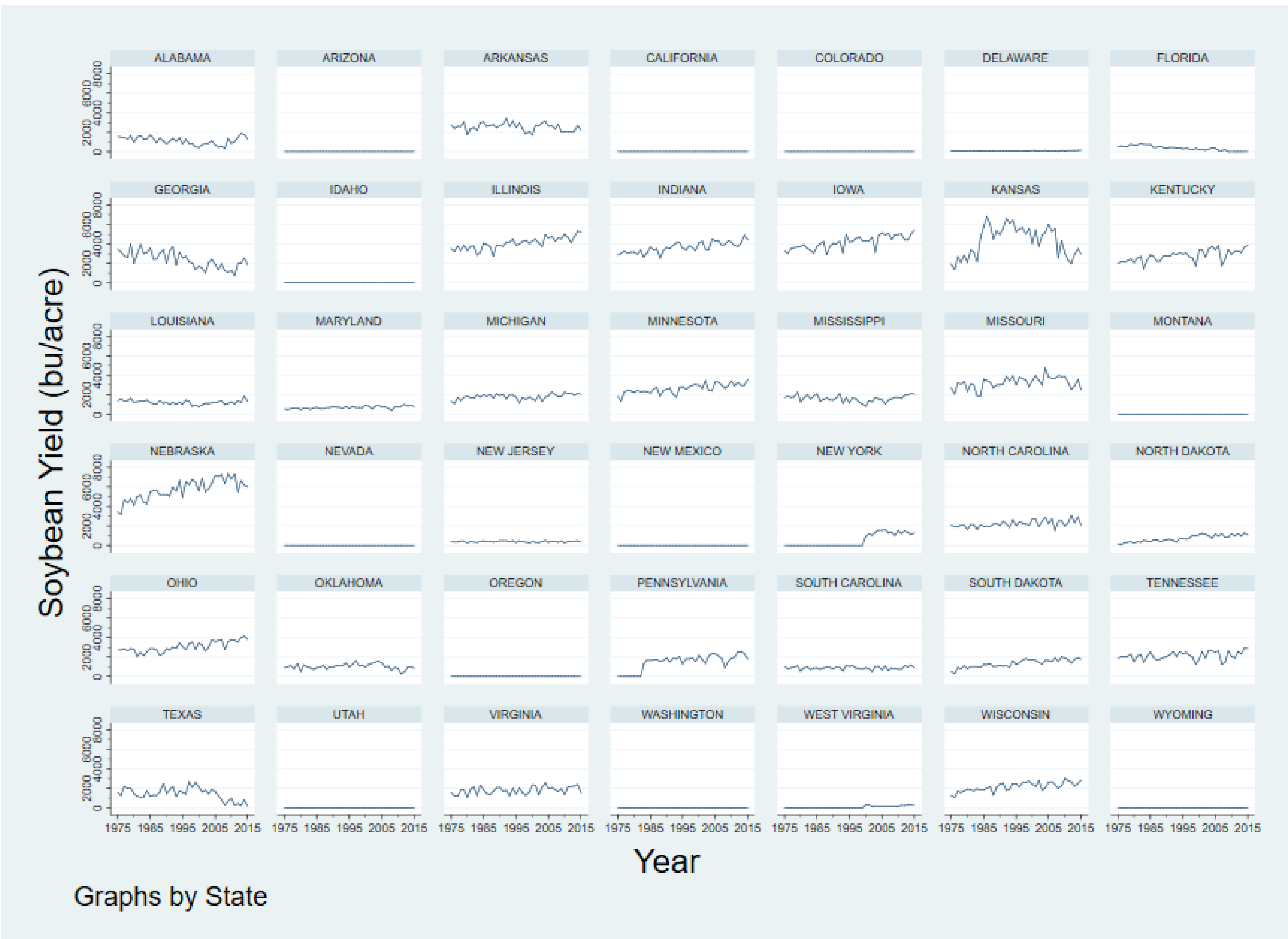

Figure 4.5: Historical soybean yields in the United States from 1975 to 2015

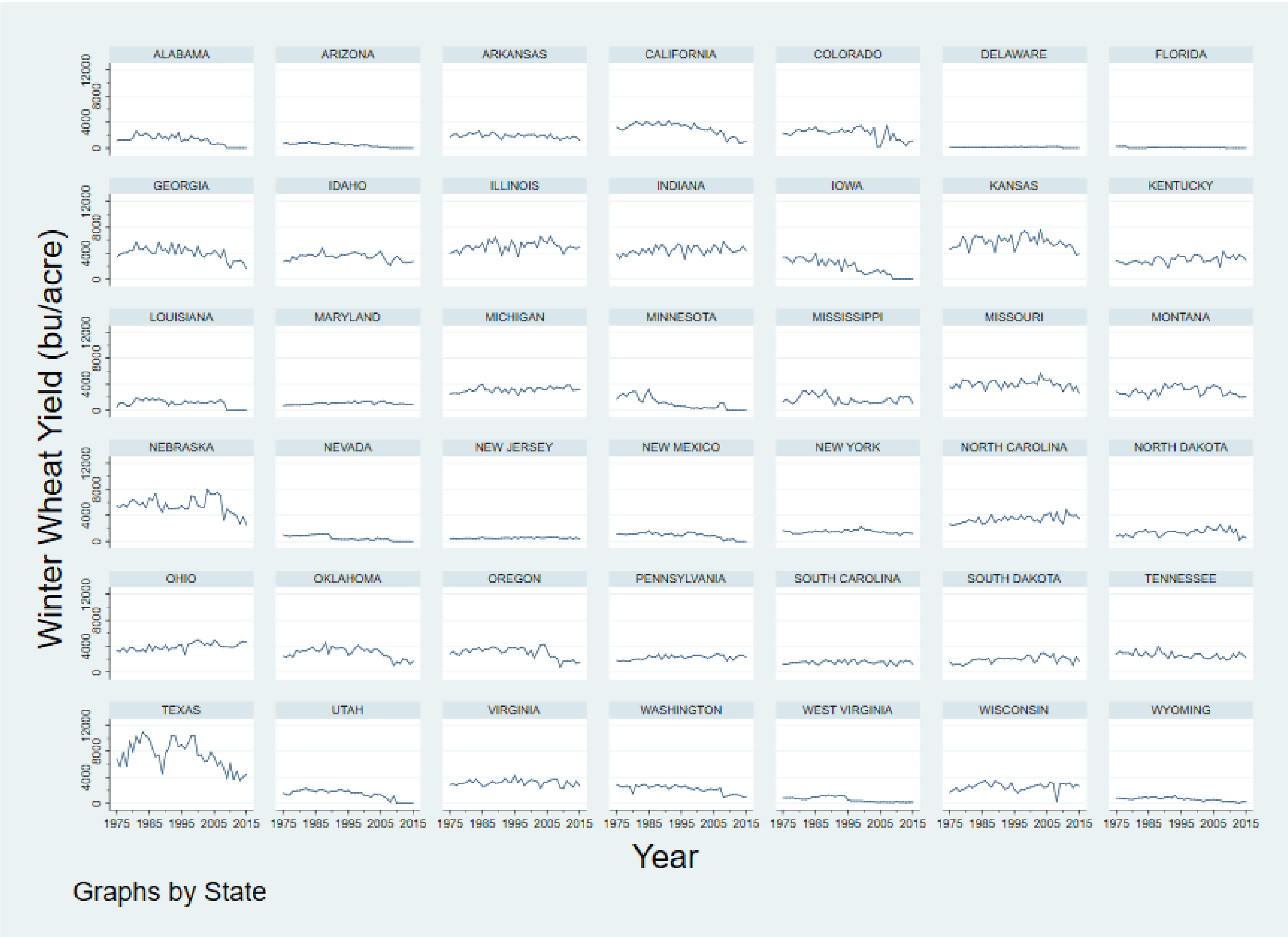

Figure 4.6: Historical winter wheat yields in the United States from 1975 to 2015

