CLIMATE UNDERGROUND: THE EFFECTS OF CLIMATE VARIABILITY ON GROUNDWATER IRRIGATION

An Undergraduate Thesis in Economics
University of Colorado

By: **Monica R. Gronseth**

Thesis Advisor:
Dr. Daniel Kaffine
Professor and Associate Chair of Undergraduate Studies
Department of Economics

Honors Council Representative:
Dr. Martin Boileau
Professor and Associate Chair of Graduate Studies
Department of Economics

Faculty Advisor:
Dr. William Kleiber
Assistant Professor
Department of Applied Mathematics

April 9th 2019

1 Abstract

This study addresses the question of groundwater use sensitivity to changes in climate. We use county fixed effect models to empirically estimate the effect of climatic changes during the growing season on groundwater use for irrigation. This study uses data from the USGS reports on industry water use and weather data from NOAA. We find both precipitation and temperature have a significant effect on groundwater irrigation, with particular prominence in areas with lower annual precipitation on average. These effect estimates are then used to model the effects of climate change on groundwater irrigation by the end of the century. We conclude that groundwater users are more responsive in their groundwater use to changes in precipitation than to changes in temperature, and that increased groundwater demand will be particularly prominent in Texas, the states overlying the High Plains Aquifer, and in parts of the Northwestern United States.

2 Introduction

In recent decades, public concerns over groundwater depletion have proliferated. These resources are essential for people's daily lives and industrial productivity, as aquifers supply 44 percent of the U.S. population with drinking water, and nearly 80 billion gallons of fresh water are used for public, private, agricultural, and industrial purposes daily (NGWA 2018). Growing scientific research supports that average temperatures and precipitation intensity, frequency, duration, and quantity are likely to change over the course of the century due to increasing greenhouse gas emissions (Trenberth et al. 2003, USDA 2013, Lall et al. 2018) and it is predicted that such changes will stress our water resources (Lall et al. 2018). According to the most recent National Climate Assessment, increased groundwater depletion is already occurring as surface water becomes more volatile from weather changes (Lall et al. 2018). Aquifer depletion could have tremendous consequences for future social use and for the balance of ecological systems. However, it is unclear how responsive people are in their irrigation choices to climate, and whether rising temperatures or changes in precipitation will have a greater effect on groundwater demand.

Existing economic theories explore imperfections in the "use market" for groundwater (Bredehoeft and Young 1970, Brown and Deacon 1972, Gisser and Sanchez 1980, Tsur 1990, Brozovic et al. 2004). Many of these theories yield subjective and opposing results, depending on the assumptions of the model. As a result, management has become heavily debated in economic literature, but with lack of real-world evidence. These theoretical findings are discussed further in the literature review, but we find empirical economic studies surrounding groundwater are severely lacking.

The sensitivity of groundwater demand to changes in precipitation and temperature are poorly understood, yet essential, for future resource management decisions. Understanding the empirical dynamics of groundwater demand under variable climate conditions will be essential for projecting groundwater supply expectations and for effective water management. This question of demand must be addressed by economists empirically, since the theoretical models are not fully representative of real-world user decisions.

This study empirically estimates changes in county groundwater use for irrigation, in response to changes in precipitation and growing season average temperature. Groundwater used for irrigation is specifically targeted as it encompasses agricultural water use. Agriculture is likely the most sensitive industry to changes in temperature and precipitation and the most vulnerable to climate change, as temperature and water are direct inputs in the production process. Since many industries utilize groundwater as a resource, studies which isolate specific sectors of groundwater demand will be more informative than uncategorized demand studies. Further, focusing specifically on the agricultural sector offers insight to the regions which may require agricultural regulations or crop choice adaptations.

The water consumption data come from the 1995, 2000, 2005, 2010, and 2015 United States Geological Survey (USGS) reports on county-level, sector-specific water use. Precipitation and temperature data over the 25 years of study come from the National Oceanic and Atmospheric Administration (NOAA) data archives. Weather is assigned to each county using a weighted distance average. Multiple county and year fixed effects models are then employed, with county groundwater use for irrigation as the independent variable of interest. Total precipitation during the growing season, and growing season average temperatures are the primary dependent variables. Additional analyses explore the difference in effects between generally arid and more precipitous counties. We then apply these effects to the Hadley3 projections for climate change to model the projected response in national groundwater irrigation.

Summary statistics for county groundwater use, precipitation, and average growing season temperatures can be found in Tables A-D. Regression results are summarized in Tables 1-3 with additional robustness checks summarized in Table 4. Tables 1 and 2 summarize the results from the linear and quadratic fixed effects models. Table 3 summarizes the estimated effects across precipitation terciles. Current Hadley3 projections, and our resulting projections for responses in county groundwater use, can be found in the Results and Discussion section.

Estimates under the linear and quadratic fixed effects models indicate a significant effect posed by both temperature and precipitation changes. While these are supported by theory, the empirical results confirm this idea, and we further determine that people are more responsive to precipitation than to temperature changes in their decisions to increase their groundwater irrigation. This study shows that the coastal plains aquifer systems in Texas, the High Plains Aquifer underlying the mid-western states, and the aquifers in the northwestern United States will experience the greatest stress due to increases in groundwater demand in those regions. These findings support the importance of climate considerations in resource management, specifically in these areas. A more detailed discussion of the estimated increases in national use, and implications for the Ogallala Aquifer specifically, can be found in the Discussion of Findings and Implications section. The paper continues with a Literature Review, Methods section, Results and Discussion section, and Conclusion.

3 Literature Review

This literature review first addresses the scientific literature surrounding groundwater and climate. This is followed by a discussion of the existing economic literature. We expose the gap in literature of empirical economic work surrounding groundwater.

3.1 Scientific Literature

It is imperative to first understand the scientific projections for groundwater. It is well accepted that precipitation and weather patterns will likely exhibit drastic changes in future years (Trenberth et al. 2003). Climate change will both directly and indirectly affect groundwater resources. The direct effects will occur through recharge changes from precipitation fluctuations, changing surface water levels, and changing sea levels. Green et al. (2011) and Taylor et al. (2012) discuss the complications of estimating the effect that climate change will have on groundwater scientifically, because of variable user demand under climate variability. Both studies discuss how demand changes complicate the scientific estimations for quality and quantity changes in aquifers, as managed agro-ecosystems do not respond to changes in precipitation in the same way natural ecosystems do (Green et al. 2011, Taylor et al. 2012). The scientific literature supports research around groundwater pumping behavior as scientific laws alone cannot address these questions for how groundwater demand will change.

The concept that demand for water resources will change is commonly reported. The USDA report on climate change (2013) states that the demand for water substitutions is the most expected response to changing precipitation and temperature, but with lacking clarity of how substantially demand will change. The report also suggests that this change may be particularly prominent in the agricultural sector. Plants often require more water at higher temperatures, so higher temperatures will likely increase total water use (USDA 2013) in the industry. But precipitation variations may amplify or lessen this effect. The sensitivity of users to temperature and precipitation will determine the effect of climate on demand. This report supports the focus of this study directly on groundwater irrigation, due to likely changes in the agricultural sector.

