Irrigation Demand in a Changing Climate: Using disaggregate data to predict future groundwater use

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Abstract

The paper estimates an irrigation water demand function using disaggregate climate and well data over a 32 year time period. Aggregating climate information over long periods, like a year, loses important details on temporal climatic variation, while aggregating climate information over space loses important details on spatial variation. This analysis uses disaggregate climate variation at a temporospatial level to determine the effects of climate on groundwater use. Results show that increased heat, measured in cooling degree-days, correlates with increased water use, while increased precipitation correlates with decreased water use. However, the effects are generally magnified for later summer months, and are generally lower earlier in the growing season, with a few notable exceptions. Other factors that significantly affect groundwater irrigation demand are soil type, the price of corn, pumping rate, and the number of certified irrigated acres.

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Introduction

Managing limited irrigation water in arid regions is a concern to both policymakers and agricultural producers. Policy changes in recent years have led to increased restrictions and allocation limits in many areas such as Kansas, Nebraska, and Texas. While agronomic research can provide guidelines about crop-water requirements, it is well known that individual producers vary in actual irrigation application rates. Understanding how producers adjust irrigation water use under a range of market and climate conditions is critical for long-term management of water resources. Observed water use between producers is not uniform, even within counties. Heterogeneity in both the physical environment, such as soil type, crop type, pumping capacity (in groundwater-dependent systems), and irrigation efficiency; and in temporospatial climatic variation, such as precipitation and temperature, presents producers with an array of individualized challenges. Market conditions such as input and output prices affect individual use of water for all irrigators. Specifically for groundwater irrigators, exogenous variables like the fuel cost associated with pumping groundwater also factor into the decision about groundwater use.

The aim of this paper is to use disaggregate climate and well data to estimate the relationship between groundwater withdrawals and local climate conditions in Chase, Perkins, and Dundy counties in western Nebraska. Economic work on the relationship between climate and water use is not new. Many papers have focused on the effect of climate change on water demand. Some of this work is theoretical and based on predicting the optimal water use for crop types globally or regionally, given climate information such as average temperature, precipitation, and evapotranspiration rates (Fischer et al., 2007; Döll, 2002; Yu and Babcock, 2010). While impacts vary by region, results consistently show that climate change will increase average water scarcity, potentially increasing the quantity of irrigation water demanded.

Other studies use data on prices and physical characteristics, along with crop production functions, to model groundwater demand (Martin et al., 1989). This is a more mechanical approach, with an assumption of profit maximization applied to estimated crop production functions. This approach is valuable for predicting producer responses when microlevel data on actual water use is not available, but it is well-known that producers do not always follow agronomic recommendations. In addition, results cannot be interpolated over broad regions. For example, in order to calculate the maximum yield, Martin et al. (1989) use a dryland yield baseline and includes coefficients on irrigation efficiency, seasonal evapotranspiration rates, and crop water requirements.

Some past research has incorporated detailed spatial analysis. Döll (2002) and Fischer et al. (2007) use a global irrigation model to analyze how climate and climate variability affects water use, and incorporate a spatial resolution of about 34 square miles. However, neither study considers intra-annual temporal variation. Adams et al. (1998) aggregates data further by looking at annual climate changes at the regional level (e.g., northeast, southeast) to estimate the general impact of climate change on water use. Results estimate average annual impacts of climate change based on expected climate change and crop water demands. However, results do not explain the intraseasonal decisions about groundwater pumping.

The shortcomings in these studies revolve around resolution and aggregation. For example, Yu and Babcock (2010) estimate drought effects on corn and soybeans and include variables similar to the ones used our analysis: monthly precipitation and monthly cooling degree-days. These variables are aggregated across counties among three Corn Belt states: Iowa, Illinois, and Indiana. For counties with fairly homogeneous climate, this might not be an issue, especially for small counties. However, for counties with more climatic disparity, aggregation fails to capture potential intra-county climate differences.