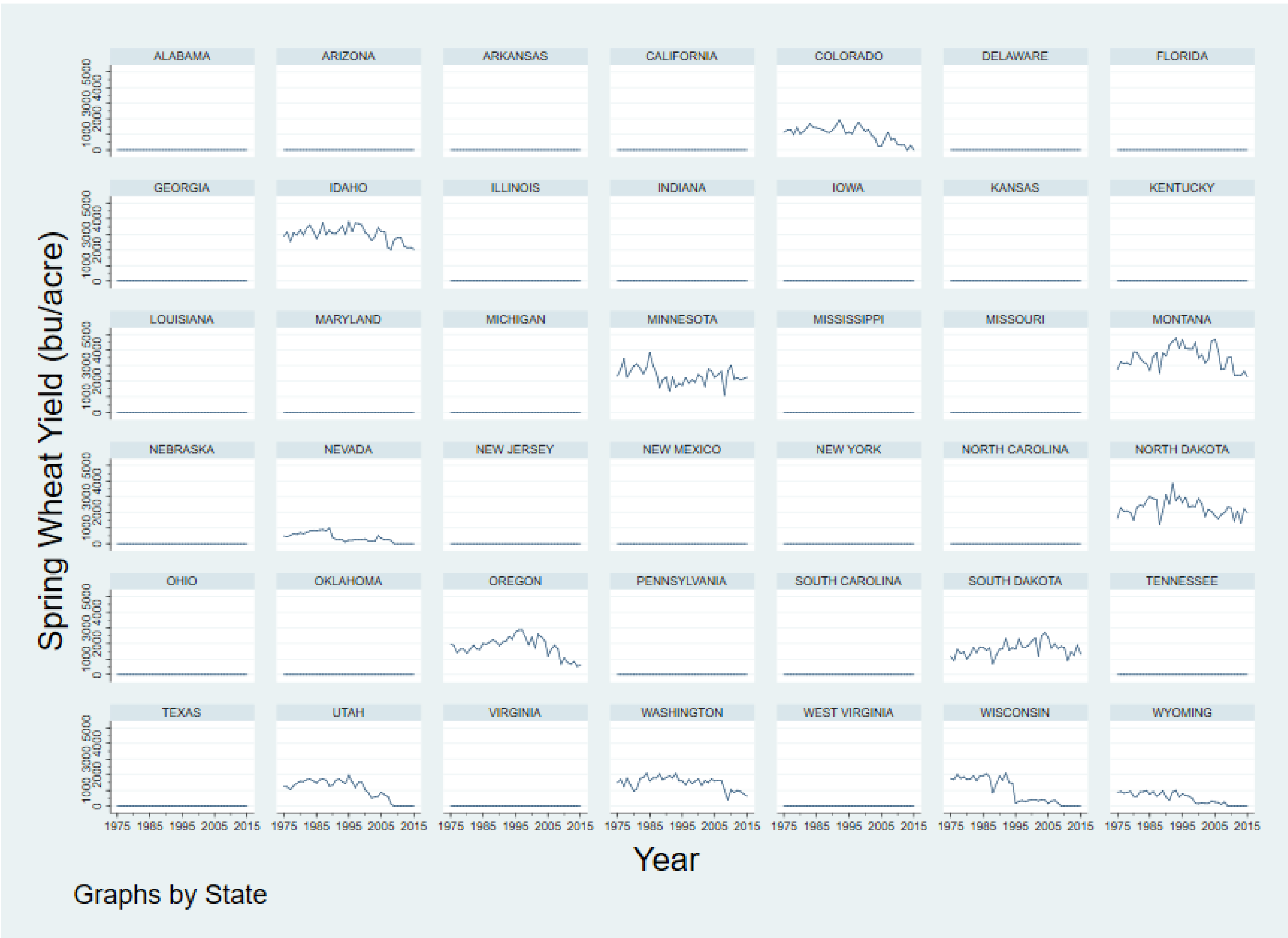

Figure 4.7: Historical spring wheat yields in the United States from 1975 to 2015

4.4.2. Climate Data

Climate data was drawn from Schlenker and Roberts, 2009. Specifically, their measures for precipitation and degree days were used. A degree day is the difference between a realized temperature and a benchmark temperature of a location simulated during the growing season, in this case the benchmark is in degrees Celsius (C). The degree days we will be considering in this study are degree day 0 (Dday 0), degree day 15 (Dday15) and degree day 30 (Dday 30). The variable Dday 0 represents the cumulative amount of days where the temperature is at or below 0° C across the days in the growing season. Dday 15 represents the cumulative amount of days the realized temperature is above 15° C during the growing season. Finally, Dday30 represents the cumulative amount above 30° C during a year. The degree days included in this analysis allows for an assessment of climate differences over time and locations. Precipitation is also used in total millimeters per year.

4.4.3. Agricultural Funding Data