3.2 Economics: Surface Water Volatility and Groundwater

Some studies explore the role of groundwater as a substitute for surface water, especially in times of drought. Green and Schuck (2001) propose a theoretical model which further explores this substitution role and its effect on the success of surface water drought pricing. The authors claim that surface water drought pricing is suboptimal because users substitute groundwater pumping which is not considered in the pricing for surface water. The authors call for more empirical work surrounding groundwater pumping behavior.

Tsur supports the idea of underpricing and offers some of the few studies to analyze the role of groundwater when surface water supply is unpredictable (Tsur 1990, Gemma and Tsur 2007). The theoretical models in these studies explain the "stabilization role" that groundwater plays in the water supply function when undesirable or unpredicted fluctuations of surface water supply occur. Tsur's explanation of the stabilization role of groundwater supports the scientific projections for increased groundwater use during times of variable precipitation through theory (Tsur 2007). Tsur uses focused empirical studies in Tamil Nadu

(2007), and in the Negev Desert (1990) to estimate the stabilization value of groundwater using the value of agricultural output and precipitation variation. These studies do not address the sensitivity of groundwater use to precipitation, but rather focus on the potential undervaluation of groundwater. Tsur does not address groundwater use directly, and does not include temperature variations as a potential variable.

3.3 Economics: The Existence of Groundwater Externalities

As many aquifers are shared by many users, groundwater exhibits an interesting reflection of the traditional Tragedy of the Commons scenario. Groundwater is rival because a specific acre-foot of water cannot be consumed by more than one party. But groundwater is not perfectly excludable by the owner. Access to the resource is partially excludable because drilling for groundwater requires land ownership or land access, but groundwater flows beneath the Earth's surface are out of the land owner's control. So, while property rights are well defined for the land above an aquifer, they cannot be perfectly defined for each acre-foot of groundwater (Pfeiffer and Lin Lawell 2012). With this in mind, economists have used theoretical models to suggest the presence of externalities based on the nature of groundwater. However, very small changes in these models result in very different conclusions and implications. So these theoretical models, while informative, are not entirely indicative of real-world groundwater use.

Gisser and Sanchez (1980) published their model of demand for groundwater under the assumption of a single-cell aquifer in the 1980's and sparked large debate over groundwater management necessity. The theoretical model suggests that farmers rely on external pricing information when optimizing groundwater use with respect to present pumping costs. They also assume a bathtub model for the aquifer, where each user is effected equally by a withdrawal from the resource, regardless of distance. The authors conclude that if an aquifer is large enough, the free market behavior is nearly equivalent to optimal control over an aquifer and that no externalities exist. However the conclusions of Gisser and Sanchez are flawed due to highly unrealistic assumptions that groundwater use can be represented under a bathtub extraction model and that energy prices are a full reflection of groundwater valuation. Later theoretical models counter the findings of Gisser and Sanchez (Provencher and Burt 1993, Brozovic et al. 2004). These models conclude that spatial externalities exist under more hydrologically realistic models.

Pfeiffer and Lawell (2012) test the theory of spatial externalities empirically. Their study is the first empirical study to estimate the relationship between groundwater users, particularly without use of a bathtub aquifer model. In their study of Western Kansas, Pfeiffer and Lawell analyze how neighboring farmers affect each other's groundwater pumping behavior. The authors use an explanatory variable and two-stage least squares to estimate the effect that neighboring farmers have on pumping decisions. The authors find empirical evidence for the existence of a spatial externality, though small in magnitude (approximately two percent of all withdrawals) (Pfeiffer and Lin Lawell 2012). However, the explanatory variable analysis arguably does not mitigate the problem of endogeneity in this study. The authors use precipitation as a control variable in their study, and use well height to estimate groundwater use rather than having direct data about groundwater use.

3.4 Economics: Climate Change and Agriculture

Existing agronomic literature relating to climate change and water focuses on farm valuation and crop yields. Mendelsohn et al. (2003) find that irrigation will help farmers adapt to climate change, as it helps to smooth the effects of variable climate on the agricultural process using a Ricardian model to test if surface water effects farm value. The authors discuss the problem in their study of endogeneity when including groundwater estimates, because groundwater availability is a function of the physical variables used in the primary regression, with poor measurement for how climate effects groundwater.

Schlenker et al. (2007) find that water availability is capitalized into land value in California, but notes the difficulty of finding accurate effect magnitudes because of the complexity in evaluating surface water supply. This raises the question of whether users truly evaluate the amount of water available in their decisions about water use. Indeed, it is more likely that the effect of water supply is negligible until it is considered to be scarce. Observable climate variables are arguably more likely to stimulate behavior changes in groundwater use decisions than uncertain surface water changes.

Deschenes and Greenstone (2007) estimate county-level agricultural profits dependent on observable determinants of land values and a series of climate variables, while controlling for county and year fixed effects. The authors use these estimates to project how climate change will affect agriculture. They conclude a greater impact will occur for non-irrigated counties, which supports the theoretical literature that groundwater will aid against climate shocks through increased groundwater irrigation.

The existing literature on externalities focuses on the effect that users have on each other rather than the exogenous effect of climate on user pumping behavior. The theoretical models are highly dependent on model assumptions, and the limited empirical work on groundwater does not directly address changes in groundwater use behavior due to climate. The agronomic literature addresses climate change but also discusses the lack of information around groundwater pumping behavior. This study contributes to the literature by offering an empirical analysis of changes in groundwater use directly, and by showing that temperature variability should be considered in water demand studies.

4 Methods

4.1 Data

The water use data are from the United States Geological Survey (USGS) national water use reports from 1995, 2000, 2005, 2010, and 2015. These reports are released every five years with information for one year of water use (e.g. the 1995 report contains use for the year of 1995). Each of these reports contains a compilation of groundwater and surface water use data for public supply, domestic, irrigation, livestock, aquaculture, mining, industrial, and thermoelectric power purposes. This information is collected at the state level for a cumulative total of 3,141 counties across the United States. Since the primary focus of this study is total groundwater withdrawals for irrigation purposes, the data on daily county groundwater use for irrigation are utilized from these reports. Two of the robustness checks also utilize the data on total irrigated acres per county.

The precipitation data are provided by NOAA's (National Oceanic and Atmospheric

Association) NCDC (National Climatic Data Center) data files. The data set includes daily precipitation and average daily temperatures from 1990-2015. For this study, the growing season is defined to be April 1 through September 30 (out-season weather is defined as any weather occurring from October 1 through March 31). An identical definition can be found throughout agricultural economic literature. The daily precipitation and temperature data from each NOAA station are compiled into cumulative in-season precipitation, cumulative out-season precipitation, and average in-season temperatures.