Missing from the literature is an analysis that incorporates both high spatial resolution, which captures more precise changes along a varied landscape, and high temporal resolution, which measures how climate patterns within a year may affect water usage. In this paper we start to fill that void. Both spatial and temporal differences are important in understanding the effects of climate change. Climate research suggests that climate change will not only affect average temperature and precipitation levels, but also the distribution of temperature and precipitation during and between years. Spatial heterogeneity is important because different parts of a water basin may respond differently to a changing climate and shifts in water policy. This heterogeneity may impact water use patterns and associated changes in agricultural ecosystems and aquifer conditions. The second is important because crops require different inputs at different stages of the plant's lifecycle (Kranz et al., 2008). In this sense, *when* drought occurs is just as important, or more important, than *if* it occurs. Aggregating climate information over a growing season blurs the relationship between the effects of weather and the changing input needs of the crop.

The analysis in this paper uses detailed historic climate measurements over a 32-year period (1980-2011) and well-specific information such as annual pumping amounts (acre-in), depth to groundwater, and soil type. In contrast to previous work, which uses annual or seasonal climate variables, we use monthly climate information. In addition to high temporal resolution, the analysis incorporates spatial heterogeneity by interpolating weather station data within a county, rather than averaging the weather data across a county. This allows each well to have potentially unique climate information, all based on empirical data. Thus, the empirical analysis can capture variation within and between years, while incorporating spatial variation between wells.

Background

There is considerable variation in precipitation across Nebraska. Nebraska straddles a climate zone that transitions from relatively humid and wet, averaging 36 inches of precipitation in the southeastern portion of the state, to arid, where average rainfall hovers around 13 inches per year in the western portion of the state.[11] This 23-inch difference occurs within 415 miles, from the eastern border to the western border, which causes heterogeneous climate patterns across the state. To put this in perspective, the three state corn-growing region of Indiana,

[1] http://www.nrdc.org/water/readiness/files/water-readiness-NE.pdf

Illinois, and Iowa have an average precipitation difference of 7.7 inches across almost 600 miles (NCDC). This means that in Nebraska going from east to west there is an inch of precipitation lost every 18 miles. For the states of Indiana, Illinois, and Iowa going from east to west there is an inch of precipitation lost every 78 miles. This heterogeneity makes Nebraska an excellent location to study agricultural production and irrigation use across a range of climate and precipitation conditions.

Uncertainty about weather is one of the main sources of risk in agricultural production. For producers in western Nebraska who operate in a more arid climate, irrigation is a necessary input. With 70 percent of all irrigated acres in 2007, corn is the primary irrigated crop in Nebraska (www.nrdc.org). The majority of irrigation water in Nebraska comes from groundwater in the High Plains Aquifer. Corn requires about 26 inches of water from its earliest growth stage until it is harvested (Kranz et al., 2008). Therefore, groundwater is crucial to harvest success and high yields, especially in the western part of the state.

This paper looks at three western Nebraska counties: Chase, Dundy, and Perkins. These three counties make up the regulatory body known as the Upper Republican Natural Resource District (URNRD). Nebraska has a system of 23 Natural Resource Districts (NRDs) which have the primary responsibility for managing groundwater. For producers in these three counties, water scarcity is especially acute; in addition to a relatively low average rainfall, there are legal and regulatory restrictions on the amount of groundwater available to pump. Average rainfall between March and October here is approximately 17 inches, less than the rainfall required to grow corn, which makes producers dependent on groundwater irrigation (Kranz et al., 2008).

The Republican River Basin, situated in southwestern Nebraska, northeast Colorado and northern Kansas, has been an area of interstate conflict over the water use and obligations of each state. Center-pivot irrigation has allowed previously marginal land to come under cultivation at the cost of increased water pumping from the High Plains aquifer. Portions of the aquifer have started to show signs of strain as water recharge is outpaced by pumping.