Agriculture research and development data was collected from the USDA Economic Research Service (USDA ERS 2019) and the Current Research Information System (CRIS 2017). The key observations used were Total Agriculture Research and Development Funding (Total Invest) inflated to 2013 USD buying power which includes both public and private agricultural funding and the share of agricultural funding that went towards Agricultural Productivity (Prod Share) and Agricultural Adaptation (Adapt Share). All of the agricultural funding and share data were lagged following Huffman and Evenson 2006. Specifically, research and development funding follows a trapezoidal pattern:

1. A beginning gestation time of two years when the impact of funding is negligible
2. Positively increasing impact of funding for the following seven years
3. High and consistent positive impact for six years

4. Declining impact over the next twenty years until the impact reaches zero

Thus, the variables were each lagged twelve years at approximately the midpoint of the total lag length. Figure 4.8 shows the trajectory of agricultural funding from 1975-2015 in the United States.

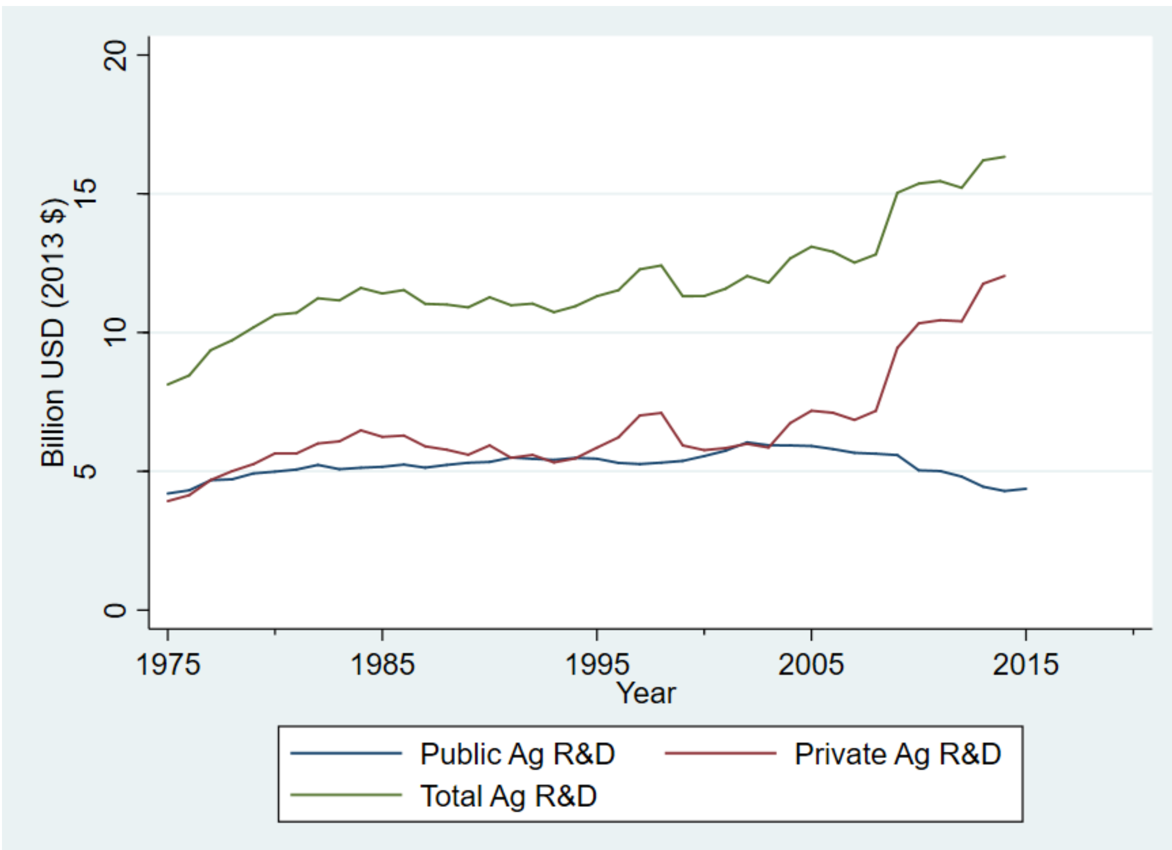

Figure 4.8: Historical public, private and total funding for agriculture research and development