Since the national weather stations in the NOAA dataset are not county specific, weather for each county in the USGS dataset is assigned by a weighted distance average using the Haversine distance from each county to every NOAA station. This method of assignment is used to provide each county with the most precise weather possible, given the NOAA station locations. For every station within 250 km of the county, the weather data is weighted by the station's inverse squared distance, summed, and divided by the sum of the weights. This minimum distance is chosen to ensure every county is assigned at least one station. This method is used to assign annual in-season precipitation, out-season precipitation, and in-season average temperature. The mathematical representation can be found below:

$$P_{ct} = \frac{\sum_n w_{cn} * P_{nt}}{\sum_n w_{cn}}$$

$$T_{ct} = \frac{\sum_n w_{cn} * T_{nt}}{\sum_n w_{cn}}$$

$$\Theta_{ct} = \frac{\sum_n w_{cn} * \Theta_{nt}}{\sum_n w_{cn}}$$

where P_{ct} represents growing season precipitation for county c in year t, T_{ct} represents growing season average temperature for county c in year t, Θ_{ct} represents out-season precipitation for county c in year t, w_{cn} is a county and station specific weight defined by $\frac{1}{(\text{haversine dist from } c \text{ to } n)^2}$ for every NOAA weather station, n, within 250 km of county c.

4.2 Summary Statistics

Tables A-D show the yearly statistics for county groundwater use, in-season precipitation, in-season average temperatures, and out-season precipitation data. Average county groundwater use each year has varied between 15.60 and 18.21 Mgal/day, with no significant trend over time, although median groundwater use has generally increased. Median groundwater use is roughly 0.2 Mgal/day while maximum groundwater use per county is roughly 1,400 Mgal/day, indicating high disparity in county level groundwater use across the United States. This is not necessarily surprising, and supports the use of a county fixed effects model to control for large baseline groundwater use levels across counties.

Cumulative growing season precipitation is much less variable over the 25 years. It has generally trended upward. The annual average has generally increased from 17.86 inches to 21.78 inches between 1995 and 2015. Mean average Temperature during the growing season has varied between 57.61°F and 70.33°F, with no obvious trend in the period of study. Out-season cumulative precipitation, which is used as a control variable, has an annual average between 11.32-13.50 inches with no obvious trend over time.

Summary Statistics Tables

Table A: Groundwater Irrigation Statistics by Year (Mgal/Day)

	Min	Median	Mean	Max	Std Dev.
1995	0.00	0.14	15.60	1,564.46	66.14
2000	0.00	0.16	18.15	1,640.35	74.75
2005	0.00	0.28	17.05	986.45	63.74
2010	0.00	0.28	15.74	1,190.34	60.52
2015	0.00	0.29	18.21	1,485.87	79.10

Table B: Cumulative Growing Season Precipitation Statistics by Year (Inches)

	Min	Median	Mean	Max	Std Dev.
1995	0.00	17.94	17.86	74.75	8.24
2000	0.00	17.28	16.13	64.21	7.53
2005	0.00	18.73	18.67	60.90	7.58
2010	0.00	22.05	21.64	50.32	7.94
2015	0.00	23.64	21.78	72.53	8.95

Table C: Growing Season Average Temperature Statistics by Year (°F)

	Min	Median	Mean	Max	Std Dev.
1995	1.31	68.43	67.89	88.64	7.15
2000	0.04	60.35	57.61	90.28	15.24
2005	0.57	68.54	68.29	87.48	7.56
2010	0.00	71.24	70.33	86.56	6.75
2015	0.64	65.52	63.27	87.77	12.66

Table D: Out-season Cumulative Precipitation Statistics by Year (Inches)

	Min	Median	Mean	Max	Std Dev.
1995	0.00	13.22	15.02	87.67	9.58
2000	0.00	11.45	11.32	97.21	9.46
2005	0.00	17.13	17.14	97.21	9.46
2010	0.00	17.88	19.25	87.70	11.03
2015	0.00	13.31	13.50	91.73	8.45

4.3 Econometric Strategy

Equation (1) is a linear, fixed effects model. County groundwater use for irrigation is regressed on in-season precipitation and in-season average temperature, with controls for out-season precipitation, year fixed effects, and county fixed effects. Equation (2) allows for diminishing marginal effects of precipitation through the introduction of a quadratic growing season precipitation variable.

$$y_{ct} = \beta_0 + \beta_1 P_{ct} + \beta_2 T_{ct} + \beta_3 \Theta_{ct} + \eta_c + \gamma_t + \epsilon_{ct}, \tag{1}$$

$$y_{ct} = \beta_0 + \beta_1 P_{ct} + \beta_2 P_{ct}^2 + \beta_3 T_{ct} + \beta_4 \Theta_{ct} + \eta_c + \gamma_t + \epsilon_{ct} \tag{2}$$

Controlling for fixed-effects by county (η_c) controls for invariant county characteristics that affect groundwater use. For example, geographical characteristics such as soil type, slope, and recharge rates may be more or less conducive to groundwater access and use, but are assumed to remain relatively constant by county. Year fixed effects, (γ_t), controls for national level time trends in groundwater irrigation.

Equations (3) and (4) are included to test the strength of the relationship estimated by equations (1) and (2) by additionally controlling for state-by-year fixed effects (α_{st}). This will account for any state and year specific shocks which effect groundwater use. Since counties in the same state are likely to experience similar weather variations each year, the state-by-year fixed effects arguably absorbs some of the effect from county precipitation and temperature variation. Thus, if a significant relationship is still established, it will strengthen the argument for significance, although these models are likely over-restrictive (Fisher et al. 2012).

$$y_{ct} = \beta_0 + \beta_1 P_{ct} + \beta_2 T_{ct} + \beta_3 \Theta_{ct} + \alpha_{st} + \eta_c + \gamma_t + \epsilon_{ct} \tag{3}$$

$$y_{ct} = \beta_0 + \beta_1 P_{ct} + \beta_2 P_{ct}^2 + \beta_3 T_{ct} + \beta_4 \Theta_{ct} + \alpha_{st} + \eta_c + \gamma_t + \epsilon_{ct} \tag{4}$$

Standard errors for equations (1)-(4) are clustered first by county to account for serial correlations among inter-county observations. These results can be found in Table 1. The same regressions are then repeated with clustering at the state level, with the consideration that spatial correlations between observations within the same state may be present. These results are listed in Table 2.

The parameters of interest for each regression are β_1 and the coefficient for average temperature. β_1 estimates the effect that an additional inch of precipitation during the growing season has on county groundwater used for irrigation in million gallons per day (Mgal/d). We expect to find that aggregate precipitation during the growing season has a negative effect on daily groundwater used for irrigation, while an increase in average temperatures is expected to have a positive effect on groundwater use. This hypothesis is founded by existing economic theory for the substitutability of groundwater for surface water and by the scientific projections for water demand (Tsur 1990, Lall et al. 2018, Provencher and Burt 1993, Green and Schuck 2001). This relationship is intuitive, as years with limited in-season precipitation and hotter temperatures should require more water for crops.

