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Until the Well Runs Dry: The Role of Freshwater Source in the Effect of Drought on Agricultural Decision-Making

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Abstract

The purpose of this thesis is to explore the role of freshwater source in the economic decisions made by farmers in response to drought. Although groundwater and surface water sources have remarkably different characteristics, the question of the effect of water source on irrigation decisions has largely been ignored. Because of variations in climate regionally in the U.S. state of Kansas, different parts of the state have nearly exclusive access to either surface water or groundwater. This climatic anomaly allows for the comparison of two kinds of farmers: groundwater farmers and surface water farmers. I utilize a panel data set of 18,710 wells to compare the amount of irrigation applied and the likelihood of upgrading to more efficient irrigation technology between groundwater farmers and surface water farmers. Groundwater farmers were found to respond to a 1% increase in drought with a 0.3% increase in irrigation from the median value, while surface water farmers were found to respond to a 1% increase in drought by reducing irrigation by 1.7% from the median value. The results do not indicate asymmetric drought responses between surface water and groundwater farmers in their likelihood of upgrading to more efficient irrigation technology. This thesis concludes with a discussion of limitations, generalizability, and policy implications.

Keywords: Groundwater, Surface Water, Agriculture, Irrigation, Farm Investment

JEL: Q12, Q15, Q16, Q25

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1 Introduction

Freshwater is a vital component of the world's agricultural system, providing the irrigation needed for crops to grow. Crops receive freshwater in two forms. First, freshwater falls onto crops naturally via precipitation. Second, farmers apply freshwater to crops to provide additional irrigation. Globally, 70% of freshwater withdrawals are made for agriculture (OECD, 2016).

A crop needs to be irrigated with the proper amount of water in order to grow optimally. Droughts, or periods of abnormally dry weather, have two main effects for farmers. First, the lack of precipitation during drought leads to reduced crop irrigation via precipitation. It follows that farmers need to apply additional irrigation in order to maintain crop yields during drought. Second, drought affects the water supply of farmers. Reduced precipitation during drought decreases water availability for farmers to irrigate with, as well as leads to uncertainty about future water availability.

There are two main types of water: groundwater and surface water. Groundwater is freshwater stored below the Earth's surface in aquifers. Surface water is freshwater stored above the surface of the Earth, such as in lakes or streams. Surface water and groundwater sources have remarkably different characteristics. Surface water sources recharge directly via precipitation, and decrease uniformly when withdrawals are made. Also, surface water sources are generally smaller and have fewer users drawing from them. Alternatively, groundwater sources are recharged via precipitation that drips through earth into the aquifer, and recharge rates vary between groundwater sources. Further, the depth of groundwater sources does not decrease uniformly with withdrawals, leading to spatial externalities that are not present with surface water sources. Finally, groundwater is stored in aquifers that tend to be larger than surface water sources, with more users accessing each aquifer. For the purposes of this thesis, the term surface water farmers will refer to farmers utilizing surface water, and the term groundwater farmers will refer to farmers using groundwater.

Farmers make a series of decisions to maximize their profits from farming activities. As such, there is a line of literature within economics that models farmers as economic agents that optimize their farming decisions. These models have been used to explore the role of water availability on farmer decisions and profits. Farmers are able to mitigate drought effects because of their ability to re-optimize (Maneta et al., 2009). In this thesis, I analyze the role of water source in the drought response of farmers by exploring two measures of farmer behavior that are common within the agricultural optimization literature: amount of irrigation applied and irrigation technology investment.

The purpose of this thesis is to analyze the role of water source in the way farmers respond to drought by attempting to answer the following research question: Do the economic decisions of groundwater farmers and surface water farmers differ in response to drought? I will attempt to answer this question by exploring the drought response of surface water farmers and groundwater farmers in regards to (a) the amount of irrigation applied, and (b) the likelihood of upgrading to more efficient irrigation technology. My hypothesis is that surface water farmers will apply less irrigation in response to drought than groundwater farmers, and will be more likely to upgrade to more efficient irrigation equipment than groundwater farmers. Justification for my hypothesis is twofold. First, surface water sources are more volatile than groundwater sources, which makes drought more impactful on availability of surface water than groundwater. Second, surface water sources are typically smaller and have fewer users than groundwater sources. Experiments implementing the public goods game in behavioral economics suggest that participants are more likely to contribute to a public good when playing with partners, rather than playing with strangers (Fehr & Gächter, 2000). Because of the more localized role of surface water sources in water systems, I argue that the findings from the public goods games indicate that surface water farmers are more likely to cooperate with other water users by increasing water conservation efforts.

This thesis is novel in exploring the effect of water source on irrigation decisions. Though unresearched in the current literature, the role of water source in drought response has important ramifications. Agricultural irrigators are relatively price inelastic in their water consumption (Koundouri, 2004), making water conservation policy difficult to implement. It follows that if drought causes increased water conservation behaviors in surface water users, then policy leading to increased use of surface water sources could allow for water conservation during drought. Further, increasingly severe droughts are expected as a result of climate change (Intergovernmental Panel on Climate Change, 2007), which makes understanding drought response progressively more important.

To analyze the role of water source, this thesis focuses on the U.S. state of Kansas because of a climatic anomaly. In many parts of the world, groundwater and surface water sources overlap, meaning that water from both sources can be used conjunctively. Such conjunctive water use obfuscates the effect of water source, because of the endogeneity of the water source decision. However, Kansas' climate limits the possibility of conjunctive water use. Western Kansas is mostly dependent upon groundwater from the Ogallala Aquifer, while eastern Kansas relies predominantly on surface water (Sophocleous and Wilson, 2000). By imposing some additional restrictions, I will argue that the water source decision is exogenous in my panel data set of 18,710 wells.

This thesis continues with background information in Section 2. Section 3 contains basic concepts of the hydrology of groundwater and surface water. Next, Section 4 provides a review of the current literature in the field. Section 5 presents the research method implemented in the empirical analysis. Section 6 displays the results of the empirical analysis and provides discussion. Finally, Section 7 concludes.

2 Background

2.1 Water Scarcity in California and the World

My interest in this area of research began with the most recent drought in my home state of California. The period between 2011 and 2015 was the driest period in the state on record (Hanak et al., 2016). Concerns of water scarcity in California extend beyond the most recent drought; it has been estimated that agricultural, urban, and environmental demand for water is greater than the supply in California by 1.9 x 10^9 m^3 annually (Gude, 2016). Water scarcity worries are not endemic to California, as groundwater depletion is a concern for many parts of the world (Konikow and Kendy, 2005).

2.2 Climate Change

Climate change is likely to accentuate current issues of water scarcity. Most current climate projections estimate there will be a 1-3° C increase in temperature over the upcoming 50 years (Le Houérou, 1996). Evapotranspiration is the cumulative process of water entering the atmosphere from both evaporation from the Earth's surface and the transpiration from plants. The predicted temperature increase is likely to increase evapotranspiration, potentially decreasing the ratio of mean annual precipitation to evapotranspiration by 4-5% (Le Houérou, 1996). With constant rainfall, this ratio decrease would mean increased aridity across the globe. Further, increasingly severe droughts are expected as a result of climate change (Intergovernmental Panel on Climate Change, 2007).

In an effort to assess the future demand of water across countries, Distefano and Kelly (2017) develop a model based on the Intergovernmental Panel on Climate Change and OECD projections. The authors predict that most countries will face decreasing water availability, and argue that climate change is an instrumental component of the increasing water scarcity in their projections.

2.2.1 Effect on Agriculture

It is projected that climate change will negatively impact the agricultural sector worldwide. As climate change progresses, South Africa is projected to become warmer and drier (Calzadilla et al., 2014). Calzadilla et al. (2014) explore ways for South Africa to mitigate the projected effects of climate change on the agricultural sector, and conclude that even doubling the irrigation development in South Africa would not offset the predicted effects of climate change.

Zhang et al. (2017) estimate that crop yields in China of rice, wheat, and corn, will decrease by 36%, 18%, and 45% respectively, by 2100, as a result of climate change. Decreasing yields will have adverse consequences for farmers across the world. Mulangu and Kraybill (2015) conduct interviews with farmers near Mt. Kilimanjaro to learn about their intended responses to climate change threats. The authors find that farmers in the region are willing to pay 7-21% of their income to access improved irrigation that would mitigate the projected crop loss from climate change. These findings suggest that climate change will lead to increased water scarcity in agriculture, and that farmers will need to find innovative ways to mitigate the effects of increasing water scarcity.

3 Groundwater and Surface Water

Understanding how the freshwater system on Earth works is imperative for an analysis of agricultural irrigation. The following is a brief overview of the hydrologic cycle on Earth. Precipitation, responsible for nearly all freshwater on Earth, falls from the atmosphere everywhere around the planet with high degrees of local heterogeneity in amount (Winter et al., 1998). Water is returned to the atmosphere via evaporation from bodies of water and transpiration from plants (Winter et al., 1998).

Water that is stored on Earth is categorized as either surface water or groundwater. Surface water consists of water stored above the surface of the earth, including water in lakes, streams, and oceans, as well as the water stored in snow and ice (Winter et al., 1998).

Alternatively, groundwater is defined as water that is stored below the surface of the earth. Groundwater is further delineated into two primary zones: the saturated zone and the unsaturated zone. The unsaturated zone is the region closest to the surface. In the unsaturated zone, water is stored along with air in the null spaces between earth (Winter et al., 1998). Water stored in the unsaturated zone is not of much use to humans, because capillary forces prevent this water from being pumped to the surface by wells (Winter et al., 1998).

On the contrary, water fully encompasses the null spaces in the saturated zone, rendering it capable of being pumped to the Earth's surface (Winter et al., 1998). The water in the saturated zone is what is referred to as groundwater, because it is the freshwater below the Earth's surface that is accessible for human consumption. The saturated zone can also be referred to as an aquifer. The terms groundwater sources and aquifers will be used interchangeably in this thesis. The water table is the area that separates the saturated and unsaturated zones.

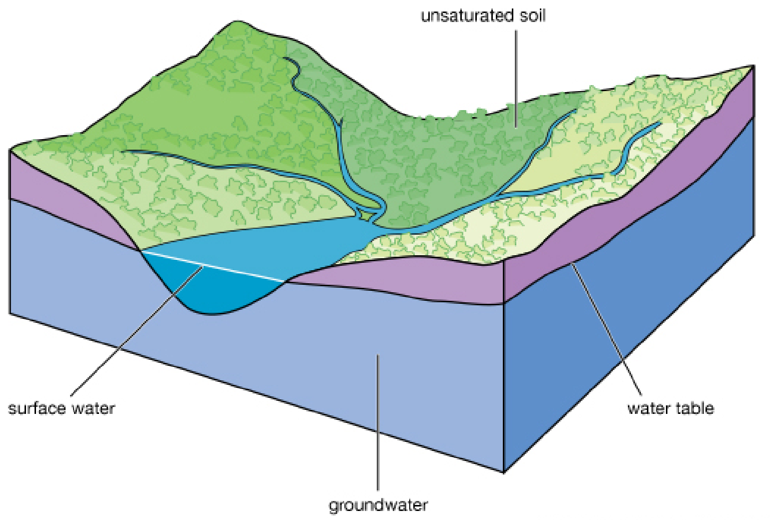

Figure 1: Surface Water, Groundwater, and the Water Table
Source: By courtesy of Encyclopaedia Britannica, Inc., copyright 2015; used with permission.