Increased pumping complicates surface water hydrology as well, and, as the dynamics of surface water and ground water interactions became better understood, the legislation regulating surface water became muddled. In the case of the Republican River, water runs from the head of the river in Colorado through the northwest corner of Kansas and into Nebraska before entering Kansas downstream. The Republican River Compact, signed in 1942, originally divided the surface water between the three states, with the majority of the allocation for Nebraska and Kansas. As acreage in the cropland in the basin increased, groundwater wells were drilled to supply irrigation water needs. Kansas sued Nebraska in 1998 over misuse of water allocations, claiming groundwater pumping in Nebraska had decreased surface water flow and that Nebraska was not supplying Kansas the full legal water allocation.

This is due to the hydrologic connectivity in the region between surface water and groundwater. As groundwater is pumped, it creates a cone of depression in the groundwater levels. If a cone is close to other wells or rivers, it depresses water levels. For the river, groundwater pumping nearby will lower the aquifer level, pulling stream water down to fill the void. This effectively lowers in-stream flows (Grant, 2005, pp. 334-337.

In 2001 the United States Supreme Court sided with Kansas and said that Nebraska was in violation of the original Republican River Compact. For producers and rural communities in the URNRD, the legal battles translate into increased regulation. However, even before the ruling, the URNRD had been actively managing groundwater use for decades and had some restrictions since 1980. The restrictions are based on a maximum allocation per certified acre.

While the limit was initially set at 22 inches per acre (acre-inches), it has been 15 inches or less since 1988 (Juchems, 2013).

Today, the URNRD limits groundwater withdrawals to 13 acre-inches per acre. However, producers may choose to use more or less, with the understanding that a producer cannot use more than 65 acre-inches per acre over a 5-year period. This allows producers to use more water in drought years, while conserving water in wet years. While the URNRD has occasionally permitted irrigation use over this limit, the meters are monitored and recorded annually. The consequence of overuse after a five-year period is a reduction of allocated water by the amount overdrawn in the previous allocation period. Legal action or a loss of irrigation rights may be taken at the discretion of the Natural Resource District in extenuating circumstances, such as cases where an irrigator deliberately bypasses the meter.

Critical analysis of irrigation water demand that incorporates local heterogeneity in land characteristics and climate conditions is necessary for future water management in this region. Producers will use more groundwater when it is hot or dry. However, because drought may occur at different times of the year and crops have different needs and sensitivities throughout their lifecycle, not all dry and hot conditions are expected to be the same. This is lost in models that aggregate climate data by year or season. The model presented in this paper addresses this issue in an effort to better understand how the pressures on Great Plains agriculture are expected to change and how the subsequent demand for groundwater will shift.

Data

The data used in this analysis is from a number of sources. First, public data on individual wells is from the Nebraska Department of Natural Resources (DNR) database. The DNR database contains technical information about each registered well. This includes the location of the well, the depth to groundwater at the time of drilling, and the pumping rate in gallons per minute (gpm). Soil type was obtained from the State Soils Geographic (STATSGO) database. The DNR and soils data has been used and documented in Kuwayama and Brozović (2013) and Pallazzo and Brozović (2014).

Panel data was provided by the URNRD. The URNRD installed meters on all irrigation wells by 1980 and collects annual data on water use and crop choice. Each well was matched to the field or field it irrigates using the URNRD database. While most of the 3,159 wells irrigate a single field, a few (82) are associated with multiple fields, either because one well irrigated two fields or administrative changes caused producers to record their use differently. These were corrected for, either by dropping a duplicate observation or, if not duplicates, by creating a separate well id to capture additional water use activity.