5 Results and Discussion

5.1 Effect Estimates for Groundwater Use

Table 1 displays the results from equations (1)-(4) with standard errors clustered by county and Table 2 exhibits the same results but with clustering standard errors by state.

Table 1: (1) Linear, (2) Quadratic, (3) Linear w/ SY, (4) Quadratic w/ SY

	(1) Groundwater (Mgal/d)	(2) Groundwater (Mgal/d)	(3) Groundwater (Mgal/d)	(4) Groundwater (Mgal/d)
In-season Precip	-0.239***	-0.539***	-0.228***	-0.307**
	(0.0315)	(0.0987)	(0.0542)	(0.151)
In-season Precip^2		0.00640***		0.00161
		(0.00184)		(0.00270)
Avg Temp	0.0904***	0.112***	0.104***	0.111***
	(0.0245)	(0.0258)	(0.0385)	(0.0421)
Out-season Precip	-0.119**	-0.120**	-0.0891	-0.0888
	(0.0539)	(0.0539)	(0.0911)	(0.0910)
Constant	15.51***	16.95***	17.82***	18.18***
	(1.582)	(1.618)	(2.325)	(2.344)
County FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
State-Year FE	N	N	Y	Y
Observations	15,685	15,685	15,685	15,685
R^2	0.006	0.007	0.107	0.107
Counties	3,141	3,141	3,141	3,141

*Notes: Standard errors clustered at the county level in parenthesis, *** p<0.01, ** p<0.05, * p<0.1. Coefficients of interest are the effects of a change in Precipitation (inches) during the growing season (April 1 - September 30) and in Avg Temperature during the growing season (°F) on Annual County Groundwater use (Mgal/day).*

Table 2: Regressions (1)-(4) Using State Clustering

	(1b) Groundwater (Mgal/d)	(2b) Groundwater (Mgal/d)	(3b) Groundwater (Mgal/d)	(4b) Groundwater (Mgal/d)
In-season Precip	-0.239**	-0.539***	-0.228*	-0.307
	(0.0933)	(0.201)	(0.119)	(0.209)
In-season Precip^2		0.00640*		0.00161
		(0.00330)		(0.00411)
Avg Temp	0.0904*	0.112**	0.104*	0.111**
	(0.0496)	(0.0530)	(0.0565)	(0.0521)
Out-season Precip	-0.119	-0.120	-0.0891	-0.0888
	(0.151)	(0.150)	(0.216)	(0.216)
Constant	15.51***	16.95***	16.08***	15.70***
	(3.498)	(3.288)	(4.128)	(4.651)
County FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
State-Year FE	N	N	Y	Y
Observations	15,685	15,685	15,685	15,685
R^2	0.006	0.007	0.107	0.107
Counties	3,141	3,141	3,141	3,141

*Notes: Standard errors clustered at the state level in parenthesis, *** p<0.01, ** p<0.05, * p<0.1. Coefficients of interest are the effects of a change in Precipitation (inches) during the growing season (April 1 - September 30) and in Avg Temperature during the growing season (°F) on Annual County Groundwater use (Mgal/day).*

Equations (1) and (2) indicate that both growing-season precipitation and average growing season temperatures have significant and opposing effects on county level groundwater use. The linear estimates from (1) indicate that an additional inch of precipitation inside the growing season decreases county groundwater use by 239,000 gallons per day, and that an increase in growing season average temperatures by 1.0°F (0.56°C) increases county groundwater use by 90,400 gallons per day. These changes are approximately 1.41% and 0.53% of average county level groundwater use respectively. These estimates are both significant at the 1% level. By controlling for state-by-year fixed effects, the linear effect estimates for in-season precipitation and in-season average temperature only vary by 0.011 Mgal/day, and the estimates remain significant at the 1% level.

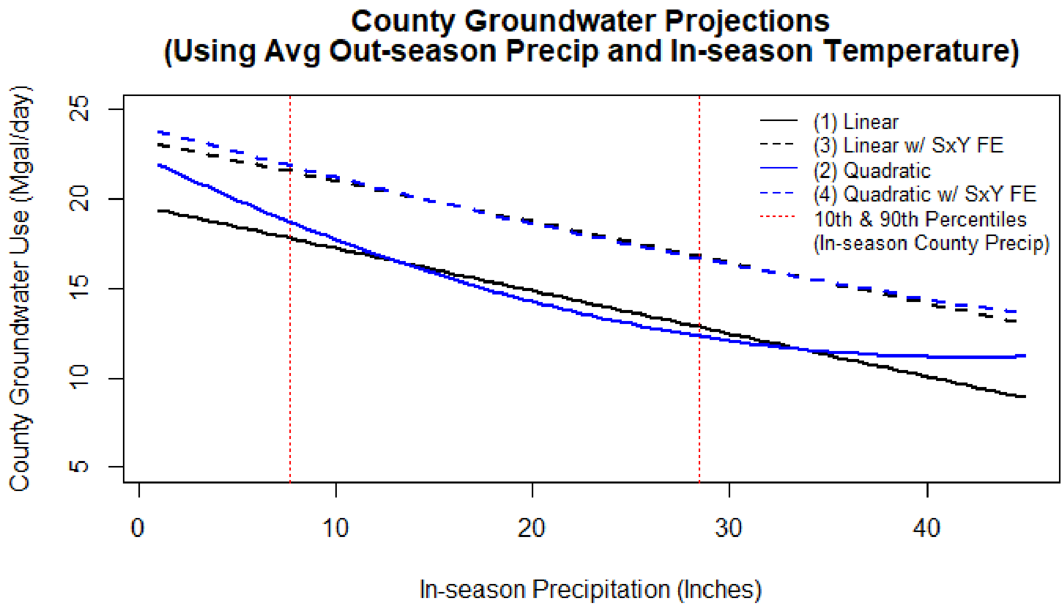

Figure 1: The linear fixed effects model projections for groundwater irrigation are plotted using average growing-season temperatures and average out-season precipitation. Equation (1) is represented by the solid black line. Equation (3), which includes state-by-year fixed effects, is represented by the dotted black line. Equation (2) is represented by the solid blue line. Equation (4) is represented by the dotted blue line. The 10th and 90th percentile for growing-season precipitation are shown by the red vertical lines.