Figure 1 provides a visual display of surface water, groundwater, and the water table. The depth of the water table is vital information for the utilization of groundwater, because it represents the minimum depth that a groundwater well must be built. Water table depth is highly variable, ranging from zero to hundreds of meters (Winter et al., 1998).

3.1 Recharge & Transmissivity

Surface water processes are relatively straightforward. Most sources of surface water are recharged directly via precipitation (Winter et al., 1998). As rain falls onto a lake, the lake fills up uniformly. Similarly, if water is pumped out of the lake for human consumption, the level of the lake decreases evenly.

Processes in groundwater sources are more complicated than surface water processes. Instead of receiving precipitation directly, aquifers are recharged by freshwater passing through the unsaturated zone. Recharge rates vary across aquifers (Winter et al., 1998). Unlike the lake example from above, the water table of an aquifer is not laterally uniform, which is demonstrated in Figure 1. Because water passes through solid earth in groundwater sources, there is an additional component of horizontal movement that is not trivial. The term transmissivity refers to the horizontal movement of water in the saturated zone (Winter et al., 1998). Rates of transmissivity vary depending on the type of earth that water must pass through (Winter et al., 1998).

The opposing examples of recharge presented above highlight a difference between surface water sources and groundwater sources that is crucial for the purpose of this thesis. The recharge of surface water sources is directly dependent upon precipitation, as water sources are filled up with rainwater. Alternatively, groundwater sources are indirectly dependent upon precipitation. Water must pass through the unsaturated zone to reach an aquifer, implying that some water will be trapped in the unsaturated zone as it descends towards the saturated zone. In some cases, aquifers are not able to recharge at all (Konikow and Kendy, 2005). In an extreme version, Kim et al. (1989) model groundwater as a non-renewable natural resource, and apply optimal control theory to derive the optimal withdrawal rate.

Slow recharge rates and widespread use of groundwater have led to concerns about future availability of groundwater. Groundwater can be depleted if more water is withdrawn than is replaced by recharge (Koundouri, 2004). Extraction exceeds recharge in parts of California, China, India, Yemen, and Spain (Giordano, 2009). There are widespread concerns about groundwater depletion in North Africa, the Middle East, South and Central Asia, North China, North America, and Australia, and more localized concerns throughout the world (Konikow and Kendy, 2005). Harou and Lund (2008) present three options to overcome groundwater depletion. The first option is to reduce water demands, which the authors deem unrealistic. Second, the authors propose substituting groundwater with surface water. This option is precarious, as if no local surface water is available, imported surface water must be cheaper than pumping groundwater. The last option to respond to groundwater depletion is the conjunctive use of groundwater and surface water. A noteable method of conjunctive use is drought cycling, in which surface water is used in wet years, and groundwater is used in dry years (Harou and Lund, 2008).

3.2 Relative Size

An additional difference between groundwater sources and surface water sources is the relative size of each source.

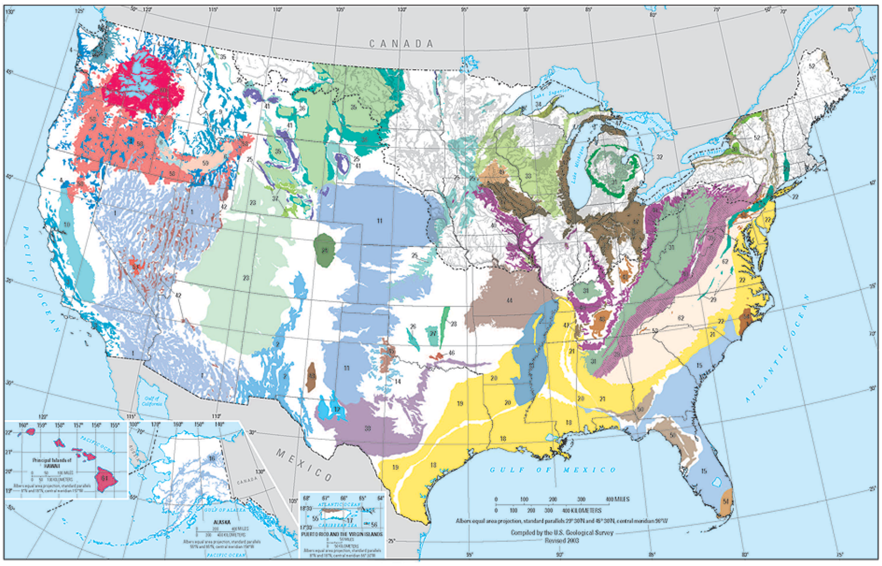

Figure 2: Main Aquifer Systems in the U.S.
Source: U.S. Geological Survey (2016b)

Figure 2 shows the main aquifer systems in the U.S. The figure demonstrates the vast size of major aquifers. These aquifers dwarf lakes, rivers, and streams that make up surface water sources. The size discrepancy between surface water and groundwater sources has implications for the number of users that draw from the different sources. Surface water plays a more localized role in water systems than groundwater, and surface water sources have relatively fewer users than groundwater sources.

4 Literature Review

4.1 Groundwater Management

4.1.1 Gisser-Sanchez Effect

One of the main topics in the groundwater literature is the successful management of groundwater resources. Gisser and Sanchez (1984), in a pioneering work in the field, argue that while groundwater management had already been a staple of the literature, previous authors had assumed large gains from proper management without any evidence. The authors apply optimal control theory to the consumption of groundwater, finding no significant difference between the social optimum and the competitive outcome. This puzzling result, known as the Gisser-Sanchez Effect, implies that there are no gains from efficient groundwater management. While the overall model is not met without criticism (Tomini, 2014), a literature review of groundwater issues (Koundouri, 2004) concludes the general results of the Gisser-Sanchez Effect to be rather robust.

4.1.2 Hydrologically Realistic Models

More recent and convincing critiques of Gisser and Sanchez (1984) have criticized Gisser and Sanchez's overly simplistic representation of groundwater. Athanassoglou et al. (2009) label the aquifer model used in Gisser and Sanchez (1984) the "bathtub model", because aquifers in the model are represented essentially as underground caves filled with water. In the bathtub model, water decreases uniformly as it is removed. This method of modeling aquifers is not realistic for the following reasons. First, the depth of the water table is not uniform (Athanassoglou et al., 2009). Second, the rate of transmissivity is lower in reality than in the bathtub model, because water must flow horizontally through material denser than air (Athanassoglou et al., 2009). Finally, when water is pumped out of an aquifer from a well, the water table lowers at a faster rate closer to the well, creating what is referred to as a cone of depression around the well. Because the water table lowers more at points closer to a well, pumping groundwater has larger impacts on groundwater users that are closer to the well than on groundwater users that are farther away from the well (Athanassoglou et al., 2009). These spatial externalities imply that spatial data is crucial for aquifer analysis (Brozovic et al., 2010).

Recent work has combined spatial data with more realistic groundwater models. Palazzo and Brozovic (2014) explore the effect of groundwater pumping rights trading in Nebraska. The authors find that cost savings from optimal groundwater management are distributed unevenly across wells, counties, and groundwater management institutions. Utilizing spatial data in western Kansas, Pfeiffer and Lin (2012) find that 2.5% of total groundwater extraction in the region is over-extracted because of spatial externalities.

Additionally, Guilfoos et al. (2013) directly address the Gisser-Sanchez Effect with spatial data from Kern County, California, and Pecos Basin, Texas. The authors calculate the welfare gain of switching from myopic behavior to the social optimum, with both the bathtub model and a spatially explicit model. Guilfoos et al. find significant welfare gains from the spatially heterogenous model only in Kern County. The authors suggest the existence of significant improvement only in Kern County because (a) total water demanded in Kern County is larger than Pecos Basin, and (b) there is a higher cost of extraction in Kern County. The authors demonstrate that, under the right conditions, there can be substantial welfare gains from management when employing a hydrologically realistic model.

While not explicitly mentioned, the bathtub model of an aquifer is fairly representative of a surface water source, because of the omission of transmissivity and lack of spatial externalities. It follows that the Gisser-Sanchez Effect would imply that there would be minimal gains from efficient surface water management. This is an indication that surface water and groundwater sources have different requirements for the role of efficient management. It follows that groundwater sources and surface water sources might vary in other dimensions, although no research has been conducted to explore this topic.

4.2 Irrigator Decisions

4.2.1 Optimization Models

A series of studies incorporating optimization models in which farmers are modeled as profit-maximizing economic agents provide insight into the decisions made by farmers. This line of literature dates back to Dudley and Burt (1973), in which the authors apply dynamic programming to economic decisions made by farmers. In this early optimization model, farmers with access to surface water optimize irrigation acreage, reservoir capacity, and distribution system capacity.

Agricultural optimization models have become increasingly complex to allow for the application to more specific scenarios. Marques et al. (2005) introduce a two-stage stochastic optimization model, in which farmers make permanent crop decisions in the first stage and annual crop decisions in the second stage. Included in both stages are decisions regarding crop selection, irrigation applied, and irrigation technology investment. The surface water source is modeled as recharging by a stochastic process representing rainfall, and the variance of this process is manipulated. The authors use this model to explore the effects of changes in the availability of water. In the model, farmers can respond to dry periods by irrigating their crops less and accepting a lower yield, investing in technology to make irrigation application more efficient, or switching to crops that need less water. Decreasing the variance of water availability increases expected profits for farmers.

Maneta et al. (2009) utilize a complex optimization model to analyze the effect of drought on land use, farm profits, and agricultural employment in Brazil. The economic optimization model is paired with a physics-based hydrology model that incorporates both surface water and groundwater. In the model, farmers optimize over 13 decision variables in their response to a simulated drought. The authors find large spatial heterogeneity in decisions made by farmers, a result of including a realistic groundwater model. Farms with better access to water had lower reductions in profits during drought periods than farms with worse access to water. The magnitude of the simulated droughts were smaller than the magnitude of the decrease in profits for farms because of the farmers' ability to mitigate drought effects by periodically re-optimizing. Reduced drought effects on profits from re-optimizing suggests that farmers prefer to be able to alter their behavior in shorter intervals. This is supported by Cook and Rabotyagov (2014), who find that irrigators prefer more variable leases.

4.2.2 Policy Relevance

The manner in which farmers alter their decisions in accordance with water availability is of vital importance to analysis of policy measures. The relatively inelastic response of water consumption for irrigation to price poses a challenge for policy intended to promote water conservation. While there have been estimates of the price elasticity of demand to be somewhat elastic (Schoengold et al., 2006), a literature review on groundwater management (Koundouri, 2004) concludes irrigation demand curves are price inelastic. The inelastic responses make it difficult to craft policies that will lead to water conservation, because increased prices from taxes are unlikely to lead to reduced water consumption.

An example of ineffective policy has been subsidizing more efficient irrigation technology. Well-meaning policy makers have implemented such subsidies, hoping that water use would decrease as a result of more efficient irrigation equipment. However, multiple studies have found that more efficient irrigation systems do not save water. Huang et al. (2017) find no overall water savings from more efficient irrigation technology in their study in China. Pfeiffer and Lin (2014) find that incorporating irrigation technology with increased efficiency actually leads to an overall increase of water consumption in Kansas.