We use climate data from the National Climate Data Center publicly available database. Specifically, we use monthly data on precipitation, cooling degree-days, average temperature, and maximum and minimum temperature. The climate data is from 17 weather stations in the three-county region.[2] In order to match climate information to a specific well, we used ArcGIS to create a shapefile of each climate variable using inverse distance weighting from the associated weather stations. This was done for each climate variable-month-year combination (e.g., March 1992 precipitation). From this, weather data was extracted by well point, creating well-specific climate information.[3]

Output prices for corn, wheat, and soybeans are from USDA. Input prices (specifically, crude oil prices) are from the U.S. Energy Information Administration. We use the average

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[2] We use some weather stations that are located just outside the three-county region for data interpolation.
[3] We are indebted to Karin Callahan, GIS specialist at the University of Nebraska School of Natural Resources, for writing the Python script to create well-level data for 3,159 wells with 72 climate variables over 33 years.

annual wholesale price for output prices and the average annual price paid at U.S. crude oil markets for the fuel price.

The final dataset is a composite of historical well groundwater use, field, and climate information, collected between 1980-2012, and organized by well ID. Table 1 shows definitions of variables used in the analysis and Table 2 shows the summary statistics.

Economic Model

We assume producers in this model are entirely dependent on groundwater for irrigation and that they choose to pump an amount of groundwater, *w*, measured in acre-inches per acre, at time, *t*, measured in years, such that they maximize profit. We define a producer's profit function as:

$$\pi = PY(w_{it} \mid z_{it}) - c_{it} w_{it}$$

where the price received by a producer for their crop at year *t* is multiplied by their yield per acre, $Y(w_{it}|z_{it})$. Assume there are *i* wells, and the yield, $Y_{it}(w_{it}|z_{it})$, is reached from the application of groundwater, *w*, given the observed variables at each well, z_{it}. The variables for z_{it} represent external forces affecting water use and include rainfall effectiveness, defined as monthly precipitation given fine, medium, or coarse soil, and cooling degree-days, measured as a monthly total using a 65 degree Fahrenheit base. A dummy variable is also included to indicate if producers employed double-cropping for well *i* at time *t*. The cost associated with pumping, c_{it} w_{it}, is a function of fuel prices in real values, the rate of pumping in gallons per minute, the number of certified acres, and the depth to groundwater, each associated with a well, *i*. By taking the first order conditions, we can solve implicitly for *w*, such that $\frac{\partial Y(w_{it} \mid z_{it})}{\partial w_{it}} = \frac{c_{it}}{p}$, where w_{it} is a function of z_{it}, c_{it}, and p.

In the empirical specifications for our model, outcome *w*, water use, at well *i* in year *t* is regressed on the cooling degree-days and precipitation, given soil type, for each month per year, z_{it}, the adjusted corn prices and fuel prices with base year of 1983, P_t, and five well-specific variables, X_{it}, (pumping water level, pumping rate, number of certified acres, and indicator variables on double-cropped fields and fields sharing wells). Pumping water level (depth to groundwater) and pumping rate are determined at the time the well is drilled and do not change over time. Certified acres, double-cropping, and shared wells can change over time. The months of November through February are combined to produce a winter variable for both cooling degree-days and precipitation. The model we use is a random-effects regression model using panel data, specified as:

$$w_{it} = \alpha + \beta_D D + \beta_R R_{it} + \beta_{1,m} R_{it} S_1 + \beta_{2,m} R_{it} S_2 + \beta S_i + \beta_p P_t + \beta_X X_{it} + u_i + \varepsilon_{it}$$

where the error term is expressed in AR(1) functional form:

$$\varepsilon_{it} = \rho \varepsilon_{i,t-1} + \gamma_{it}$$

Subscripts *m, i,* and *t* denote month, well, and year respectively. The error term, ε_{it}, captures random factors consistent with an AR(1) model which depends linearly on its own previous values. The AR(1) random-effects GLS estimator model is chosen because the disturbance is first order autoregressive (modified Bhargava et al. Durbin-Watson value of 1.177) and the climatic differences between wells is expected to influences the dependent variable, which is consistent with a random-effects model.