Equation (2) indicates a significant diminishing marginal effect of growing-season precipitation, but this quadratic relationship does not drastically change the projections given by the linear model. Especially for counties which lie between the 10th and 90th percentiles of annual rainfall, the basic linear model (1) portrays extremely similar projections for county groundwater use as the quadratic model (2). This is shown in Figure 1. Model (3) is also shown in Figure 1, which exhibits the minimal change that the addition of state-by-year fixed effects has on the marginal effect of precipitation estimated by model (1). The inclusion of state-by-year fixed effects does remove the significant quadratic effect in model (4). However, model (4) indicates a nearly identical marginal effect of precipitation as linear models (1) and (3) (see Figure 1). As discussed, including this many fixed effects is highly restrictive, so it is not surprising that the significance of the quadratic effect is mitigated. Even so, the effects of both growing-season precipitation and average temperature remain significant under this constraint in the linear model (3). These results indicate that the linear effect estimates given by model (1) have substantial robustness. We continue with linear models in our further robustness checks.

It is important to note that clustering by state noticeably increases the standard error for each climate variable coefficient estimate. This increase in the standard error implies a potential relation between observations within the same state, which would cause the error terms of inter-state observations to have nonzero covariances. By using state clustering, it corrects for potential spatial correlations across counties within the same state, while the county clustering only corrects for serial correlation among inter-county observations. While it is feasible that there may exist some spatial correlation between observations, it is unclear if it is truly at the state level. For example, observations from border counties may be more related to neighboring county observations than to distant counties within the same state. These findings are supported by Pfeiffer and Lawell (2012) in their study of Western Kansas, where they find that farmers do not change their pumping behavior based on other farmers further than 3 miles away, and that changes within such a radius are minimal.

5.2 Additional Robustness Checks

The significant quadratic relationship originally found by (2) may indicate diminishing linear effects across counties with different precipitation on average. An additional inch of rain may have a greater effect on counties which are drier on average, since precipitation is typically less frequent. This theory is further explored by separating the counties into terciles based on annual average precipitation and using an interaction variable to distinguish between terciles The mathematical representation can be found below.

$$y_{ct} = \beta_0 + \beta_1 P_{ct} * \Psi + \beta_2 T_{ct} + \beta_3 \Theta_{ct} + \Psi + \eta_c + \gamma_t + \epsilon_{ct}, \tag{5}$$

$$y_{ct} = \beta_0 + \beta_1 P_{ct} * \Psi + \beta_2 T_{ct} * \Psi + \beta_3 \Theta_{ct} + \Psi + \eta_c + \gamma_t + \epsilon_{ct} \tag{6}$$

Where Ψ is a vector of interaction variables for each tercile. The findings of this additional analysis are summarized in Table 3 with standard errors clustered at the county level. Employment of this method is also supported by the concept that there may be a greater concern for increases in groundwater use for counties that are typically water scarce. For counties with limited precipitation on average, groundwater conservation is likely more essential. Distinguishing between precipitation terciles allows us to address this potential disparity in the sensitivity of groundwater use changes across climatic regions.

The effect for all three terciles are significant at the 1% level for both in-season precipitation and average temperature, but there is no clear relationship between average county precipitation and the effect of temperature changes on groundwater irrigation. A decrease of in-season precipitation by one inch results in an estimated increase in groundwater use by 493,000-499,000 gal/day for counties in the first tercile, 273,000-283,000 gal/day for counties in the second tercile, and 274,000-278,000 gal/day for counties in the third tercile. In relation to national averages, these magnitudes equates to a 2.94%, 1.63%, and 1.64% increase respectively.

Overall, we do find that the driest counties exhibit a greater change in groundwater irrigation due to changes in growing season precipitation. The difference in effects of temperature among terciles is not obvious. For the first, second, and third terciles, the estimated relative effects of a change in temperature by 1.0°F are, respectively, 0.67%, 0.46%, and 1.58% of the historical national average. This is somewhat surprising, as we might expect counties in the first tercile to also be more sensitive to increases in temperature. This could be an indication of measurement error in the assignment of temperature which is discussed further in the limitations section.

Table 3: Testing for Tercile Differences

	(5) Groundwater (Mgal/day)	(6) Groundwater (Mgal/day)
In-season Precip x Ψ_1	-0.499***	-0.493***
	(0.109)	(0.112)
In-season Precip x Ψ_2	-0.273***	-0.283***
	(0.0637)	(0.0643)
In-season Precip x Ψ_3	-0.274***	-0.278***
	(0.0528)	(0.0532)
Avg Temp	0.113***	
	(0.0271)	
Avg Temp x Ψ_1		0.114***
		(0.0305)
Avg Temp x Ψ_2		0.0788**
		(0.0326)
Avg Temp x Ψ_3		0.267***
		(0.0631)
Ψ_2	-3.319	-0.589
	(2.351)	(2.945)
Ψ_3	-0.855	-11.20***
	(2.357)	(3.794)
Out-season Precip	-0.202***	-0.233***
	(0.0693)	(0.0736)
Constant	18.20***	18.31***
	(1.688)	(1.750)
County FE	Y	Y
Year FE	Y	Y
State-Year FE	N	N
Observations	15,685	15,685
R^2	0.008	0.008
Counties	3,141	3,141

*Notes: Standard errors clustered at the county level in parenthesis, *** p<0.01, ** p<0.05, * p<0.1.*

Table 4 shows additional tests for potential effects from historical weather and for further exploration of the found effects. Since groundwater use decisions may depend on rainfall from prior years, we introduce variables for cumulative precipitation from the previous year in equation (7) and from the previous five years in equation (8). This tests for potential bias in the original estimates due to omitting historical weather data. In equations (9) and (10) we run the original linear regression (1) on Total Irrigated Acres and on Groundwater Use Per Irrigated Acre instead of on groundwater use. These are implemented to help explain the cause of the effects found in Table 1.

Table 4: Testing Some Omitted Variables

	(7) Groundwater (Mgal/day)	(8) Groundwater (Mgal/day)	(9) Total Irrigated Acres	(10) GW per Acre (Mgal/day)
In-season Precip	-0.238***	-0.240***	-0.0453**	-0.00481***
	(0.0315)	(0.0314)	(0.0176)	(0.00118)
Avg Temp	0.0914***	0.0840***	0.00361	0.00144
	(0.0252)	(0.0254)	(0.0120)	(0.00122)
Out-season Precip	-0.112*	-0.132**	-0.0486**	0.000442
	(0.0582)	(0.0564)	(0.0210)	(0.000558)
Previous-Yr Precip	-0.00508			
	(0.0174)			
Previous-5-Yrs Precip		0.00865		
		(0.00527)		
Constant	15.59***	14.68***	19.73***	0.510***
	(1.527)	(1.549)	(0.664)	(0.0374)
County FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
State-Year FE	N	N	N	N
Observations	15,685	15,685	15,685	14,525
R^2	0.006	0.006	0.006	0.004
Counties	3,141	3,141	3,141	3,063

*Notes: Standard errors clustered at the county level in parenthesis, *** p<0.01, ** p<0.05, * p<0.1.*

Neither the cumulative precipitation from the previous year nor the previous five years yield a significant effect on groundwater use. This suggests that increases in groundwater pumping is a response to immediate changes in climate. These findings support Tsur's (1990, 2007) explanation of the stabilization role that groundwater plays under conditions of climate variability. Equations (9) and (10) show that growing season precipitation has a negative and significant effect on total irrigated acres and on groundwater applied to each irrigated acre. This suggests that an increase in groundwater irrigation from decreased precipitation (shown by the initial analysis), is likely a combination of an increase in the total number of acres being irrigated and the amount of groundwater applied to each irrigated acre.