4.4.4. Time Trends and Year Dummy Variables

Though derived data, a linear (T Trend) and an squared (T Trend Sq) time trend are created and added to the panel data. The time trends are included to detect any trends that might be inherent in the crop yield data. Also included are two dummy variables, one for the year 2000 (D2000) and another for the year 2010 (D2010). These dummy variables are included to determine if there is a break or a change in the rate of growth on the crop yields mentioned above during those years.

4.4.5. Data Descriptive Statistics

Descriptive statistics of the independent and dependent variables are shown in Table 4.1. The number of observations, means, standard deviations (std. dev.), min, and max are given. Note that there are observations for individual crop yield as well as observations for yields that were irrigated.

Table 4.1: Summary statistics of independent variables

	OBS	MEAN	STD. DEV.	MIN	MAX
CORN	11,267	3186.946	3429.867	28	29577.41
CORN IRRIG	11,267	10.30855	26.73057	0	100
COTTON	3,170	4133.885	3794.494	36.85	28067
COT IRRIG	3,170	13.24157	25.72543	0	100
HAY	6,116	44.10045	26.7608	1.05	178.83
HAY IRRIG	6,116	5.885156	18.90221	0	100
SORGHUM	5,092	1003.546	1997.551	10	20778.62
SOR IRRIG	5,093	6.012837	17.24768	0	100
SOYBEANS	8,686	290.4538	207.7851	4.65	1791
SOY IRRIG	8,686	4.09819	15.9877	0	100
WWHEAT	10,656	376.33	266.8417	6.6	2147.5

	OBS	MEAN	STD. DEV.	MIN	MAX
WW IRRIG	10,656	74.74848	40.47007	0	100
SWHEAT	2,436	305.7413	227.7266	10	1695
SW IRRIG	2,436	54.2753	43.29185	0	100
DDAY0	11,267	4830.508	1275.094	2063.712	9006.451
DDAY15	11,267	1284.476	580.9541	289.1608	3674.295
DDAY30	11,267	45.57185	53.77217	0.001114	545.0902
PREC	11,267	949.7509	386.6638	81.13434	2394.422
TOT INVEST	7,830	10.92053	0.974784	8.127998	12.41909
PROD SHARE	7,830	0.62523	0.009397	0.587746	0.630026
ADAPT SHARE	7,830	0.025521	0.019594	0.016044	0.06889

4.4.6. Correlation Matrix

Before moving forward with the analysis, a correlation matrix of the independent variables was made to determine if any variables are correlated with each other. The correlation matrix of climate and technological advancement variables is shown in Table 4.2. We can see there is some correlation within our climate variables and within time trends. Dday 0 and Dday 15 have a high correlation of 0.981 and Dday 0 and Dday30 as well as Dday15 and Dday30 have relatively high correlation of 0.7303 and 0.7966 respectively. This is expected as they are both measuring the degrees over the standard on different days of the growing season. T Trend and T Trend Sq also have a high correlation factor of 0.9894 as T Trend Sq is the square of T Trend. All of the Ag. funding variables are highly correlated with the time trends which is expected. Finally, if we look at the share of irrigated acres of each crop, the greatest correlation can be seen between CORN IRRIG and SOY IRRIG at 0.7532 and a negative correlation of -0.6024 between CORN IRRIG and WW IRRRIG. The points seen in both HAY IRRIG and SW

IRRIG are there because the number of observations of irrigated acres was either too few or zero.

Table 4.2: Correlation matrix of independent variables

	T TREND	T_2 TREND	DDAY0	DDAY15	DDAY30	PREC	TOT INVEST	PROD SHARE	ADAPT SHARE	D2000	D2010
T TREND	1										
T2 TREND	0.9895	1									
DDAY0	-0.2118	-0.2114	1								
DDAY15	-0.042	-0.036	0.9151	1							
DDAY30	0.2163	0.2264	0.1843	0.5087	1						
PREC	-0.3492	-0.3581	0.4031	0.0961	-0.6309	1					
TOT INVEST	0.6906	0.6223	-0.2106	-0.1187	0.0643	-0.1362	1				
PROD SHARE	-0.6023	-0.675	0.1658	0.0278	-0.1694	0.2171	-0.3608	1			
ADAPT SHARE	0.5447	0.627	-0.1312	0.027	0.2838	-0.2589	0.306	-0.7262	1		
D2000	0.0554	0.0248	-0.0056	0.0421	0.136	-0.0671	0.0482	0.0763	-0.0607	1	
D2010	0.2307	0.2536	-0.0713	0.0287	0.1146	-0.1446	0.2503	-0.4729	0.5198	-0.0299	1
CORN IRRIG	0.1308	0.1446	-0.4397	-0.2339	0.3024	-0.6039	0.0234	-0.1118	0.1131	-0.0445	0.0343
COT IRRIG	-0.0206	-0.0245	0.1042	0.2164	0.4002	-0.2648	-0.0759	0.0545	-0.0809	0.0272	-0.0404
HAY IRRIG	.	.	.	.	.	.	.	.	.	.	.
SOR IRRIG	-0.0801	-0.0865	-0.0996	0.0598	0.4172	-0.4743	-0.0732	0.0873	-0.1363	-0.0187	-0.0679
SOY IRRIG	0.0793	0.0667	-0.3747	-0.2659	0.0752	-0.3521	0.0633	-0.0061	-0.0635	-0.0162	-0.04
WW IRRIG	0.0524	0.0554	0.3723	0.1421	-0.4011	0.6341	0.0563	-0.064	0.0843	0.0403	0.0547
SW IRRIG	.	.	.	.	.	.	.	.	.	.	.