The vector *D* includes data on cooling degree-days per day, measured in degrees Celsius with a base of 65 degrees Fahrenheit, over the 9 month variables (March-October and winter). The vector *R* includes precipitation over the same 9 months, while S_1 and S_2 are indicators for medium and coarse soil. *P* is a vector of fuel and corn prices in year *t*, and *X* captures the five well-specific variables (pumping water level, pumping rate, number of certified acres, and indicator variables on double-cropped fields and fields sharing wells).

Precipitation is measured in centimeters per month. Soil type is reflected as course, medium, or fine, with fine as the omitted category in the estimation. This reveals physically how much water is held in the soil during precipitation or irrigation events, and thus how efficient the soil is at capturing water. The less efficient the soil is at holding water, the more farmers need to irrigate to maintain optimal growing moisture levels (Kranz et al., 2008). Therefore, we account for the efficiency of monthly precipitation in this factor variable. We include interaction terms for the soil and precipitation variables in the estimation. We expect that the same amount of precipitation will have different effects on irrigation water demand of different soil types due to the variation in water holding capacity.

Additionally, pumping water level and the inflation-adjusted crude oil prices are included to capture the cost of pumping groundwater. The cost of pumping groundwater increases with a higher energy price and an increase in the depth to groundwater. Variables similar to these have been used to model the marginal costs of extracting groundwater, with the assumption that as groundwater is extracted and the water table falls, the cost of pumping will increase (Gisser and Sanchez, 1980; Koundouri, 2004)..

The rate at which water can be pumped, in gallons per minute, and the certified acres allocated to each well are included. These variables are meant to reflect the size and scope of each operation to account for the scale of production. We estimate the water use per acre but include certified acres as there may be economies of scale in irrigation technology that makes it more efficient to irrigate larger fields. Additionally, an indicator variable for double-cropping is included. Double-cropping is a farming practice in which a second crop is planted after the first has been harvested. This was self-reported in the field data. Hypothetically, if producers plan on double-cropping, they may be more conservative in how much water to irrigate their first crop with, especially because of the annual pumping limit of 13 acre-inches per acre in the URNRD.

Few farms grow anything other than corn, thus the price of corn, adjusted for inflation, is included as well. When expected corn prices are high, it increases the marginal value of irrigation water and producers choose to increase irrigation to maximize profit.

Results

Table 3 reports the estimation results. Using well-specific data, we estimate the demand for groundwater, measured in acre-inches per acre. The R-squared for a single well between years is 0.3805; the R-squared between wells for a single year is 0.2961; while the overall R-squared value is 0.3516. As expected, there is significant variation between months for both precipitation and cooling degree-days, as well as between soil types. However, some months provided unexpected results in terms of the sign of the coefficient. April and October are both significant and negative for cooling degree-days, which implies that, the warmer the climate is in these two months, the less water producers will extract.

The rest of the months are consistent with our expectations about the effect of degree-days on groundwater demand. An increase in degree-days in May through September lead to more groundwater demanded, although the magnitude varies by month. May, June, and July have similar marginal effects, with an increase of one degree Celsius leading to an additional 0.25, 0.28, and 0.29 inches per acre applied irrigation, respectively. Average cooling degree-days per day for coefficients with positive values, included in Table 2, range from 0.74 in May to 5.947 in July.

Cooling degree-days coefficients are negative for April (-1.347), October (-1.264), and winter (-20.31) and significant at the 1 percent level. These coefficients are much larger, reflecting a decrease in water use when these fringe months are warmer. There are relatively few average cooling degree-days per day for these months, with an average of 0.097, 0.0015, and 0.071 cooling degree-days per day in October, winter, and April respectively. March cooling degree-days are insignificant at the 10 percent level.

The factor variables for soil type, which account for the porosity of the soil in relation to rainfall, give more detail about the effect of precipitation on groundwater use. The interaction effects are generally consistent with expectations in both sign and magnitude, although some are not statistically significant. Medium soil is insignificant when compared to fine soil for June, August, October, and the winter months. Coarse soil is insignificant when compared to fine soil only in June and August at the 10 percent level, but insignificant in October at the 5 percent level.