5.3 Climate Projections and Aquifer Implications

It is expected that average annual temperatures across the United States will increase by between 2.7°F and 8.1°F by the end of the century with variable changes to precipitation (Walsh et al. 2014). This study emphasizes the effect of precipitation and temperature changes on groundwater irrigation particularly in arid counties. We use the latest Hadley3 projections for county level temperature and precipitation changes by 2070-2099 (Fisher et al. 2012) to estimate groundwater use changes. We emphasize that national climate projections are highly dependent on global GHG emissions over the next few decades, and different weather projections may change the magnitude of the following projections for groundwater.

County level precipitation changes for the growing season are calculated by multiplying the Hadley3 projected county changes for annual precipitation by the historical county level ratios of in-season precipitation to total annual precipitation from our data. The same method is used to estimate the projected changes in out-season precipitation for calculations of the groundwater projection estimates. County estimates for changes in average temperature during the growing season are calculated by dividing the estimated change in growing degree days by the length of the growing season (182 days). Fisher's calculation for changes in growing degree days is based on average daily temperatures summed over the growing season, so this method should roughly reflect the change in growing season average temperatures. The projections for growing season climate changes are depicted by Figures 2 and 3.

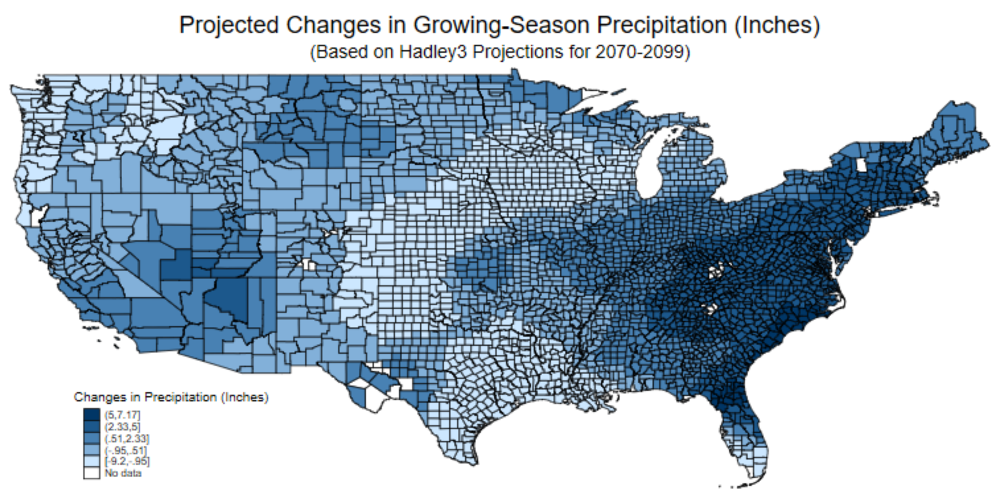

Figure 2: Predicted Changes in Growing-season Precipitation by 2070-2099 Using Hadley3 Climate Projections

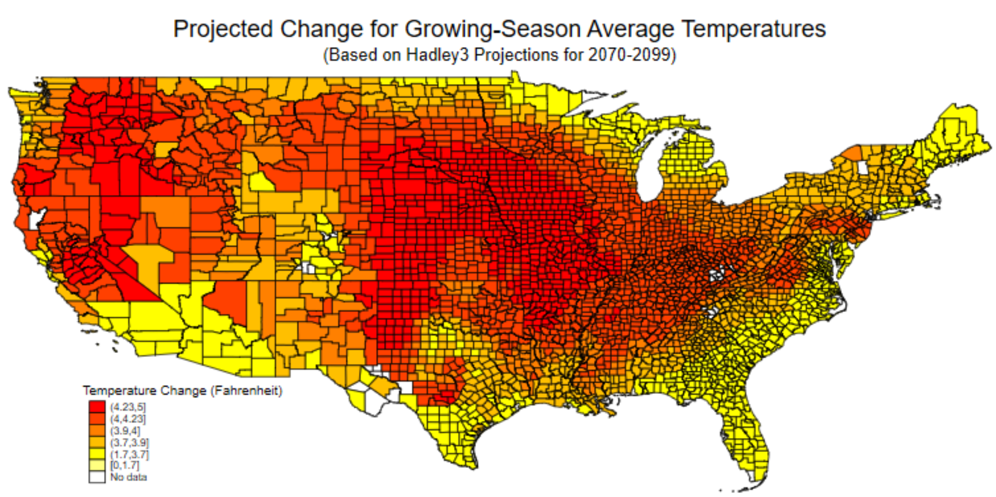

Figure 3: Predicted Changes in Growing-season Average Temperatures by 2070-2099 Using Hadley3 Climate Projections

Based solely on these climate projections, it is unclear what the effect will be on groundwater use across the country. Many places indicate significant rises in temperature with simultaneous increases in precipitation. We have shown in this paper that these two climate variables have significant and opposing effects on groundwater irrigation decisions, which raises the question of what the overall effect on demand will be. However, using the models developed in this study, we can estimate the effect that climate change will have on county groundwater irrigation across the United States.

The projections for changes in groundwater use based on Model (1) are shown in Figure 4. We also map the projections for county groundwater use changes according to Model (5) estimates (Figure 5), because the difference in effects found across precipitation terciles may present different implications. The results of each model are nearly identical in their regional distinction of areas that will exhibit the greatest increases and greatest decreases in groundwater use by the end of the century.

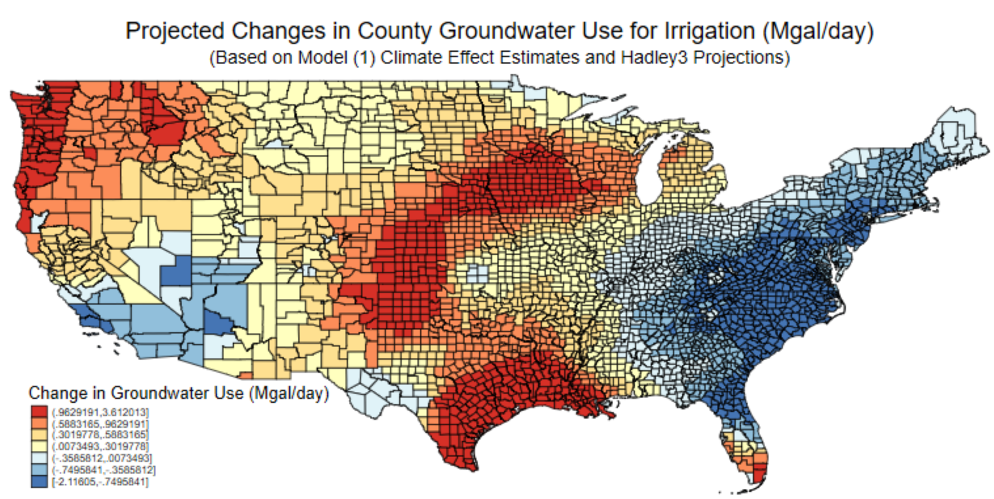

Figure 4: Projected Changes in County groundwater use from climate change by 2070-2099 Based on Basic Linear Model (1) effect estimates and Hadley3 Climate Projections