Table 4.2 Continued

	CORN IRRIG	COT IRRIG	HAY IRRIG	SOR IRRIG	SOY IRRIG	WW IRRIG	SW IRRIG
T TREND							
T2 TREND							
DDAY0							
DDAY15							
DDAY30							
PREC							
TOT INVEST							
PROD SHARE							
ADAPT SHARE							
D2000							
D2010							
CORN IRRIG	1						
COT IRRIG	0.0966	1					
HAY IRRIG	.	.	.				
SOR IRRIG	0.4736	0.5899	.	1			
SOY IRRIG	0.7532	-0.0899	.	0.3191	1		
WW IRRIG	-0.6024	-0.3132	.	-0.564	-0.3739	1	
SW IRRIG	.	.	.	.	.	.	.

4.5. Methodology

With the panel data considered in this study, the potential for unobserved variables and the knowledge provided by past literature, we consider a fixed effects model. The classical fixed effects model (Wooldridge 2010) is shown below:

$$\boldsymbol{y_{it} = x_{it}\beta + c_i + u_{it}} \qquad \textbf{(1)}$$

such that y_{it} is the dependent variable observed for individual *i* in time *t*, x_{it} is the time varying independent variable vector, β is the coeeficient of x_{it}, c_i is the unobserved time invariant individual effect and u_{it} is the error term. Because c_i is unobserved the fixed effects model removes it by demeaning the variables in equation **(2)**, leaving us with equation **(3)** to estimate.

$$\boldsymbol{y_{it} - \bar{y}_i = (x_{it} - \bar{x}_{it})\beta + (c_i - c_i) + (u_{it} - \bar{u}_i)} \qquad \textbf{(2)}$$

$$\boldsymbol{\ddot{y}_{it} = \ddot{x}_{it}\beta + \ddot{u}_{it}} \qquad \textbf{(3)}$$

More specifically we will be looking at:

$$\boldsymbol{Corn\ddot{Y}ield_{it} = Ag\ddot{F}und_{it}\beta + Climate\ddot{I}nicators_{it}\theta + T\ddot{i}me_{i}\delta + \ddot{u}_{it}} \qquad \textbf{(4)}$$

$$\boldsymbol{Cotto\ddot{n}Yield_{it} = Ag\ddot{F}und_{it}\beta + Climate\ddot{I}nicators_{it}\theta + T\ddot{i}me_{i}\delta + \ddot{u}_{it}} \qquad \textbf{(5)}$$

$$\boldsymbol{Hay\ddot{Y}ield_{it} = Ag\ddot{F}und_{it}\beta + Climate\ddot{I}nicators_{it}\theta + T\ddot{i}me_{i}\delta + \ddot{u}_{it}} \qquad \textbf{(6)}$$

$$\boldsymbol{Sorgh\ddot{u}mYield_{it} = Ag\ddot{F}und_{it}\beta + Climate\ddot{I}nicators_{it}\theta + T\ddot{i}me_{i}\delta + \ddot{u}_{it}} \qquad \textbf{(7)}$$

$$\boldsymbol{Soybe\ddot{a}nYield_{it} = Ag\ddot{F}und_{it}\beta + Climate\ddot{I}nicators_{it}\theta + T\ddot{i}me_{i}\delta + \ddot{u}_{it}} \qquad \textbf{(8)}$$

$$WinterWheatYield_{it} = AgFund_{it}\beta + ClimateInicators_{it}\theta + Time_{\iota}\delta + \ddot{u}_{it} \quad (9)$$

$$SpringWheatYield_{it} = AgFund_{it}\beta + ClimateInicators_{it}\theta + Time_{\iota}\delta + \ddot{u}_{it} \quad (10)$$

such that:

i	is the USDA agricultural crop reporting district.
t	is years from 1975-2015 of the study.
$CornYield_{it}$-$SpringWheatYield_{it}$	are the crop yields at district i and time t.
$AgFund_{it}$	is a set of lagged research funding variables Total Invest, Prod Share and Adapt Share
β	is a vector of estimated coefficients for $AgFund_{it}$.
$ClimateInicators_{it}$	is a set of climate variables DDay0, DDay15, DDay30, and Precipitation.
θ	is the vector of coefficients of $ClimateInicators_{it}$.
$Time_{it}$	houses the time trend variables T Trend and T Trend Sq and dummy variables D2000 and D2010.

$\boldsymbol{\delta}$	is a vector of estimated coefficients for $\ddot{Time}_{it}$.
$\ddot{u}_{it}$	is the error term.

4.6. Regression Results

Table 4.3 shows the fixed effects regression results for each crop by irrigation status. The significance of each coefficient in the regressions is identified by the probability-value (p-value) and associated test-statistic (t-statistic). The p-value reports the probability that the estimated coefficient equals zero. When the p-value is very small, less than 0.05, we can say that the difference is significant. Similarly, the t-statistic is a statistical hypothesis test that determines the number of standard deviations that zero is away from the estimated coefficient. To determine the goodness of fit of the model, we consider R_2. The statistical measure R_2, represents the amount of variance in the dependent variable that is explained by the independent variables in a regression model, in other words, a goodness of fit measure. The adjusted R_2, is similar to R_2 except that it adjusts for the number of independent variables within the model.