4.2.3 Public Goods Games

Research from behavioral economics provides insight into decision making in the presence of public goods. This is relevant to the topic at hand because surface water and groundwater sources are public goods. A vital tool for research regarding public goods within behavioral economics is the public goods game. A typical version of the public goods game is as follows. Participants of the experiment are given an endowment and grouped into small teams. Next, participants choose how much of their endowment to contribute to a public good. Contributions to the public good multiply by a factor less than the number of people in the group and are distributed evenly between group members. For instance, a four-person version of the game might stipulate that every dollar doubles when contributed to the public good. It follows that each participant would receive $0.50 for every dollar contributed to the public good.

While it is socially optimal for participants to contribute all of their endowment, an incentive to free-ride exists because of the sub-optimal return on personal contributions. Fischbacher et al. (2001) find that most people are conditional cooperators, meaning that participants cooperate as long as other people are doing so. Once free-riding is observed, most participants resort to free-riding. Additionally, participants are more likely to contribute if they are playing with partners rather than strangers (Fehr & Gächter, 2000).

To disincentivize free-riding, some versions of the game have included punishment (Fehr & Gächter, 2000; Masclet et al., 2003). Fehr & Gächter (2000) find that monetary punishment is a useful tool to induce cooperation among participants. Masclet et al. (2003) extend the concept of punishment, finding that non-monetary punishment, such as displays of disapproval, are useful in ensuring contributions.

While these findings from public goods games come from highly structured laboratory experiments, they have implications for farmers drawing from public water sources. Water conservation decisions made by irrigators are parallel to contributions from the public goods games. Irrigators can contribute to a public good, their water source, by personally sacrificing by reducing water consumption or upgrading to more efficient irrigation equipment that reduces water waste.

4.3 Contribution to the Literature

This section will address how this thesis fits into the existing field of literature. Initial groundwater management literature incorrectly modeled groundwater sources, including features that were more characteristic of surface water sources than groundwater sources. While this mistake has been rectified in recent papers that have incorporated more realistic models of groundwater, the literature has failed to address the role of water source in irrigation decisions.

Distinctions in key characteristics of surface water and groundwater sources make it likely that surface water farmers and groundwater farmers have asymmetric drought responses. First, surface water sources are more volatile than groundwater sources. Surface water sources are directly dependent upon rainfall, making these sources susceptible to large variance of levels based on fluctuations in precipitation. While aquifers are recharged by precipitation, the slow recharge and larger capacities of the aquifers make them more stable sources. This implies that drought has a larger effect on water availability in surface water sources than groundwater sources. Also, surface water sources are smaller than groundwater sources. It follows that there are less users drawing from each surface water source than each groundwater source, implying that surface water sources play a more localized role in water systems. The research regarding public goods games indicates that participants are more likely to contribute to a public good when playing with partners instead of strangers. Surface water farmers are more likely to share more of their water source with members of their direct community, while groundwater farmers are spread out across multiple states. Therefore, surface water farmers more closely resemble the partner treatment in the public goods game, and surface water farmers might be more likely to contribute to their surface water source, a public good, by decreasing water consumption.

With this thesis, I intend to expand on the economic decisions facing farmers presented by the optimization literature discussed in Section 4.2.1. Marques et al. (2005) create a model in which farmers react to changing water availability by optimizing decisions regarding crop selection, amount of irrigation applied, and irrigation technology investment. While data utilized in this thesis does not render itself to explore the effect of drought on crop selection, I will proceed with analyzing the role of water source in drought effects on irrigation applied and irrigation technology investment.

5 Research Method

This section will discuss the method for answering the research question of this thesis: Do the economic decisions of groundwater farmers and surface water farmers differ in response to drought? I will begin this section by discussing the data utilized in this study and finish by presenting the identification strategy of the empirical analysis.

5.1 Economic Decisions of Farmers

Farmers make a series of economic decisions in an effort to maximize their profits from farming. The following is a simplified outline of decisions and actions made by a farmer, and how these decisions relate to drought. For the purposes of this example, I will present the case of a farmer growing corn in Kansas, as corn is the most frequently grown crop in my data set, which is demonstrated in Table 2. At the beginning of each year, a farmer decides on the type and amount of crop that they will plant. The goal of the farmer is to maximize their profit, and the farmer optimizes over the projected market rate of crops. If at this stage a farmer has limited access to water, or is concerned about future water availailability, the farmer might choose to plant less water-intensive crops in an effort to conserve water. After the decision regarding crop type and farmland allocation has been made, the farmer is ready to plant for the season. Corn is typically planted between 10 April and 25 May in Kansas (U.S. Department of Agriculture, 1997).

After the spring planting season, crops grow throughout the summer months. The crops need freshwater in order to grow, so a vital component of the farmer's job is to ensure that the crops receive adequate freshwater. Crops receive freshwater from precipitation, and the farmer applies additional irrigation. As a profit maximizer, the farmer makes the decision of how much to irrigate the crops based on the expected profit from doing so. Although the farmer owns the right to pump water for irrigation, applying irrigation is not costless. Farmers must pay for the electricity required to pump water from the well. At this stage a farmer can practice water conservation by stress-irrigating their crops.[1] The first step in exploring the role of water source in drought response by farmers in this thesis will be to compare the amount of irrigation groundwater and surface water farmers apply in response to drought.

Finally, the farmer harvests corn crops in the fall, typically occurring between 5 September

[1]Stress-irrigating is an irrigation method in which the farmer applies a sub-optimal amount of irrigation to the crops and accepts lower yields.

and 10 November in Kansas (U.S. Department of Agriculture, 1997). The farmer decides on when exactly to harvest the corn, and whether or not to employ additional labor to help with the process. In addition to these seasonal profit-maximization decisions, the farmer continually has the opportunity of investing in upgraded farm equipment, including irrigation application equipment. More efficient irrigation technology reduces waste from water that is distributed from the sprinkler system, but does not make it to the crop. Further discussion regarding the efficiency of irrigation technology is included in Section 5.3.1. If a farmer is constrained by the availability of water, they have the option of upgrading to more efficient irrigation technology in order to reduce water consumption.

Drought has two main effects on farmers. First, the lack of precipitation during drought leads to reduced crop irrigation via precipitation. It follows that, during drought, farmers need to apply additional irrigation in order to maintain crop yields. I will refer to the increased need for water from drought as the "push" effect of drought. Second, drought affects the water supply of farmers. Decreased precipitation results in reduced water availability, as surface water sources and groundwater sources are not recharging. The reduced availability of freshwater means that the farmer has less water available currently, and is more incentivized to make efforts to conserve water for the future. I will refer to this as the "pull" effect of drought.

My hypothesis is that there is an asymmetric drought response in the economic decisions made by groundwater farmers compared to surface water farmers. I believe that the differences between surface water and groundwater sources presented above make surface water farmers more susceptible to the pull effects of drought than groundwater users. First, the volatility of surface water sources makes drought more impactful on surface water sources than groundwater sources. Because the capacity of surface water sources is more volatile as a result of drought than groundwater sources, surface water farmers are more likely than groundwater farmers to have less water available, and be more likely to be incentivized to conserve water for future use. Further, surface water sources are smaller and are more likely to have fewer users per source than groundwater sources. The results from public goods games suggests that people are more likely to contribute to public goods with partners rather than strangers. Because surface water sources play more localized roles in water systems, surface water farmers are more likely to have increased interaction with a higher share of users of their water source. This mimics the partner treatment of the public goods games, because other users of the water source are more likely to be members of the surface water farmer's direct community.

My hypothesis is that surface water farmers will be more likely to conserve water than groundwater farmers in response to drought. I will be measuring drought response in terms of the amount of irrigation farmers apply and the likelihood of upgrading to more efficient irrigation technology. In regards to each measure, my hypothesis is that surface water farmers will apply less irrigation in response to drought than groundwater farmers, and surface water farmers will be more likely to upgrade to more efficient irrigation technology in response to drought.

5.2 Exogeneity of Water Source Decision

An exogenous water source decision is required for an empirical analysis of the role of water source in drought response. Groundwater and surface water are simultaneously available in many places, making it difficult to find a place where the water source decision is exogenous. In areas where both water sources are available, irrigators can choose whichever water source better suits their needs, or irrigators can use both surface water and groundwater conjunctively. However, both water sources are not simultaneously available everywhere. For this reason, I utilize a data set from the U.S. state of Kansas. The Ogallala Aquifer, known also as The High Plains Aquifer, is the main source for groundwater in many states in the American Midwest (Pfeiffer and Lin, 2014b).

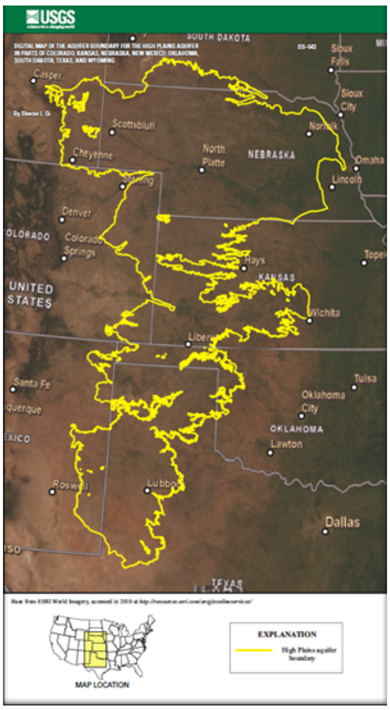

Figure 3: The Ogallala Aquifer
Source: Qi, S. (2010)

Figure 3 shows the Ogallala Aquifer, expanding over 8 states in the U.S.[2] The Ogallala Aquifer approximately divides the state of Kansas (KS) in two. In western Kansas, which lies over the Ogallala Aquifer, there is little access to surface water (Sophocleous and Wilson, 2000). Because of the lack of availability of surface water, groundwater is the principal freshwater source in western Kansas (Sophocleous and Wilson, 2000). Alternatively, there is insufficient access to groundwater in eastern Kansas to meet the needs of residents, making surface water the principal freshwater source in the region (Sophocleous and Wilson, 2000).

The skewed distribution of water source across Kansas is apparent in Table A1. Table A1 presents the percentage of observations utilizing groundwater at the county level, for all observations of my original data set. Most of the counties have an extreme proportion of either groundwater or surface water. While the majority of counties are predominantly using either groundwater or surface water, there are still counties that have more equal shares of both water sources. The more even the split between groundwater and surface water, the more likely that the water source decision is endogenous. This is a problem, because no comparison of groundwater farmers and surface water farmers can be made if the water source decision is endogenous.

The most fundamental assumption of this thesis is that the decision of the water source is exogenous for the farmer, which is admittedly a strong assumption. It is possible for a farmer to have two wells with different water sources and switch between the wells. Additionally, it is possible that a farmer, when building a well, chooses to draw either groundwater or surface water based on the characteristics of their farm. Both of these examples would indicate that the water source decision is not exogenous. However, these decisions would not be possible if a farmer is in an area where there is access to only either surface water or groundwater. The climate in Kansas limits the possibility of endogenous water decisions because of limits on regional availability of groundwater and surface water.

Because of the importance of water source exogeneity in my identification strategy, I am imposing additional restrictions on my sample. First, I am limiting the sample to only include observations in counties where there is at least a 90% share of either groundwater or surface water. A farmer in a county in which at least 90% of the water rights are either surface water or groundwater is unlikely to have much agency in choosing water source. Additionally, I am omitting observations from five counties because of their location.[3] While these counties meet

[2]The Ogallala is also referred to as the High Plains Aquifer.