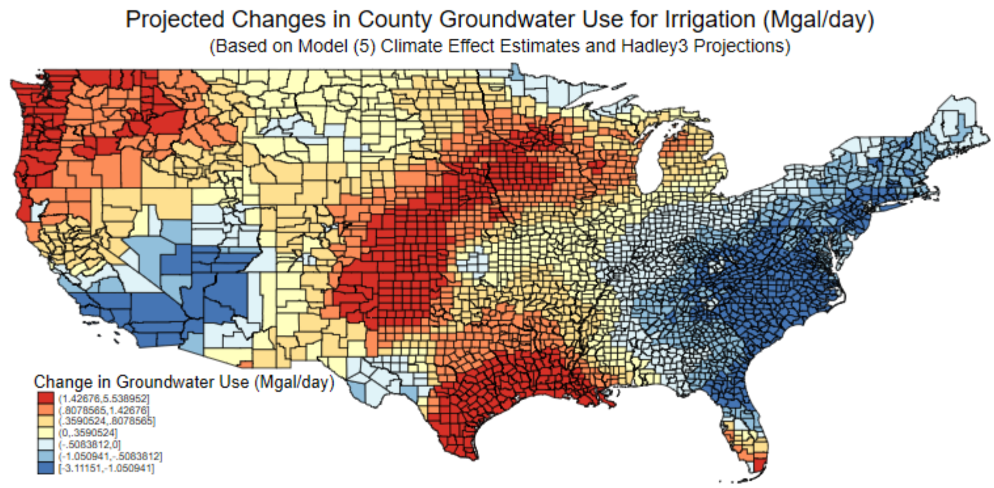

Figure 5: Projected Changes in County groundwater use from climate change by 2070-2099 Using Tercile Interaction Model (5) effect estimates and Hadley3 Climate Projections

5.4 Discussion of Findings and Implications

Both projection models indicate a clear relation to the areas of the country which are predicted to experience declines in precipitation. They also suggest that the greatest increases in groundwater irrigation are predicted to occur in the southeastern and northern parts of Texas, the mid-western states which overlap the High Plains (Ogallala) Aquifer, and the northwest corner of the United States. While there has been public conversation about California water shortages, based on this model, some areas in the southern part of the state may experience enough precipitation increases to actually decrease their groundwater irrigation.

These models estimate the average change in county groundwater irrigation to be between 0.162 Mgal/day (Model (1)) and 0.233 Mgal/day (Model (5)), which is a 1%-2% increase in average county groundwater use. The most drastic increases reach 3.612 Mgal/day increase under Model (1) and 5.539 Mgal/day under Model (5), which is a 21%-33% increase when compared to historical county averages. By summing the projected change in groundwater use in Mgal/day across every county, we calculate the expected aggregate increase in United States groundwater irrigation to be between 491-709 Mgal/day. This ultimately implies that by the end of the century, roughly 179-260 billion gallons of additional groundwater will be extracted each year for irrigation purposes, in response to changes in climate. This is enough water to supply between 490-715 million average Americans with water for a year[1] .

Based on these models, the High Plains Aquifer is likely to experience increased stress due to climate change responses. Our models estimate that the increase in groundwater irrigation in states reliant on the High Plains aquifer[2] will be between 223-334 billion gallons per year. These same states used roughly 6 trillion total gallons of groundwater for irrigation in 2015, so we estimate an approximate 3.7%-5.7% increase in groundwater irrigation for states overlying the High Plains Aquifer if users have no pumping restrictions. As depletion rates are already a topic of scientific concern, this increase in demand is likely to exacerbate the rate of depletion. Note that these estimates do not include the additional increases in groundwater demand for other use purposes, such as growing populations and public supply, and such additions may further increase stresses on groundwater resources.

The economic and policy implications of these projections are highly dependent on the goals for aquifer storage. If it is assumed that groundwater volumes should be maintained for future use and ecological balances, it is necessary to consider these projections for groundwater irrigation. In areas where demand is estimated to increase substantially, groundwater use monitoring and policy among all users will play an essential role in the management

[1] The USGS estimates that the average American uses roughly 100 gallons per day
[2] CO, KS, NE, NM, OK, SD, TX, WY

of groundwater resources. As these projections are highly dependent on precipitation, this study places particular emphasis on groundwater regulation under drought conditions. This supports Green and Schuck's (2001) theoretical conclusion that drought pricing should include groundwater if the intention of such policies are to conserve both surface and groundwater resources.

Our study also shows that effective water policy should consider temperature changes, as users increase their pumping under hotter conditions. Further policy may include implementations of permits where nonexistent, limitations on the number of groundwater permits, or limitations on water-intensive crop acreages during the planting season. Particularly for the mentioned regions, minimizing water-intensive crop acreages will be important for limiting the effects of climate on aquifer resources.

5.5 Limitations and Further Research

As with any empirical study, there are limitations that should be noted. This study is arguably limited by the infrequency of the existing data, since USGS only releases full county-level water reports every five years. Other groundwater data sources are inconsistent between 1995-2015, so while the water use data for this study is the most consistent county-level panel data, more frequent annual data would be preferable to solidify the estimated effects. Also, there are a handful of observations which contain near zero average temperatures during the growing season. This may indicate inclusion of counties in the data set which experienced potential measurement error for temperature. Since temperature is positively correlated with groundwater use, this potential measurement error may cause negative bias in the estimated effect of temperature for some counties. This may explain the lack of clarity in the tercile analysis with regard to the effect of temperature. Since this study utilizes a large sample and the annual medians of average temperatures are not obviously skewed, it is likely that this potential error only applies to a handful of county observations. Thus, the potential negative bias in the estimate for the coefficient for temperature is likely small in magnitude.

The other noticeable limitation of these results are that they are based on temperature averages and cumulative precipitation, which do not account for extreme weather events. Schlenker and Roberts (2008) emphasize the importance of weather extremes on crop yields, as they find a nonlinear, asymmetric relationship between temperature and yields. This may imply potentially significant relationships between extreme weather events and water use, which are not captured by responses to changes in weather averages. Average growing season temperature and cumulative precipitation are both affected by extreme weather events, but fail to reflect the difference that an extreme event has on groundwater pumping choices. Altering the way growing season weather is measured, or increasing the number of climate conditions, could prove a great modification to this study.