Table 4.3: Crop Yield Regression Results

	CORN	COTTON	HAY	SORGHUM	SOYBEAN	WINTER WHEAT	SPRING WHEAT
DDAY0	-1.007	3.302	**0.0141***	**-1.886*****	**-0.126****	**0.242*****	**0.213****
	(-1.77)	(1.48)	(2.32)	(-7.21)	(-3.27)	(4.36)	(3.71)
DDAY15	-0.00877	-1.847	-0.0156	**3.860*****	**0.390****	**-0.484****	**-0.776****
	(-0.01)	(-0.40)	(-0.85)	(7.06)	(3.51)	(-3.19)	(-3.80)
DDAY30	0.764	**-13.15***	-0.089	**-3.626***	**-2.44*****	-0.133	-0.436
	(0.19)	(-2.32)	(-1.37)	(-2.67)	(-7.49)	(-0.33)	(-0.29)
PREC	-0.344	0.0783	**-0.010***	**-0.703*****	-0.0278	**-0.124****	**-0.429****
	(-0.99)	(0.09)	(-2.41)	(-5.39)	(-1.06)	(-2.97)	(-3.87)
TOT INVEST	**-180.3****	**980.5****	2.046	**109.3****	4.324	-9.396	10.82
	(-2.93)	(3.21)	(1.86)	(2.9)	(1.43)	(-1.35)	(0.54)
PROD-SHARE	-7230.9	**63836.6****	-88.08	**-21119*****	**-584.4***	232	1405.2
	(-1.55)	(3.18)	(-1.80)	(-4.55)	(-2.85)	(0.66)	(2.11)
ADAPT-SHARE	**-6982.8***	-19252.5	-15.18	5793.9	**846.6*****	429.1	243.6
	(-2.42)	(-1.16)	(-0.27)	(1.48)	(8.06)	(1.66)	(0.63)
D2000	**241.9*****	168.1	1.314	**-305.3*****	-0.0499	7.494	-3.823
	(4.82)	(0.61)	(1.4)	(-5.92)	(-0.01)	(0.95)	(-0.45)
D2010	**-265.8****	1074.1	1.968	**-882.8*****	**-36.90****	13.74	**67.40***
	(-3.17)	(1.53)	(1.27)	(-5.82)	(-3.67)	(0.7)	(2.45)
T TREND	**381.7*****	-422.9	1.168	67.51	**7.771****	4.284	-2.13
	(5.16)	(-1.46)	(1.08)	(1.12)	(3.16)	(0.9)	(-0.13)
T_2 TREND	**-7.571*****	9.734	-0.0394	**-2.944***	**-0.145****	-0.0623	0.000674
	(-5.34)	(1.69)	(-1.88)	(-2.37)	(-3.27)	(-0.69)	(0.00)
IRRIGATE	**27.21****	**37.61***	**0.289****	-4.75	**5.277****	**-1.53*****	-0.308
	(3.64)	(2.57)	(4.48)	(-0.84)	(3.94)	(-5.52)	(-0.54)
CONSTANT	10526.7***	-57972***	41.09	18384.1***	720.6***	-48.33	-555
	(4.37)	(-4.50)	(1.61)	(6.47)	(4.76)	(-0.21)	(-0.90)
N	7830	2156	4672	3089	6143	7268	1604
R-SQ	0.249	0.22	0.151	0.142	0.205	0.09	0.197
ADJ. R-SQ	0.248	0.215	0.149	0.139	0.203	0.089	0.19

Note: 1) t-statistics are in parentheses
2) * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

First, we examine the results for the climate variables Dday 0, 15 and 30. Dday 0 is significant for hay, and both Dday 0 and Dday15 are significant for sorghum, soybeans and winter wheat and spring wheat. This means that the cumulative amount the temperature was at or below 8° C had a significant effect on crop yields, as well as cumulative amount when the temperature was at or above 15° C. However, we see that the direction of effect of Dday0 and Dday15 are different. For Dday 0, there is a negative effect on sorghum and soybean but a positive effect on hay, winter wheat and spring wheat. For Dday15, the weather shows positive effects for sorghum and soybean and a negative effect on winter and spring wheat. Dday 30, which represents extremely hot days shows significantly negative effects on yields of cotton, sorghum and soybean. Precipitation has consistently negative effects on yields for hay, sorghum, winter wheat and spring wheat. To understand this better we consider the share of acres that are irrigated (Irrigate) and how crop yields are affected. The share of irrigated acres has a significant positive effect on yields for corn, cotton, hay and soybean and a significant negative effect on winter wheat.

If we look at the coefficients of interest, Total Invest, Prod Share and Adapt Share we see some surprising results. First, Total Invest has a significantly negative impact on corn yields but a very significant and positive effect on cotton and sorghum. We must also note that Total Invest is highly correlated with T Trend which is significant. Next, if we look at share of funds that go towards crop productivity, large positive effect on cotton but a negative effect on sorghum and soybean. If we instead look at the share of funds for adaptation, we see a negative effect on corn and a large positive effect on soybean. The significant coefficients that are positive on Adapt Share may be because of the movement of interests from sorghum and soybean productivity to soybean adaptation. Considering Total Invest, Prod Share and Adapt Share, we can assume that both governmental and private entities are now allocating more funds to adaption to increasing climate stressors on crop production as opposed to strict crop productivity. Soybeans are the top agricultural export of the United States (USDA FAS 2018). This is understandable as soybeans are used globally as animal feed and human consumption. With increasing population, food demand and climate change, there may be a need to raise funding for adaptation strategies for soybean.