Coarse soil causes precipitation to be less effective at reducing groundwater use. This is because the lower water holding capacity of coarse soil does not allow the plant to utilize additional precipitation as efficiently as with medium or fine soil. For example, an additional centimeter of precipitation in May will reduce groundwater irrigation by 0.26 inches per acre for fine soil, but only by 0.22 inches and 0.21 inches per acre for medium and coarse soil, respectively. July has a similar pattern as May.

We do not find the same pattern for all months. March and April have the opposite pattern, with additional precipitation resulting in lower annual water demand for medium and coarse soils relative to fine soils. In September, precipitation over fine and coarse soil types appears to increase groundwater withdrawals, with fine soils increasing withdrawals by 0.057

acre-in per acre for every centimeter of precipitation, while coarse soil increases withdrawals by 0.017 for the same amount of precipitation. Medium soil has the opposite effect, with a marginal effect of -0.025.

Variables that affect the costs of production including pumping water level, pumping water rate, the number of certified acres, and the adjusted price of fuel all have the expected sign. Fuel price is the only insignificant variable of the four; the rest are significant at the 1 percent level. Pumping water level, with a coefficient of -0.011, is one of the best indicators of pumping costs, with an increase in 1 foot of depth to water correlated to a decrease in 0.01 acre-inches per acre of water applied. The number of certified acres, the number acres irrigated by a single well, has a coefficient of -0.0065, indicating a slight efficiency gain in water use as farmers increase the scale of production. Pumping water rate, with a coefficient of 0.00032, reflects a tendency to irrigate more as technology eases technological limitations on irrigation pumping.

The adjusted price of corn is significant at the 1 percent level, with a coefficient of 0.210. As the price of corn increases, the water applied per acre increases as well; in this model, for every dollar per bushel increase in the price of corn, we expect producers to add over 0.2 acre-in per acre of groundwater, reflecting an anticipated yield increase at the intensive margin of production. This is consistent with economic theory; higher corn prices are correlated to increased groundwater withdrawals.

The factor variables for double-cropping and shared wells are both significant. 8.5 percent of observations were reported to have more than one crop planted in a year, and 2.15 percent of observations watered more than one field. The coefficient for double-cropping is -0.871, indicating a decrease in water use per acre when multiple crops are planted in a year. The coefficient for shared wells is -0.865, indicating a decrease in water use per acre when multiple fields rely on a single well. Both are significant at the 1 percent level.

Table 4 has the estimated marginal effects for the variables in the interaction terms (soil type and precipitation). The marginal effects show that both soil type and precipitation have significant effects on groundwater demand. Compared to medium and fine soils, coarse soil increases water demand, which is consistent with the conventional understanding of soil hydrology (Kranz et al., 2008). The marginal effect of 1.529 inches per acre is both statistically and economically significant, showing that on average, a field with coarse soil uses about 11.4 percent more water than the average field in the URNRD. This is consistent with observed soil retention efficiency (Kranz et al., 2008). Soil classified as "medium" appeared to have no significant effect on water usage compared to fine soils.

The marginal effects of precipitation, regardless of soil type, are negative from March through August and positive in September and October. All are significant at the 1 percent level, except for September, which is significant at the 5 percent level. Winter precipitation is insignificant at the 10 percent level. For the months with negative coefficients, the effects of precipitation vary from a high of -0.103, in April, to a low of -0.290, in July. This means an increase of one centimeter in April precipitation reduces irrigation application by 0.103 inches per acre. In July, during the critical period for plant growth, the same increase of one centimeter reduces irrigation application by 0.290 inches per acre. Unexpectedly, we find positive marginal effects for September and October precipitation, although the magnitudes of the marginal effects are much smaller than in the other months.