[3]The omittied counties are Cloud County, Shawnee County, Jefferson County, Douglas County, and Doniphan

the 90% observation cut-off, they are located substantially east of the majority of groundwater counties and do not overlap the Ogallala Aquifer. I omit these counties in order to ensure that the vast majority of groundwater observations are from the Ogallala Aquifer. These five omitted counties are all groundwater counties. Because my sample contains so many groundwater observations, I am not concerned that the omission of these five counties will bias my results. I include a robustness check in Table A3, located in the Appendix, to demonstrate that the results are not biased by the omission of these five counties.

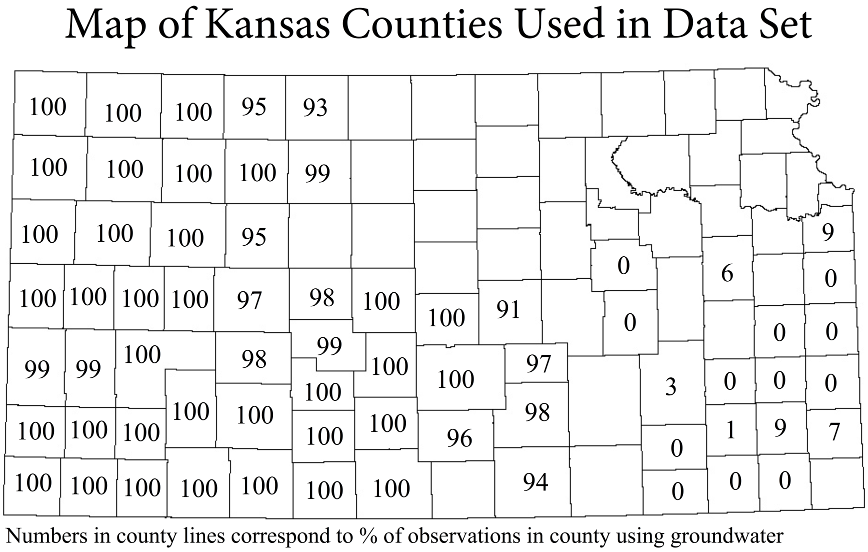

Figure 4: Kansas Counties Used in Data
Source: Author rendering from data

Ultimately, I have omitted 37/105 counties in Kansas from the data set. Figure 4 shows the Kansas counties utilized in the data set and the percentage of groundwater observations in each county. Each county that has a number in it is used in the data set. Counties with no numbers inside the county border were omitted from the sample for one of the two reasons mentioned above. Figure 4 demonstrates that the data set captures what is intended. All of the groundwater observations lie in western Kansas, consistent with the fact there is little availability of surface water in western Kansas (Sophocleous and Wilson, 2000). Further, the groundwater counties in Figure 4 overlap with the Ogallala Aquifer shown in Figure 3. Alternatively, all of the surface water counties are located in the southeast part of the state, which coincides with the part of Kansas in which there is little groundwater available (Sophocleous and Wilson, 2000).

Because of Kansas' climatic anomaly and the limitations that I have imposed on the data, I

County.

am arguing that the water source decision for farmers is exogenous. The purpose of arranging the data in this way is to obtain a data set with two distinct groups: surface water farmers and groundwater farmers. I will compare these two groups with the regression strategy presented in Section 5.4.

5.3 Data

Table 1: Descriptive Statistics

Source	af_used	acres_irr	elec_price	ITU	D1	D2	D3	D4
Ground								
Count	256,284	251,020	241,030	256,284	256,284	256,284	256,284	256,284
Mean	156.72	142.37	7.94	0.053	38.96	23.72	12.20	4.00
SD	120.34	86.36	1.47	0.22	35.23	31.38	21.87	11.58
Min	0	0	6.2	0	0	0	0	0
Median	138	126	7.44	0	28.14	3.77	0	0
75th%	203.08	150	9.24	0	72.12	47.74	14.77	0
Max	1,950.90	3900	10.24	1	100	100	97.52	69.8
Surface								
Count	3,919	3,518	3,672	3,919	3,919	3,919	3,919	3,919
Mean	79.66	95.11	7.87	0.035	23.39	11.33	4.40	1.04
SD	590.43	238.55	1.45	0.18	27.29	19.56	11.63	4.84
Min	0	0	6.2	0	0	0	0	0
Median	28.78	64.5	7.44	0	12.97	0	0	0
75th%	62	116	9.24	0	43.49	12.53	0	0
Max	22,114	8,000	10.24	1	100	100	70.43	63.47
Total								
Count	260,203	254,538	244,702	260,203	260,203	260,203	260,203	260,203
Mean	155.56	141.72	7.94	0.053	38.73	23.53	12.08	4
SD	140	90.39	1.47	0.22	35.18	31.27	21.77	11.52
Min	0	0	6.2	0	0	0	0	0
Median	136	126	7.44	0	28.01	3.71	0	0
75th%	202	150	9.24	0	70.88	47.06	13.53	0
Max	22,114	8,000	10.24	1	100.00	100	97.52	69.8

af_used: Acre-Feet Used, acres_irr: Acres Irrigated, elec_price: KS Commercial Electricity Price,
ITU: Irrigation Technology Upgrade, D1: Moderate Drought, D2: Severe Drought,
D3: Extreme Drought, D4: Exceptional Drought

Table 2: Frequency Statistics for Most Recurrent Categorical Variables

		Frequency	Percent	Cum. Percentage
crop_code	Corn	99,343	36.94	36.94
	Multiple	41,014	15.25	52.19
	Soybeans	24,318	9.04	61.23
	Corn & Wheat	18,001	6.69	67.92
	Alfalfa	14,094	5.24	73.16
type_system	Center Pivot LEPA	176,579	65.66	65.66
	Center Pivot	33,574	12.48	78.14
	Flood	30,051	11.17	89.31
	Center Pivot & Flood	17,075	6.35	95.66
	Sprinkler Besides Center Pivot	5,877	2.19	97.85
ITU	No Upgrade	258,084	95.96	95.96
	Upgrade	10,857	4.04	100

crop_code: Crop Type, type_system: Type of Irrigation Technology, ITU: Irrigation Technology Upgrade

Table 3: Cross-Correlations

	af_used	acres_irr	elec_price	ITU	D1	D2	D3	D4
af_used	1.0000							
acres_irr	0.7069	1.0000						
elec_price	-0.0280	-0.0180	1.0000					
ITU	0.0163	0.0188	-0.067	1.0000				
D1	0.1767	0.0793	0.3125	-0.0017	1.0000			
D2	0.1661	0.0741	0.3323	-0.0045	0.9004	1.0000		
D3	0.1456	0.0549	0.3706	-0.0161	0.7459	0.8898	1.0000	
D4	0.1246	0.0467	0.3003	-0.0150	0.4664	0.5978	0.7609	1.0000

af_used: Acre-Feet Used, acres_irr: Acres Irrigated, elec_price: KS Commercial Electricity Price,
ITU: Irrigation Technology Upgrade, D1: Moderate Drought, D2: Severe Drought,
D3: Extreme Drought, D4: Exceptional Drought

5.3.1 Water Use Reporting Data

Well-level data from farmers was collected from the Water Information Management and Analysis System (WIMAS), which is a joint project between the Kansas Department of Agriculture and the Kansas Geological Survey. As a result of the Water Appropriation Act in Kansas, residents must receive a permit to use freshwater for all purposes besides solely domestic purposes (Kansas Department of Agriculture). The process for obtaining a water right for a farmer in Kansas is as follows. First, the farmer must file an application and receive a permit from the Division of Water Resources. After the farmer has received the permit, construction of the well or pump-site can occur. Upon completion of the well or pump-site, the Division of Water Resources conducts a field inspection and calculates the maximum rate of diversion for the well or pump-site. Water users do not pay the Division of Water Resources for water, so the cost of water is only comprised of extraction costs, which are the electricity costs of pumping water. Finally, water users must submit an annual water use report. The annual report contributes to the data that is publicly available from WIMAS.

The WIMAS data is detailed and includes data about the well, the geographic location of the well, and the annual water use report. Because it is so comprehensive, the WIMAS data has been utilized in other studies (Hendricks and Peterson, 2012; Lin and Pfeiffer, 2010; Pfeiffer and Lin, 2012; Pfeiffer and Lin, 2014a; Pfeiffer and Lin, 2014b). Because of the availability of drought data dating back to 2000, I utilize WIMAS data for the time period 2000-2016. To only include data for farmers, I only collected data for which the water purpose was irrigation. To ensure that all irrigation use was for farming, I dropped all observations that do not have any data for crop type.

I utilize data for irrigation applied, acres irrigated, crop type, and irrigation technology type directly from WIMAS. In order to assess the drought effect on likelihood of upgrading to more efficient irrigation technology, I needed to create a new variable for an irrigation technology upgrade. First, I will define an irrigation technology upgrade, and then I will explain how this is implemented. The WIMAS data provides information regarding the type of irrigation equipment at the well-level for every observation. Different types of irrigation technology have different levels of efficiency. When water is distributed from a sprinkler system, some water doesn't get applied to the crop, because the water misses the crop or evaporates before hitting the crop. Irrigation systems are rated based on their efficiency of distributing water to the the crop. A 100% efficient irrigation system would imply that every drop of water that leaves the irrigation system makes it onto the intended crop.

Modern irrigation development in Kansas began in the 1970's with the implementation of flood irrigation (Pfeiffer and Lin, 2014b). Flood irrigation applies freshwater to a field from a pipe, and requires flat, uniform farmland (Pfeiffer and Lin, 2014b). Flood irrigation is relatively inefficient, estimated to be 65-75% efficient (Pfeiffer and Lin, 2014b). Center pivot technology, a method of irrigation in which an overhead sprinkler delivers crops water, provides farmers an upgrade from flood irrigation. Center pivot irrigation is estimated to be 80-90% efficient (Pfeiffer and Lin, 2014b).

A more recent shift in technology has been the shift from center pivot to center pivot Low Energy Precision Application (LEPA). This method of irrigation lowers the height of the sprinkler, so that there is less space between the sprinkler and the crop. By reducing the space from the sprinkler to the crop to 8-18 inches, less water is lost to evaporation and wind drift (New and Fipps, 1990), increasing the efficiency of center pivot LEPA irrigation to 95-98% (Pfeiffer and Lin, 2014b).