Finally, the time trends and dummy variables are considered in the regression. The T Trend assumes a linear trend in crop yields and the T Trend Sq. assumes a nonlinear trend in crop yields. The results show that different crops follow different time trends. Corn and soybean yields show a high significance with the linear time trend and thus increasing growth in crop yields. However, when we look at the squared time trend, we can see that the rate of crop yield growth is decreasing. Thus, yields are increasing at a decreasing rate.

4.7. Conclusion

With growing agricultural demand and limited resources technological progress is vital but climatic change is a threat to progress. As climate factors continue to influence agricultural production, it is important to appropriately adapt so as to limit effects. One such source of adaptation is through the investment in agricultural research and development as well as appropriately allocating funds towards adaptation. This study shows that total agricultural research and development investment can positively and negatively affect crop yields. There are also positive and negative effects on crop yields when considering the dynamic effects of the share of funds that go to either crop productivity or adaptation. This may be because of changing public and private interests as well as a comparative advantage that may exist with crops that can be used for energy and crops that are a large share of agricultural exports. The main finding is that both public and private agricultural funding of research and development is essential in meeting growing demand for food in addition to overcoming the negative effects of climate change on yields.

4.8. References

Alston, J. M., B. A. Babcock and P. G. Pardey. 2010. “The Shifting Patterns of Agricultural Production and Productivity Worldwide” (CARD Iowa State, 2010; (http://lib.dr.iastate.edu/card_books/2), vol. CARD Books. 2.

Burke, M. and K. Emerick. 2016. “Adaptation to Climate Change: Evidence from US Agriculture.” *American Economic Journal: Economic Policy* 8(3):106-140.

Chen, C.C., B.A. McCarl and D.E. Schimmelpfennig. 2004. “Yield Variability as influenced by Climate: A Statistical Investigation.” *Climatic Change* 66: 239-261.

Deschênes, O. and M. Greenstone. 2007. “The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather.” *American* Economic Review 97 (1): 354–85.

Ehrlich, P. R. and J. Harte. "Opinion: To feed the world in 2050 will require a global revolution." *Proceedings of the National Academy of Sciences* 112.48 (2015): 14743-14744.)

Food Administration Organization (FAO). 2009. High Level Expert Forum - How to Feed the World in 2050. Office of the Director, Agricultural Development Economics Division Economic and Social Development Department Viale delle Terme di Caracalla, 00153 Rome, Italy

Huffman, W.E. and R.E. Evenson. 2006. “Do Formula or Competitive Grant Funds Have Greater Impacts on State Agricultural Productivity?” *American Journal of Agricultural Economics* 99 (4): 783-798.

International Panel on Climate Change (IPCC). 2014. *Climate Change 2014: Synthesis Report.* Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Just, R. and R.D. Pope. 1979. “Production Function Estimation and Related Risk Considerations.” *American Journal of Agricultural Economics* 61:277–284.

Johnson, J. J., C. F. Runge, B. Senauer, J. Foley and S. Polasky. 2014. “Global agriculture and carbon trade-offs.” *Proceedings of the National Academy of Sciences* 111:12342-12347.

Kapilakanchana, M. 2016. “The effect of Technological Progress, Demand, and Energy Policy on Agricultural and Bioenergy Markets.” PhD dissertation, Department of Agricultural Economics, Texas A&M University.

McCarl, B.A, X. Villavicencio, and X. Wu. 2008. "Climate Change and Future Analysis: Is Stationarity Dying?" *American Journal of Agricultural Economics* 90(5):1241-1247.

Mendelsohn, R., W.D Nordhaus and D. Shaw. 1994. "The impact of global warming on agriculture: A Ricardian analysis." *American Economic Review* 84:753–771.

Schlenker, W. and M. J. Roberts. 2009. "Nonlinear temperature effects indicate severe damages to US crop yields under climate change." *Proceedings of the National Academy of Sciences* 106(37): 15594–98.

Tai, A. P. K., M.V. Martin, and C. L. Heald. 2014. "Threat to future global food security from climate change and ozone air pollution." *Nature Climate Change*. 4:817.

United Nations. 2017. *World Population Prospects: The 2017 Revision.* https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html (accessed October 18, 2019).

U.S. Department of Agriculture, Current Research Information System (CRIS). 2017. https://cris.nifa.usda.gov/. (accessed October 18, 2019).

U.S. Department of Agriculture, Economic Research Service (ERS). 2019. *Agricultural Research Funding in the Public and Private Sectors*. https://www.ers.usda.gov/data-products/agricultural-research-funding-in-the-public-and-private-sectors/ (accessed October 10, 2019)

U.S. Department of Agriculture, Economic Research Service (ERS). *Crops.* https://www.ers.usda.gov/topics/crops/ (accessed October 10, 2019)

U.S. Department of Agriculture, Foreign Agricultural Service (FAS). 2018. *Top US Agricultural Exports in 2017*. https://www.fas.usda.gov/data/top-us-agricultural-exports-2017 (accessed October 18, 2019).

U.S. Department of Agriculture, National Agricultural Statistics Service (NASS) Database. 2019. “USDA/NASS QuickStats Ad-hoc Query Tool.” https://quickstats.nass.usda.gov/ (accessed September 12, 2019).

Villavicencio, X., McCarl, B. A., Wu, X. M., and W. E. Huffman. Climate change influences on agricultural research productivity. *Climatic Change*. 119, 815–824 (2013).