With regard to the projections for the effects of climate change on groundwater use, the models do not allow for the flexibility of users to adapt to changing climate over time. The temperature and precipitation projections are for the end of the century, while the estimates for the effects of climate on groundwater use are based on short term user responses. If these projections for climate change occurred instantaneously, our projected effects on groundwater would likely depict the true effect. However, users may increase their groundwater pumping out of necessity in the short run until proper adaptation to the progressively changing climate of the region can occur. Due to this limitation, the model is likely more accurate for depicting short run projected changes in groundwater use, rather than long-run effects.

Lastly, there exists a concern for potential omitted bias in this study from stochastic groundwater pumping costs. Pumping costs are a function of technology, energy costs, and the depth to groundwater. Rainfall and temperature act as exogenous catalysts for groundwater use decisions, but if the cost of groundwater pumping exceeds the returns from irrigation, users will either sacrifice agricultural revenue and bear the high cost, or they will sacrifice their crops to avoid pumping groundwater. The models presented in this paper only address observed pumping behavior and do not include the monetary consequences of such decisions. Because the model does not account for changing groundwater pumping costs, it may overstate increased groundwater pumping activity over time, especially if such increases are large enough to substantially effect depths to groundwater and ultimately increase pumping costs.

6 Conclusion

This study aims to estimate the effect of climate changes during the growing season on groundwater irrigation. Based on the USGS data from 1995-2015 and NOAA climate weather data on daily temperatures and precipitation, we conclude a significant effect of both growing season precipitation and growing season average temperatures on groundwater use for irrigation. A decrease in precipitation during the growing season by one inch is estimated to increase groundwater use for irrigation by roughly 1% of average groundwater irrigation levels. An increase in growing season average temperature by 1.0°F is estimated to increase groundwater use for irrigation by roughly .05%. While these marginal effects are small, we show that large changes in climate have substantial effects on groundwater use. We show that users are more sensitive to precipitation changes than to temperature changes, and find that drier counties on average exhibit much greater marginal sensitivity to precipitation than other counties.

Using our models, we project that Texas, states overlying the High Plains Aquifer, and parts of the northwest are likely to exhibit the greatest increase in groundwater pumping by the end of the century as a response to changing climate. These results suggest that groundwater management will be particularly important for these areas to avoid over-extraction of groundwater resources. This study is one of the few empirical economic studies on groundwater use. We show that empirical and theoretical studies for groundwater use should include temperature as a determining variable in water irrigation decisions, and that very small marginal changes in resource use can have large implications when applied to climate change models. We encourage the continuation of empirical research surrounding further environmental variations and their effects on groundwater pumping decisions. Increasing the empirical literature in this space will provide the necessary insight for prioritizing where management strategies are essential, and in determining the necessary considerations for effective resource policy.

Bibliography

Bredehoeft, J., & Young, R. (1970). The temporal allocation of ground water–A simulation approach. *Water Resources Research*, 6(1), 3–21.

Brown Jr., G., & Deacon, R. (1972). Economic optimization of a single-cell aquifer. *Water Resources Research*, 6(3), 557–564.

Brozovic, N., Sunding, D. L., & Zilberman, D. (2004). Measuring the gains from management of spatially heterogenous resources: the case of groundwater. *Journal of Economic Surveys*, 18(5), 703–740.

Deschenes, O., & Greenstone, M. (2007). The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather. *American Economic Review*, 97(1), 354–385.

Fisher, A. C., Hanemann, W. M., Roberts, M., & Schlenker, W. (2012). The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather: Comment. *American Economic Review*, 102(No. 7), 3749–3760.

Fisher, A. C., Hanemann, W. M., Roberts, M., & Schlenker, W. (2012). The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather: Comment: Dataset. *American Economic Review*, 102(No. 7), 3749–3760.

Gisser, M., & Sanchez, D. A. (1980). Competition Versus Optimal Control in Groundwater Pumping. *Water Resources Research*, 16(4), 638–642.

Green, T. R., Taniguchi, M., Kooi, H., Gurdak, J. J., Allen, D. M., Hiscock, K. M., ... Aureli, A. (2011). Beneath the surface of global change: Impacts of climate change on groundwater. *Journal of Hydrology*, 405(3–4), 532–560.

Lall, U., Johnson, T., Colohan, P., Aghakouchak, A., Brown, C., McCabe, G., ... Sankarasubramanian, A. (2018). U.S. Global Change Research Program, Washington, DC, USA. (2018). *Ch 3: Water* (pp. 145–173).

Mendelsohn, R., Nordhaus, W. D., & Daigee, S. (1994). The Impact of Global Warming on Agriculture. *American Economic Review*, 84(4), 753–771.

(NGWA) National Groundwater Management Association. (2018). *Groundwater Fundamentals*. Retrieved from https://www.ngwa.org/what-is-groundwater/About-groundwater

Pfeiffer, L., & Lin Lawell, C. C.-Y. (2012). Groundwater Pumping and Spatial Externalities in Agriculture. *Journal of Environmental Economics and Management*, 64, 16–30.

Provencher, B., & Burt, O. (1993). The Externalities Associated with the Common Property of Exploitation of Groundwater. *Journal of Environmental Economics and Management*, 24(2), 139–158.

Schlenker, W., Hanemann, W. M., & Fisher, A. C. (2007). Water Availability, Degree Days, and the Potential Impact of Climate Change on Irrigated Agriculture in California. *Climate Change*, 81(1), 19–38.

Schlenker, W., & Roberts, M. (2008). Estimating the Impact of Climate Change on Crop Yields: The Importance of Nonlinear Temperature Effects. NBER Working Paper 13799.

Taylor, R. G. (2012). Ground Water and Climate Change. *Nature Climate Change*, 3 (April 2013), 322–329.

Trenberth, K. E., Dai, A., Rasmussen, R. M., & Parsons, D. B. (2003). The Changing Character of Precipitation. *Bulletin of the American Meteorological Society*, (September 2003). Retrieved from https://journals.ametsoc.org/doi/pdf/10.1175/BAMS-84-9-1205

Tsur, Y. (1990). The Stabilization Role of Groundwater when Surface Water Supplies are Uncertain: The Implications for Groundwater Development. *Water Resources Research*, 26(5), 811–818.

USDA. (2013). *Climate Change and Agriculture in the United States: Effects and Adaptation*. Retrieved from https://www.usda.gov/oce/climate_change/effects_2012/CC%20and%20Agriculture%20Report%20%2802-04-2013%29b.pdf

Walsh, J., Wuebbles, D., Hayhoe, K., Kossin, J., Kunkel, K., Stephens, G., … Somerville, R. (2014). *Ch. 2: Our Changing Climate*(pp. 19–67). U.S. Global Change Research Program.