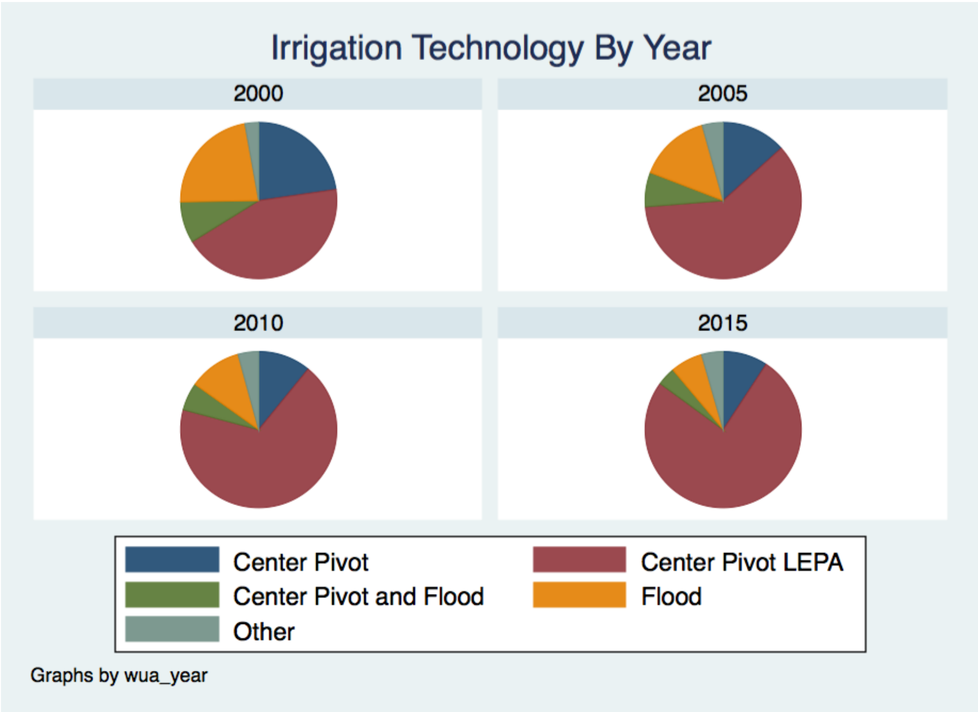

Figure 5: Irrigation Technology Shifts Over Time
Source: Author rendering from WIMAS (2017) data

Figure 5 represents the shift in irrigation technology throughout the observed time period in the data set. There are two major shifts in technology occurring over the time period of the study. First, irrigators are moving away from flood irrigation. This can be seen in that both the percentage of flood irrigation and the percentage of center pivot and flood irrigation are decreasing over time. Second, there is a large shift from center pivot to center pivot LEPA. In the beginning of the time period, less than half of the wells irrigate with center pivot LEPA technology. However, by the end of the time period, roughly three-quarters of the irrigators use center pivot LEPA technology. For the purposes of this thesis, an irrigation technology upgrade is defined as upgrading from flood irrigation to any other type of irrigation technology, or from upgrading from center pivot irrigation to center pivot LEPA technology.

Now that an irrigation technology upgrade has been defined, I will explain what the irrigation technology upgrade variable encompasses. If the well was using flood irrigation technology in year t, and any other irrigation type in year $t + 1$, then the value of the dummy variable for irrigation technology upgrade is one for the well in year $t + 1$. The same logic applies for observations in which the well irrigated with center pivot technology in year t and center pivot LEPA technology in year $t + 1$. Table 2 displays the total amount of irrigation technology upgrades.

Finally, I will address the timing of the decision to upgrade irrigation technology. While the economic decision of choosing how much irrigation to apply in a certain year is dependent directly upon the amount of rainfall during that year, the decision of whether or not to upgrade technology is not such a straightforward process. Farmers can upgrade their irrigation technology at any point during the year. It might be the case that a farmer responds to a severe drought in time t by investing in upgraded irrigation technology in time t or in time $t + 1$. Because of this, the model for irrigation technology upgrade will be run with the independent variable of drought level in the same year, and with a lagged effect, making the independent variable drought level in the previous year.

5.3.2 Drought Data

I collected drought data from the United States Drought Monitor. The U.S. Drought Monitor tracks drought across the United States, and categorizes droughts by their severity.

Table 4: U.S. Drought Monitor Drought Classifications

Drought Classification	**Definition**	**Possible Impacts**
D0	Abnormally Dry	Short-term dryness
D1	Moderate Drought	Some damage to crops
D2	Severe Drought	Crop losses likely
D3	Extreme Drought	Major crop losses
D4	Exceptional Drought	Exceptional & widespread crop losses

Table 4 displays the the U.S. Drought Monitor drought level classifications. The drought classifications are based on five indicators that are weighted based on location within the U.S.: the Palmer Drought Severity Index, the CPC Soil Moisture Model, USGS Weekly Streamflow, the Standardized Precipitation Index, and Objective Drought Indicator Blends (U.S. Drought Monitor).

The U.S. Drought Monitor provides weekly updates of drought intensity across the U.S. I used data for the most localized geographic area available, county-level data, for this analysis. I collected data for the percentage of the county afflicted by each drought classification for each week in each county during the time period. Next, I calculated fifty-two week averages to create annual drought observations at the county level. Finally, I matched well-level WIMAS data with the annual county-level drought data.

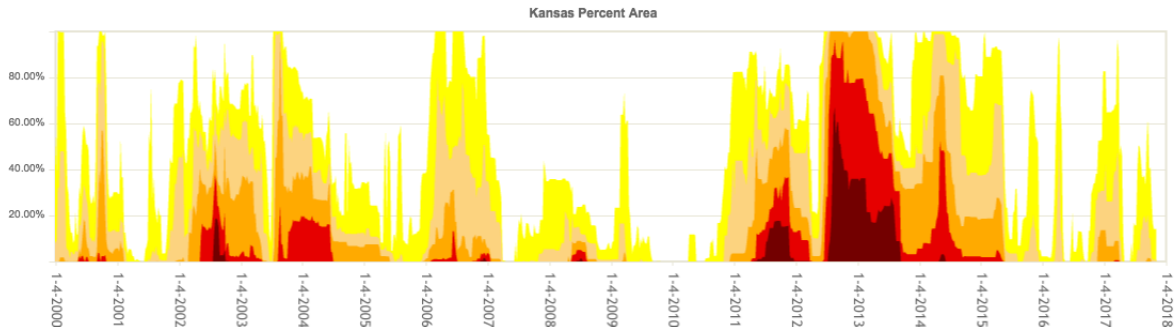

Figure 6: Kansas Statewide Drought Levels 2000-2016
Source: United States Drought Monitor

Figure 6 shows state-level drought observations for Kansas during the time period used in this thesis. Drought specifications range from “Abnormally Dry” in yellow to “Exceptional Drought” in dark red. The most intense periods of drought occurred between 2002 and 2004 and between 2011 and 2015. For the purposes of this study, I prefer to use the most severe drought specification in the analysis, as drought effects are likely to be most apparent with a more severe drought specification. However, I utilize Severe Drought (D2) as the main drought specification in this analysis for two reasons. First, the data set includes a rather small amount of observations with widespread Exceptional Drought. Additionally, it is difficult to distinguish between reductions from drought pull effects and reductions from lack of access to water or the imposition of water restrictions by county. It is more likely that lack of access or imposed water restrictions are driving the results in the more severe drought specifications. Alternatively, it is more likely that the pull effects of drought are driving the results in the less severe drought specifications because there is less likely to be loss of access to water or water restrictions under Moderate Drought or Severe Drought.

5.3.3 Electricity Price Data

Farmers with water rights do not have to pay directly per unit of water, but they do have to pay for the cost of pumping water from the well. Therefore, I will include controls in my model that account for these pumping costs. I collected data regarding electricity prices from the U.S. Energy Information Administration.

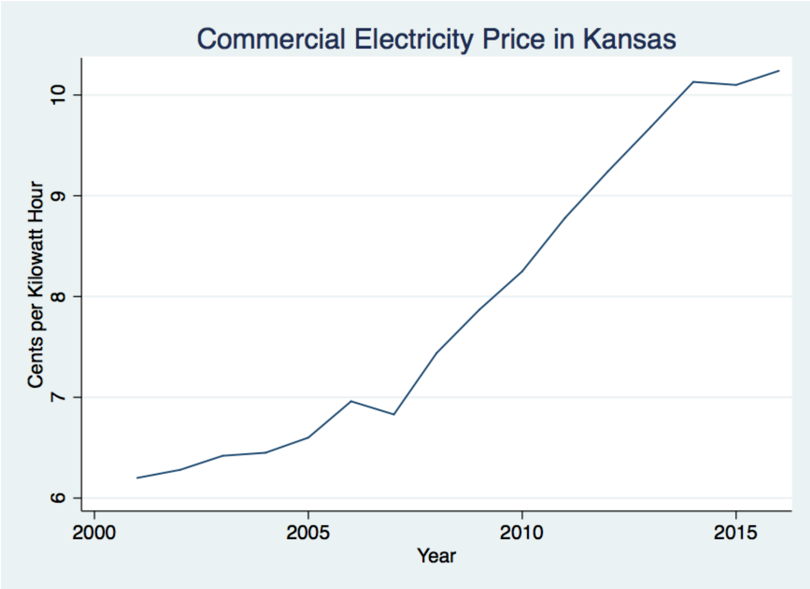

Figure 7: Commercial Electricity Price in Kansas
Source: Author rendering from U.S. EIA (2017) data

Figure 7 displays commercial prices for electricity statewide in Kansas during the time period of this thesis. The cost of electricity was steadily rising throughout the time period. While it seems that including year fixed effects would be sufficient to control for electricity costs, Table 3 shows that commercial electricity cost is positively correlated with the more severe drought classifications. This implies that it is important to implement a control for pumping costs into the models to avoid a case of omitted variable bias.

5.4 Econometric Models

The purpose of this research is to compare drought responses of surface water farmers and groundwater farmers. As suggested in the optimization literature, farmers can mitigate drought effects by optimally changing behavior. I will compare surface water farmers and groundwater farmers on their drought responses in regards to the amount of irrigation applied and the likelihood of upgrading to increasingly efficient irrigation technology.

5.4.1 Effect on Irrigation Applied

In order to assess drought effects on irrigation applied for groundwater and surface water farmers, the panel data set discussed in the previous section is estimated to the following fixed effects model:

$$IRR_{w,t} = \alpha_w + \beta S_{w,t} + \gamma d_{c,t} + \delta S_{w,t} * d_{c,t} + \zeta e_t + \eta S_{w,t} * e_t + Y_t + \sum_{i=1}^{n} \iota_i C_{w,t} + \epsilon_{w,t} \quad (1)$$

where $IRR_{w,t}$ is the amount of irrigation applied by well w in year t
α_w is the well-specific constant to account for time-invariant heterogeneity
$S_{w,t}$ is a dummy variable for water source of well w in year t
$d_{c,t}$ is the percentage of area afflicted by specified drought level in county c in year t
$S_{w,t} * d_{c,t}$ is the interaction effect between water source and drought level
e_t is the commercial electricity price in Kansas in year t
$S_{w,t} * e_t$ is the interaction effect between water source and commercial electricity price
Y_t is a dummy variable for year to control for year fixed effects
$C_{w,t}$ is a vector of n control variables for well w in year t
$\epsilon_{w,t}$ is an error term for well w in year t

In this model, irrigation applied is the dependent variable. Irrigation applied is measured in acre-feet. The independent variable for water source, $S_{w,t}$, is a dummy variable that equals 0 for groundwater and 1 for surface water. The second independent variable is drought level, d_t. Drought level is the average percentage of the well's county afflicted by the drought specification annually. The main drought classification implemented in the model is D2, or Severe Drought. After the main drought classification, a sensitivity analysis will be conducted, utilizing alternative drought specifications D1, D2, and D4, for Moderate Drought, Severe Drought, and Exceptional Drought.

Additionally, there is an interaction effect between water source type and drought, $S_{w,t} * d_{c,t}$. The coefficient of this interaction effect, δ is the main coefficient of interest of this study. If the effect of drought on irrigation applied is different for surface water farmers and groundwater farmers there will be an interaction effect, and δ will be significantly different from zero. As mentioned above, the dummy variable for water source, $S_{w,t}$, will equal 0 for groundwater, and 1 for surface water. It follows that the effect of drought for groundwater farmers is γ, and the effect of drought for surface water farmers is $\gamma + \delta$.