Wooldridge, J. M. 2010. "Econometric Analysis of Cross Section and Panel Data," MIT Press Books, The MIT Press, edition 2, volume 1, number 0262232588.

5. CONCLUSIONS

This study addresses economic aspects of freshwater supply for municipalities and hydraulic fracturing along with aspects of agricultural technical progress under time, investment levels and climate stressors. To do this, we examined three cases 1) cost and emissions involved with provision of water to regions without permanent water supplies using diminished quality water; 2) cost and reuse alternatives for provision of water to hydraulic fracturing and 3) the effects of research investments, time and climate on crop yields.

In the first study, cost and GHG emissions estimates were constructed for provision of water to Texas colonias without potable supplies via a mobile solar powered water nanofiltration unit. That system was also compared to conventional alternatives. The analysis was done in the context of water supply to communities in South Texas (Chapter 2).

The second study looks at water usage in the Texas hydraulic fracturing industry and cost of current supplies plus the breakeven hauling distance for freshwater where recycling produced water becomes competitive (Chapter 3).

In the third study, an analysis was done on the effects of agricultural research and development funding, time and climate change on US major field crop yields as observed from 1975 to 2015 (Chapter 4).

Several main findings arose. For the mobile unit study in the South Texas colonias case study, the main finding is that the most cost and GHG emission efficient water delivery system, excluding the unlikely tap water possibility, is the mobile solar powered nanofiltration unit. This is in line with the findings in Olmstead 2004. Having a low emitting cost efficient mobile water treatment unit offer a tangible solution for governmental agencies wishing to provide water in colonias without available supplies. Furthermore, the cost is in line with levels of recent funding with the provision to all red colonias amounting to approximately $53.5 million dollars

The main findings for the Texas hydraulic fracturing industry case are 1) the water use in the Eagle Ford shale is forecasted to increase; 2) pumped water is expensive costing $0.55 per barrel or approximately $4,300.00 per acre foot and 3) as supplies become more distant, thus increasing the transportation cost of raw water, reuse of produced water is economic for hauling distances above the average of 314 miles.

The main findings in the crop yield study are:

1) Yield increases are slowing down over time for most crops and climate change is contributing to this. We also find total agricultural research and development funding increases cotton and sorghum yields and decreases corn yields.

2) Precipitation negatively affects yields of hay, sorghum, winter wheat and spring wheat. This is counter intuitive but is likely due to the increased precipitation intensity over fewer days that is becoming increasingly standard due to climate change (Knutti and Sedlácek 2013) and negatively affects yields. To better understand the results, share of irrigated acres were also considered and had a positive effect on corn, cotton, hay and soybeans but a negative effect on winter wheat.

3) Low temperatures have both a positive and negative effect on crops while high temperatures have consistently negative effects on all crop yields. This follows Schlenker and Roberts (2009) findings that the national agricultural crop yields increase until a certain threshold at which point there is a sharp decrease in production.

4) Total agricultural funding of research and development along with allocation of funding to adaptation strategies are key factors in increasing crop yields and reaching global demand while adapting to climate change.

This study also has limitations, thus, further possible research to be considered includes:

1. The cost and greenhouse gas (LCA) analysis developed in chapter 2 does not take into account upstream energy and emissions costs such as the manufacture of the mobile unit or installation of facilities to allow tap water supply. Including these costs will provide a more robust evaluation on the cost of water supply within the Texas colonias case.

2. Also in Chapter 2, our analysis was not informed by an on the ground implementation of the mobile water filtration system and such a study could be done to extend this research and make the findings more reliable Namely such an implementation could highlight issues within the system that are not sustainable. It would also identify hidden costs that were not considered such

as solar panel maintenance (dust is an issue) or training of a water quality technician.

3. Finally, in Chapter 2, the choice of sharing a filtration unit between two colonias was chosen due to the filtration time of the required amount of water over six days with a single travelling and set up day in the nearby colonia. An avenue of future research could be to do a sensitivity analysis to determine if a dedicated unit or a centralized one with water conveyance methods might be more beneficial than the mobile unit proposed, if the mobile unit should travel between more than two colonias and the allowable distance between them.

4. In constructing Chapter 3's hydraulic fracturing forecast we used monthly data over six years and forecast an additional ten years. Because the industry is in its infancy the forecast has a large amount of uncertainty because the historical data is not yet available to create a more accurate forecast far out in the future. In time, increased historical data will strengthen future forecasts as well as including dependency on oil prices.

5. The breakeven study on the Eagle Ford shale in Chapter 3 uses general data made available through journal publications and not from a private source. Acquiring private data on costs of recycled water infrastructure as well as freshwater transportation costs would increase study accuracy and credibility.

6. Also, in Chapter 3, a deeper study into the environmental policy surrounding hydraulic fracturing in Texas may lead to further insights as to the differences in produced water recycling and disposal seen between the Eagle Ford shale and the Marcellus shale.

7. The agricultural funding in Chapter 4 did not specifically categorize funding by crop. Instead it was a total amount that was used in each crop regression. Further research could try to obtain and used data on funding allocation to specific crops.

8. In Chapter 4, the correlation matrix shows high correlation between total funding and time. This can lead to a less precise understanding of how research investment and time along with other correlated independent variables affect the dependent variable, in this case crop yields. Future work would need to address this multi-collinearity and test its significance in impacting the variable of interest.

9. Finally, including more diverse climate variables in Chapter 4 should be considered to determine more accurately where the impact on crop yields lie and thus future adaptations in response.