The model implements fixed effects by including a well-specific constant, α_w, which controls for time-invariant heterogeneity at the well-level. A Hausman Test allows for one to determine whether to use a fixed effects or random effects model by testing for statistically significant differences in coefficients of explanatory variables that change over time (Woolridge, 2013). The model presented in Equation 1 will be used if the Hausman test indicates that a fixed effects model should be used, and a random effects version of the model presented in Equation 1 will be implemented if the Hausman test indicates that a random effects model is the proper model for the data. In addition to incorporating fixed effects at the well-level, the model includes a set of year fixed effects, represented by Y_t. These year fixed effects control for the influence of time-series trends.

Table 3 shows that the correlation between commercial electricity price and the two most severe drought specifications is not negligible. It follows that a control for electricity costs, e_t, should be included in the model. Electricity costs are measured in cents per kilowatt hour. Groundwater must be pumped further distances than surface water, because of the location of groundwater below the water table. This implies that pump costs might have different effects between surface water farmers and groundwater farmers. Therefore, I include an additional control that is an interaction term between electricity price and source, $S_{w,t} * e_t$.

Finally, the model incorporates a vector of additional control variables. While the individual fixed effects control for time-invariant heterogeneity, they do not control for variables that fluctuate over time. It follows that the controls included are variables from the WIMAS data that change over time. The full model includes controls for the number of acres irrigated, the type of irrigation technology, and the type of crop planted.

For the main specification of the model with D2, Severe Drought, as the drought specification, I will run a series of regressions. The regression series will begin with the most simple form of the model that includes well-specific fixed effects and no controls. Additional controls will be added one by one leading up to the presentation of the full model. Doing so will allow me to analyze the effect of each additional control. Upon completion of the main specification, I will conduct a sensitivity analysis, in which I will run the full model under all drought specifications.

5.4.2 Effect on Irrigation Technology Upgrade

The second measure for the drought response of farmers is the likelihood of upgrading to more efficient irrigation technology. Irrigation technology upgrade, defined in Section 5.3.1, is a binary dependent variable. One has a multiple options when selecting a model when the dependent variable is binary. The first distinction is whether to choose a linear probability model or a nonlinear probability model. It is not convention to use linear probability models, because linear probability models can provide predictions of less than 0 or greater than 1, outside the range of possible values for dummy variables (Woolridge, 2013). While it can be difficult to interpret interaction effects in nonlinear probability models (Mood, 2010), I will proceed with a nonlinear probability model.

Logit and probit models are implemented in most nonlinear probability models; probit models are typically favored as their normal distributions imply simpler analysis (Woolridge, 2013). However, I will proceed with a logit model for a technical reason. The Stata probit command only allows for the application of random effects models, while the logit command allows for either random effects or fixed effects. For this reason, I will proceed with a logit model and employ a Hausman test to decide between the random effects and fixed effects versions of the model. Equation 2 is the fixed effects logit model for the empirical analysis:

$$Pr(ITU_{w,t} = 1|d_{c,t}) = \Lambda\Bigg(\alpha_w + \kappa S_{w,t} + \mu d_{c,t} + \rho S_{w,t} * d_{c,t} + \sigma e_t + \tau S_{w,t} * e_t + Y_t + \sum_{i=1}^{n} \omega_i C_{w,t} + \epsilon_{w,t}\Bigg) \tag{2}$$

where
$ITU_{w,t}$	is a dummy variable for irrigation technology upgrade in well w in year t
Λ	is the logistic function
α_w	is the well-specific constant to account for time-invariant heterogeneity
$S_{w,t}$	is a dummy variable for water source of well w in year t
$d_{c,t}$	is the percentage of area afflicted by specified drought level in county c in year t
$S_{w,t} * d_{c,t}$	is the interaction effect between water source and drought level
e_t	is the commercial electricity price in Kansas in year t
$S_{w,t} * e_t$	is the interaction effect between water source and commercial electricity price
$C_{w,t}$	is a vector of n control variables for well w in year t
Y_t	is a dummy variable for year to control for year fixed effects
$\epsilon_{w,t}$	is an error term for well w in year t

To account for a binary dependent variable, logit models calculate the effect of independent variables on the probability that the value of the dependent variable will be 1 rather than 0. $\Lambda(z)$ is the cumulative distribution function for a standard logistic random variable.[4] Within the cumulative distribution function, the model for irrigation technology upgrade is nearly identical to the previous model for irrigation applied. Both models include the same independent variables

[4] $\Lambda(z)$ is defined as $\Lambda(z) = \frac{exp(z)}{1+exp(z)}$ (Woolridge, 2013).

and individual and year fixed effects. However, the irrigation technology upgrade model will not include a control for technology type, as technology type is accounted for in the dependent variable. Irrigation applied will be implemented as a control variable in the irrigation technology upgrade model.

The coefficient of interest is once again the coefficient of the interaction term, which is now ρ. For groundwater farmers, the effect of drought on the likelihood of upgrading technology is μ. For surface water farmers, the effect of drought on the likelihood of an irrigation technology upgrade is $\mu + \rho$.

As with the previous model for irrigation applied, I will run the irrigation technology upgrade model several times, incorporating an additional control with each regression. Similarly to the previous model, I will run a sensitivity analysis with alternate drought specifications.

6 Results and Discussion

This section will go over the results from the regression estimations. The effect on irrigation applied will be addressed first, followed by the effect on irrigation technology upgrade.

6.1 Effect on Irrigation Applied

Table 5: Effect on Irrigation Applied - Severe Drought

	(1)	(2)	(3)	(4)	(5)	(6)
D2	0.373***	0.524***	0.519***	0.436***	0.437***	0.460***
	(0.00540)	(0.00531)	(0.00590)	(0.00924)	(0.00929)	(0.00902)
SourceXD2	-0.757*	-0.802*	-0.769*	-0.941*	-0.940*	-0.935*
	(0.352)	(0.376)	(0.390)	(0.393)	(0.393)	(0.394)
Elec. Price		-6.553***	-6.238***	-9.246***	-9.095***	-8.978***
		(0.136)	(0.168)	(0.234)	(0.231)	(0.232)
SourceXElec.		2.771	3.825	4.009	3.942	3.847
		(2.207)	(2.249)	(2.267)	(2.275)	(2.288)
Acres Irr.			0.433***	0.432***	0.431***	0.425***
			(0.115)	(0.116)	(0.116)	(0.118)
Cons.	146.9***	193.2***	132.3***	159.6***	153.7***	145.5***
	(0.140)	(1.079)	(17.30)	(18.09)	(17.93)	(29.63)
Year Fixed Effects	NO	NO	NO	YES	YES	YES
Irrigation Type Cont.	NO	NO	NO	NO	YES	YES
Crop Type Cont.	NO	NO	NO	NO	NO	YES
N	260203	244702	239249	239249	239249	239249

Robust standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5 presents the results from the fixed effects model with irrigation applied as the dependent variable.[5] To determine drought effect for surface water farmers and groundwater farmers, the coefficients of interest are the coefficients for drought specification, D2, and the coefficient of the interaction effect, SourceXD2. First, I will discuss the effects of adding additional controls from columns (1) through (6). For the coefficient of drought, D2, the most basic model with only individual fixed effects in column (1) provides an estimate of 0.373 acre-feet, significant at the 0.001 level. Incorporating the control for commercial electricity price and the interaction effect for source and commercial electricity price in column (2) increases the coefficient of D3 to 0.524 acre-feet, significant at the 0.001 level. Adding a controls for acres irrigated, year fixed effects, irrigation technology type, and crop type in columns (3) through (6) only marginally effects the estimate. In the full model in column (6), the coefficient for D2 is 0.460 acre-feet, significant at the 0.001 level.

The coefficient for SourceXD2 captures the different drought effect for surface water farmers

[5]Results from a Hausman Test indicated that the fixed effects model is the appropriate model for the data.

and groundwater farmers. If there is indeed an asymmetric drought response between groundwater farmers and surface water farmers, the coefficient of this interaction term will be significant. Under the model with only individual fixed effects in column (1), the value for the coefficient of SourceXD2 is -0.757 acre-feet, significant at the 0.05 level. Incorporating commercial electricity price and an interaction betweeen source and commercial electricity price, as well as a control for acres irrigated in columns (2) and (3) has little effect on the estimate. Adding year fixed effects in column (4) increases the magnitude of the estimate to -0.941, significant at the 0.05 level. Controlling for technology type and crop type in columns (5) and (6) has minimal effect on the estimates. The estimate for the coefficient for the interaction effect under the full model in column (6) is -0.935 acre-feet, significant at the 0.05 level.

Because the coefficient for the interaction effect is significant at the 0.05 level, I can reject the null hypothesis that there is no interaction effect, in favor of the alternative hypothesis that there is an interaction effect. Recall Equation 1:

$$IRR_{w,t} = \alpha_w + \beta S_{w,t} + \gamma d_{c,t} + \delta S_{w,t} * d_{c,t} + \zeta e_t + \eta S_{w,t} * e_t + Y_t + \sum_{i=1}^{n} \iota_i C_{w,t} + \epsilon_{w,t} \quad (1)$$

Under the full model presented in column (6), it follows that $\gamma = 0.460$ and $\delta = -0.935$ For groundwater farmers, the effect of drought is γ. The effect of drought for surface water farmers is $\gamma + \delta$.

Table 6: Simplified Effect of Severe Drought

Source	Severe Drought
Groundwater	0.460
Surface Water	-0.475

Table 6 shows a more concise representation of the effect of drought on the different types of farmers. In response to Severe Drought, groundwater farmers increase their overall water consumption. For groundwater farmers, this estimation implies that a 1% increase in the area of land classified as Severe Drought in a farmer's county leads to 0.460 acre-feet more water applied by the farmer. Alternatively, surface water farmers respond to Severe Drought by reducing their amount of irrigation applied. A 1% increase in the area of land classified as Severe Drought in a surface water farmer's county leads to a 0.475 acre-feet reduction in irrigation applied for surface water farmers.

Finally, I will discuss the magnitude of the effects. The median amount of irrigation applied for groundwater farmers is 138.00 acre-feet per year.[6] As 0.715 acre-feet is roughly 0.3% of the median value for irrigation applied for groundwater farmers, a 1% increase in Severe Drought within a groundwater farmer's county would imply a roughly 0.3% increase in irrigation applied from the median value. The drought effect for surface water farmers has a larger magnitude than for groundwater farmers. The median amount of irrigation applied for surface water farmers is 28.78 acre-feet per year, so a 1% increase in Severe Drought in a surface water farmer's county implies a 1.7% reduction of irrigation applied from the median value for surface water farmers.

6.1.1 Sensitivity Analysis

While the previous results provide support for my hypothesis that droughts cause surface water farmers to reduce their water consumption more than groundwater farmers, only one drought specification has been used. As a robustness check, I re-run the regressions for the full model with all other drought specifications. Table A2, located in the Appendix, shows the results from these additional regressions.

Table 7: Simplified Effect of All Drought Specifications

Source	D1	D2	D3	D4
Groundwater	0.449	0.460	0.715	0.656
Surface Water	-0.313	-0.475	-0.385	-0.691

Table 7 presents a simplified representation of the results of the magnitude of the drought effect for groundwater farmers and surface water farmers across the different drought specifications. Both coefficients of interest are significant at the 0.05 level for all drought specifications. Additionally, Table A3, located in the Appendix, presents a robustness check for the omission of the five groundwater counties because of my second restriction on my sample. The similar results from this additional robustness check indicate that this secondary restriction on my sample is not driving the results.

In addition to acting as a robustness check, the sensitivity analysis in Table 7 provides a deeper understanding of the role of water source in the drought response of farmers. Drought has two simultaneous effects for farmers, as discussed in Section 5.1. First, the push effect of drought increases the need for irrigation during drought because of reduced precipitation.

[6] One acre-foot is the amount of water that would occupy one acre (0.405 hectares) of area one foot deep (0.305 meters). This translates to 43,560 cubic feet, or 1233.5 cubic meters.

Second, the pull effect of drought leads to water conservation efforts because of reduced water availability during drought.

The results suggest that the push effect of drought outweighs the pull effect of drought for groundwater farmers. This is supported by the persistently positive and significant coefficients for groundwater farmers. Under each drought specification, groundwater farmers increase their irrigation applied. Going from Extreme Drought to Exceptional Drought, the magnitude of irrigation increase reduces for groundwater farmers. While this reduction in magnitude seems to imply that groundwater farmers are receptive to drought pull effects, it could also be the case that this reduction is the result of lack of access to freshwater, or the imposition of water restrictions because of the severity of drought. It is difficult to discern which of these two drivers is causing the results because Exceptional Drought is the most severe drought category that likely has ramifications for water availability and potential water restrictions. Because the reduced magnitude of drought effects only occurs at the most severe drought specification, I argue that it is more likely that lack of water access or the presence of water restrictions is most likely driving the results.

Alternatively, surface water farmers respond to all drought specifications by reducing their amount of irrigation applied. As discussed in the previous paragraph, it is difficult to determine if drought pull effects are truly driving the results, rather than lack of access or the imposition of water restrictions. However, the likelihood of a lack of water access or the imposition of water restrictions is lower in the less severe drought specifications. Because the irrigation reductions are persistent from the outset under Moderate Drought, I argue that surface water farmers are at least somewhat responsive to the pull effects of drought.

In my hypothesis, I present two potential reasons that could lead to asymmetric drought pull effects between surface water farmers and groundwater farmers. First, because surface water sources are more volatile than groundwater sources, surface water farmers might be reducing their irrigation applied because drought has a stronger effect on the availability of surface water than groundwater. Additionally, more localized surface water sources imply that surface water farmers might be more likely to contribute to the public good of their water source by conserving water. The results from public goods games suggest that people are more likely to cooperate with partners than strangers. The Ogallala Aquifer is a vast groundwater source that ranges over eight states, whereas surface water sources are more localized and have fewer users. It follows that because surface water sources are more localized, users of surface water sources are more likely to share the water source with members of their direct community. Of these two potential drivers of drought pull effects, it is not possible to tell which is responsible for the results.

6.2 Effect on Irrigation Technology Upgrade

6.2.1 Same Year Irrigation Technology Upgrade

Table 8: Effect on Irrigation Technology Upgrade - Severe Drought

	(1)	(2)	(3)	(4)	(5)
D2	0.000207	0.00258***	0.00258***	0.00287***	-0.000732
	(0.000289)	(0.000322)	(0.000325)	(0.000336)	(0.000588)
SourceXD2	-0.000425	-0.00420	-0.00588	-0.00611	-0.00518
	(0.00433)	(0.00455)	(0.00493)	(0.00493)	(0.00503)
Elec. Price		-0.238***	-0.244***	-0.247***	-1.190**
		(0.00719)	(0.00727)	(0.00732)	(0.442)
SourceXElec.		0.254***	0.282***	0.283***	0.253***
		(0.0696)	(0.0718)	(0.0718)	(0.0700)
Acres Irr.			-0.000672**	-0.000481	-0.000429
			(0.000247)	(0.000248)	(0.000244)
AF Used				-0.000497***	-0.000562***
				(0.000147)	(0.000155)
Year Fixed Effects	NO	NO	NO	NO	YES
Crop Type Cont.	NO	NO	NO	NO	YES
N	139717	131494	128455	128455	128455

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 8 presents results from the fixed effects logit regression estimation for irrigation technology upgrade.[7] As before, controls are added one regression at a time in order to analyze their effects. Under the simplest version of the model in column (1) that includes only fixed effects, the coefficient for drought, D2, is initially -0.0207%, and is statistically insignificant. Including controls for commercial electricity price and the interaction between source and commercial electricity price in column (2) leads to a positive coefficient for D2 that is significant at the 0.01 level. The coefficient for D2 persists at a similar magnitude and significance through the inclusion of controls for acres irrigated and acre-feet used in columns (3) and (4). I add both

[7]Results from a Hausman Test indicated that the fixed effects model is the appropriate model for the data.

year fixed effects and crop controls in column (5), in order to make the table more presentable. Including the full model in column (5) leads to a negative and insignificant coefficient for D2.

The coefficient for the interaction term SourceXD2 remains insignificant throughout all versions of the model. Table A4, located in the Appendix, displays the results from the sensitivity analysis with regressions from the full model with all of the different drought specifications. The coefficient for the interaction effect is not statistically significant for any of the drought specifications. Because the coefficient of the interaction term between source and drought is not statistically significant, I am unable to reject the null hypothesis of a symmetric drought response. I conclude that there is no evidence to support my hypothesis that drought in the same year causes surface water farmers to be more likely to upgrade to more efficient irrigation technology than groundwater farmers.

6.2.2 Lagged Irrigation Technology Upgrade

Table 9: Effect on Irrigation Technology Upgrade - Severe Drought Lagged

	(1)	(2)	(3)	(4)	(5)
Lag D2	-0.00291***	0.00211***	0.00222***	0.00221***	-0.000272
	(0.000299)	(0.000342)	(0.000346)	(0.000346)	(0.000574)
SourceXLagD2	0.00537	0.00208	0.000128	0.000129	-0.000805
	(0.00429)	(0.00486)	(0.00544)	(0.00544)	(0.00557)
Elec. Price		-0.246***	-0.252***	-0.253***	-1.336**
		(0.00744)	(0.00751)	(0.00752)	(0.483)
SourceXElec.		0.188*	0.223**	0.223**	0.209**
		(0.0759)	(0.0804)	(0.0804)	(0.0797)
Acres Irr.			-0.000657**	-0.000588*	-0.000445
			(0.000249)	(0.000254)	(0.000246)
AF Used				-0.000173	-0.000620***
				(0.000144)	(0.000154)
Year Fixed Effects	NO	NO	NO	NO	YES
Crop Type Cont.	NO	NO	NO	NO	YES
N	130675	130675	127713	127713	127713

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 9 displays results from regressions run with a lagged drought specification. In the initial model including only individual fixed effects in column (1), the coefficient for lagged drought is -0.291%, significant at the 0.01 level. Including controls for commercial electricity price and an interaction between source and commercial electricity price in column (2) changes the sign of the coefficient, making the estimate 0.211%, significant at the 0.01 level. Including controls for acres irrigated and acre-feet used in the regressions from columns (3) and (4) has a marginal effect on the coefficient. I add both year fixed effects and crop controls in column (5), in order to make the table more presentable. Including year fixed effects and a control for crop type in the regression in column (5) reduces the coefficient to -0.027%, and this coefficient loses statistical significance.

The coefficient of the interaction term between source and lagged drought steadily reduces from 0.537% to 0.081% with the inclusion of various controls in columns (1) through (6). At no point is the coefficient statistically significant.

Table A5, located in the Appendix, displays the results from the full model run with all four drought specifications. The coefficient for the interaction between source and lagged drought is insignificant for all drought specifications. Once again, I am unable to reject the null hypothesis of a symmetric drought response in likelihood of upgrading to more efficient irrigation technology between groundwater and surface water farmers. The results provide no evidence to support the claim that groundwater farmers and surface water farmers respond differently to drought in the previous period in regards to adoption of more efficient irrigation technology.

The low amount of total irrigation technology upgrades could be a contributing factor to the lack of significant results. As shown in Table 1, the average of the irrigation technology upgrade variable is only 0.053, making it very close to the lower limit of 0. The fixed effects estimation of the logit model in Stata drops all observations that have no within-subject variability. Because of this, the number of observations reduces from 239,249 in the model with irrigation applied as the dependent variable to 128,455 with irrigation technology upgrade as the dependent variable. Nearly half of the observations are lost as a result of the low number of total irrigation technology upgrades.

Future research could more adequately address drought effects on the likelihood of upgrading technology between surface water and groundwater farmers by focusing on the intensive margin, rather than the extensive margin. While the data for this thesis only includes information about the entire irrigation system in place, it could be the case that farmers make investments incrementally in their attempt to implement more efficient irrigation systems. Implementing data that includes information regarding the amount of money invested in irrigation technology each year, including smaller irrigation technology investments, would allow the researcher to retain more of the sample.

6.3 External Validity

Before I proceed, I would like to make a note regarding the scope of the results from this thesis. The asymmetric drought response between surface water and groundwater farmers only applies to farmers that have access to only one type of water source. As discussed previously, this is not the norm, so generalizing the results to all farmers would be an over-application of the results. It follows that the following analysis is in reference to farmers that have access to either surface water or groundwater.

The empirical analysis finds groundwater farmers increasing their amount of irrigation applied in response to drought and surface water farmers reducing their amount of irrigation applied in response to drought. I am arguing that this is because surface water farmers are responding to the pull effect of drought, while the groundwater farmers are not. I have presented two potential reasons why surface water farmers are receptive to the pull effect of drought, but groundwater farmers are not. First, the capacities of surface water sources are more impacted by drought than groundwater sources. Second, with less other users drawing from smaller surface water sources, surface water farmers might be susceptible to cooperation by reducing water consumption. At this point, there is no way to know which of the effects is driving the asymmetric drought pull effect; I will discuss the generalizability of the results first in the case that the increased volatility of surface water sources is driving the results, and second that the smaller and more localized role of surface water sources is driving the results.

First, I will discuss the generalizability of the results if the increased volatility of surface water sources is driving the results. In this case, I believe these results would generalize to other regions for surface water farmers, because recharge does not vary between surface water sources. Alternatively, I believe that the results would not necessarily hold for groundwater farmers, because of varying recharge rates across aquifers. The Ogallala Aquifer recharges relatively slowly, with an average potential annual recharge of 1.25 inches (Pfeiffer and Lin, 2014a). It follows that if increased recharge rates are driving the results, farmers drawing from aquifers with faster recharge rates might be more susceptible to the pull effect of drought. This implies that results from this thesis would overestimate the prediction of increased irrigation applied in response to drought for groundwater farmers.

Alternatively, it could be the case that cooperation incentives from surface water sources being smaller and having relatively fewer users are driving the results. If this is the case, I believe the results would not necessarily hold for surface water farmers generally. From the WIMAS data it is unclear where the surface water is coming from. It could be the case that surface water farmers are drawing from large reservoirs, shared with many other users across counties, or that surface water farmers are drawing from small lakes near their property that have few other users drawing from it. If a surface water farmer is drawing from a large reservoir, they might be less responsive to the pull effect, similar to groundwater farmers of the vast Ogallala Aquifer. For groundwater farmers, I think it is likely that the results of this thesis would hold for other groundwater farmers if the driver of these results is the relative size of the surface water and groundwater sources. Groundwater farmers are typically drawing from aquifers in which there are many other users, even in smaller aquifers. This implies that drought response for groundwater farmers would likely be similar to the response found in this thesis.

6.4 Further Research

In this thesis, groundwater farmers were found to increase their total amount of irrigation applied in response to drought, and surface water farmers were found to decrease their overall amount of irrigation in response to drought. As alluded to previously, it is unclear whether the driver of these results is differences in recharge rates between surface water and groundwater sources, or differences in sizes and number of users of the water sources. Future research could aim to distinguish between these two potential causes by exploring drought effects on surface water farmers with access to surface water sources of different sizes. For example, a group of surface water farmers drawing from a large reservoir could be compared to a group of surface water farmers with small lakes shared with few users. Although the number of users drawing from the water sources differ, both water source types recharge at the same rate. It follows that an asymmetric drought response between these two groups of surface water farmers would imply that the results in this thesis are driven by the fact that the Ogallala Aquifer is large and spread out. Constant drought response between the two surface water groups would indicate that the results of this thesis were likely driven by differing recharge rates between groundwater and surface water sources.

As I alluded to in Section 6.3, the results from this thesis apply to farmers with access to either surface water or groundwater. While this thesis is a starting point for research exploring the role of water source in irrigator decisions, the case in which a farmer has access to only either surface water or groundwater is not the norm. This is because in most of the world farmers have access to both freshwater sources. It follows that further research could explore the drought response of farmers in contexts in which farmers have access to both sources of freshwater.

6.5 Policy Implications

The results from this thesis suggest that surface water farmers are more likely to reduce irrigation in response to drought, while groundwater farmers are more like to increase consumption in response to drought. This implies that drought can be taken advantage of to induce water conservation. While farmers in general are mostly inelastic to price changes (Koundouri, 2004), this study has shown that surface water farmers reduce their water consumption in response to drought. It follows that increased reliance on surface water sources can be a catalyst for water conservation.

Increased availability of surface water in the U.S. could come from altering the prioritization of the Endangered Species Act. The Endangered Species Act gives endangered species in the U.S. the highest priority (Ward and Booker, 2003). To benefit endangered species, in-stream flow requirements limit the amount of diversions that can be made from rivers. The labeling of over 30 populations of fish species endangered in the 1990's has forced many water users to reduce or give up their water rights to meet in-stream flow requirements (Bricker and Filippa, 2000). Limiting diversions for agriculture has negative impacts on farmers. Ward et al. (2006) find that in-stream flow requirements had large negative impacts on agricultural water users in New Mexico and Texas. While the survival of endangered species is critical in an era of rapid biodiversity loss, giving unchecked first priority to endangered species increases reliance on groundwater sources, resulting in additional overdraft from aquifers. Giving unconditional first priority to endangered species ignores the complex interactions that takes places within ecosystems, and doesn't allow for a nuanced approach to water systems management. By altering the priorities from the Endangered Species Act, policy could be crafted that allows flow requirements that that are based on cost-benefit analyses. Such policy would likely create a more balanced approach to water systems management, addressing the complexity of water system interactions with refined policy measures.

7 Conclusion

The purpose of this thesis has been to analyze the role of water source in drought response by farmers. By conducting a fixed effects empirical analysis, I have attempted to answer the following question: Do the economic decisions of groundwater farmers and surface water farmers differ in response to drought? My hypothesis was that drought would cause surface water farmers to reduce the amount of irrigation applied more than groundwater farmers, and drought would cause surface water farmers to be more likely to upgrade to more efficient irrigation technology than groundwater farmers.

The results of this thesis support my hypothesis that farmers using surface water reduce consumption more than farmers utilizing groundwater in response to drought. These results were significant across the three most severe drought specifications. Surface water farmers were found to reduce their consumption in response to drought, while drought caused a net increase in water consumption by groundwater farmers. However, the results indicate no support for my hypothesis that surface water farmers are more likely to adopt more efficient irrigation technology than groundwater users. No difference between surface water farmers and groundwater farmers was found in regards to their likelihood to upgrade to more efficient irrigation technology.

The push effect and the pull effect are the two main effects of drought for farmers. The push effect refers to the increased need for irrigation because of less precipitation during drought, and the pull effect refers to the increased likelihood of water conservation because of decreased water availability. The results suggest drought causes surface water farmers to reduce their amount of irrigation applied in response to drought, while drought causes groundwater farmers to increase their amount of irrigation applied. I argue that groundwater farmers are responsive to the push effect, but not the pull effect. Alternatively, surface water farmers reduced their consumption in response to drought, indicating responsiveness to both the push and pull effects. Further research including more specific data regarding the size of surface water sources could help to explain why surface water farmers seem to be susceptible to the pull effect of drought, while groundwater farmers do not appear to be.

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A Appendix

Table A1: Groundwater Observations Percentage by County

County	% Groundwater	County	% Groundwater	County	% Groundwater
AL	0	**GW**	3	**OS**	6
AN	0	**GY**	100	**OT**	87
AT	52	**HG**	98	**PL**	93
BA	100	**HM**	99	**PN**	99
BB	0	**HP**	80	**PR**	100
BR	30	**HS**	100	**PT**	86
BT	100	**HV**	97	**RA**	100
BU	41	**JA**	18	**RC**	100
CA	100	**JF**	95	**RH**	98
CD	96	**JO**	9	**RL**	84
CF	14	**JW**	57	**RN**	100
CK	33	**KE**	99	**RO**	99
CL	57	**KM**	96	**RP**	80
CM	100	**KW**	100	**RS**	100
CN	100	**LB**	0	**SA**	79
CQ	0	**LC**	83	**SC**	100
CR	7	**LE**	100	**SD**	100
CS	0	**LG**	100	**SF**	100
CY	86	**LN**	0	**SG**	98
DC	100	**LV**	69	**SH**	100
DG	97	**LY**	54	**SM**	82
DK	80	**MC**	22	**SN**	95
DP	96	**ME**	100	**ST**	100
ED	100	**MG**	0	**SU**	94
EK	0	**MI**	0	**SV**	100
EL	88	**MN**	64	**SW**	100
EW	72	**MP**	91	**TH**	100
FI	100	**MR**	0	**TR**	95
FO	100	**MS**	42	**WA**	100
FR	13	**MT**	100	**WB**	82
GE	72	**NM**	26	**WH**	100
GH	100	**NO**	9	**WL**	1
GL	100	**NS**	97	**WO**	0
GO	100	**NT**	95	**WS**	63
GT	100	**OB**	63	**WY**	81

County observations are rounded to the nearest %

Table A2: Effect on Irrigation Applied - All Drought Specifications

	(1)	(2)	(3)	(4)
D1	0.449***			
	(0.00826)			
SourceXD1	-0.762*			
	(0.349)			
D2		0.460***		
		(0.00902)		
SourceXD2		-0.935*		
		(0.394)		
D3			0.715***	
			(0.0137)	
SourceXD3			-1.100*	
			(0.457)	
D4				0.656***
				(0.0161)
SourceXD4				-1.347*
				(0.565)
Elec. Price	-9.520***	-8.978***	-8.628***	-8.571***
	(0.235)	(0.232)	(0.235)	(0.240)
SourceXElec.	3.800	3.847	3.453	0.441
	(2.739)	(2.288)	(1.935)	(1.647)
Acres Irr.	0.424***	0.425***	0.425***	0.424***
	(0.118)	(0.118)	(0.118)	(0.118)
Cons.	147.7***	145.5***	148.3***	141.3***
	(28.49)	(29.63)	(27.81)	(29.04)
N	239249	239249	239249	239249

Robust standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

All regressions include controls for year fixed effects, irrigation equipment type, and crop type

Table A3: Robustness Check: Effect on Irrigation Applied - All Drought Specifications

	(1)	(2)	(3)	(4)
D1	0.443***			
	(0.00791)			
SourceXD1	-0.735*			
	(0.325)			
D2		0.452***		
		(0.00874)		
SourceXD2		-0.912*		
		(0.372)		
D3			0.687***	
			(0.0131)	
SourceXD3			-1.093*	
			(0.431)	
D4				0.653***
				(0.0158)
SourceXD4				-1.376*
				(0.559)
Elec. Price	-9.403***	-8.910***	-8.581***	-8.520***
	(0.226)	(0.224)	(0.227)	(0.232)
SourceXElec.	3.672	3.781	3.377	0.551
	(2.429)	(2.072)	(1.754)	(1.506)
Acres Irr.	0.422***	0.423***	0.423***	0.422***
	(0.117)	(0.117)	(0.117)	(0.117)
Cons.	144.4***	142.5***	145.0***	138.4***
	(28.43)	(29.49)	(27.71)	(28.86)
N	246959	246959	246959	246959

Robust standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

All regressions include controls for year fixed effects, irrigation equipment type, and crop type

All regressions include five omitted counties from secondary restriction

Table A4: Effect on Irrigation Technology Upgrade - All Drought Specifications

	(1)	(2)	(3)	(4)
D1	-0.00105			
	(0.000583)			
SourceXD1	-0.00569			
	(0.00380)			
D2		-0.000732		
		(0.000588)		
SourceXD2		-0.00518		
		(0.00503)		
D3			-0.00128	
			(0.000894)	
SourceXD3			-0.00583	
			(0.00777)	
D4				-0.00173
				(0.00131)
SourceXD4				0.00737
				(0.0148)
Elec. Price	-1.290**	-1.190**	-1.152**	-1.137**
	(0.447)	(0.442)	(0.440)	(0.440)
SourceXElec. Price	0.269***	0.253***	0.243***	0.222**
	(0.0713)	(0.0700)	(0.0693)	(0.0682)
Acres Irr.	-0.000428	-0.000429	-0.000433	-0.000428
	(0.000244)	(0.000244)	(0.000245)	(0.000244)
AF Used	-0.000552***	-0.000562***	-0.000558***	-0.000567***
	(0.000155)	(0.000155)	(0.000154)	(0.000154)
N	128455	128455	128455	128455

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

All regressions include controls for irrigation equipment type and crop type

Table A5: Effect on Irrigation Technology Upgrade - All Drought Specifications Lagged

	(1)	(2)	(3)	(4)
Lag D1	0.000405			
	(0.000546)			
SourceXLagD1	0.000557			
	(0.00415)			
Lag D2		-0.000272		
		(0.000574)		
SourceXLagD2		-0.000805		
		(0.00557)		
Lag D3			-0.00201*	
			(0.000890)	
SourceXLagD3			0.00271	
			(0.00794)	
Lag D4				-0.00259
				(0.00135)
SourceXLagD4				0.00574
				(0.0156)
Elec. Price	-1.088*	-1.336**	-1.531***	-1.256**
	(0.489)	(0.483)	(0.460)	(0.443)
SourceXElec.	0.199*	0.209**	0.183*	0.190**
	(0.0801)	(0.0797)	(0.0773)	(0.0716)
Acres Irr.	-0.000438	-0.000445	-0.000452	-0.000448
	(0.000246)	(0.000246)	(0.000247)	(0.000246)
AF Used	-0.000622***	-0.000620***	-0.000608***	-0.000610***
	(0.000154)	(0.000154)	(0.000154)	(0.000154)
N	127713	127713	127713	127713

Standard errors in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

All regressions include controls for irrigation equipment type and crop type