Discussion

The motivation for this work is an expectation that using disaggregate climate and well time-series data can provide a more accurate estimation of the effects of weather on a producer's irrigation demand. The results show that irrigation water use is responsive to month-to-month changes in climate at the well level, and that different months in the growing season have heterogeneous impacts on from the same change in climate conditions. Although there are basic, biologically-determined irrigation requirements, increased heat or drought can impact a producer's water use substantially. This is a concern in areas like the Upper Republican Natural Resource District, where groundwater pumping limits have been set to improve instream flows in the Republican river, which is hydraulically connected to aquifer. For producers who use close to the established groundwater pumping limit, a hot or dry year could lead to noncompliance with water use regulation.

Water use is particularly susceptible to September heat and July and August rainfall, the months with the biggest effects on water use for those variables. This is not surprising, since corn water requirements peak in July as the plant begins to tassel and silk, and then taper off into September as the plant stops fruiting and reaches maturity (Kranz et al., 2008).

Precipitation reduces water use from March through August, with precipitation in July, August, and May showing the most response to water use. These three months, again correspond to particular stages in a corn plant's life cycle, with the highest response to rain corresponding with times of greatest water use by the plant. Our analysis showed that, in July and August, an additional inch of rain would reduce water use by almost 0.75 acre-inches per acre. In May, that number is about 0.58 acre-in per acre, and in less critical months, can be as low as 0.26 acre-in per acre (in April), which is still a significant amount for producers with an allocation of only 13 acre-inches per acre.

Precipitation deviates from the expected trend in September and October, with additional amounts of irrigation in these months correlating to an increase in groundwater use, not a decrease. These coefficients have much smaller in absolute terms than in March through August, but are still statistically significant. These results may reflect the overall decline in water consumption by the plants in these months, or the production practices among producers during the end of the growing season, when growth is no longer a key concern. The reasons behind this trend are still unclear.

In some cases precipitation also varies markedly across soil types, with precipitation during certain months having differential effects on groundwater use. On average, the largest impacts of precipitation are in July and August. This is consistent with agronomic requirements for crop water needs for crop growth during these months. In July the effect of precipitation varies by soil type although August shows no statistical difference by soil type.

May and July exhibit the expected pattern in which precipitation over a field with coarse soil decreases groundwater pumping less than fine soils. This is predicted based on the experimentally determined carrying capacity for coarse, medium, and fine soils (Kranz et al., 2008). However, March and April record the opposite trend, with precipitation over coarse and medium soils showing better reductions in water use than for fine soils.

The end results do not paint a clear picture, but they do signify the importance of precipitation in concert with the soil over which that precipitation falls. The land quality affects the efficacy of precipitation, and producers seem to respond differently during various stages of the crop growth season when managing their irrigation practices. The interaction terms for May through July are consistent with the expectation that precipitation is important in reducing groundwater withdrawals, with soil type affecting the marginal impact of precipitation on a producer's groundwater demand in some months.

Temperature, measured by the average cooling degree-days per day each month, indicates that warmer temperatures do increase irrigation water demand, at least between May and September. An increase of one degree Celsius per day in May, June, and July, increases water use between 0.25 and 0.29 acre-in per acre.

However, temperature shows unexpected patterns for April, October, and during winter. The odd results in these months are likely due to the small number of observations. All of these months have an average of less than 0.1 cooling degree-days per day, reflecting the rarity of temperatures above 65 degrees Fahrenheit during these months. This is especially pronounced in the winter degree-day variable, and is a reflection on the very rare number of cooling degree-days ever experienced between November and February. It seems, based on the real application of the data, this winter result is a spurious correlation based on very few observations. For October and April, the average number of cooling degree-days is also very small (e.g., October has 30 cooling degree days compared to 1,523 in August). Although these months point to warmer weather leading to lower water use, they are likely to be spurious correlations based on a rarity of empirical observations. Otherwise, these months are at the edges of the growing season and may reflect harvest practices unrelated to growing corn (e.g., field maintenance).

Monthly climate patterns, therefore, matter very much. Aggregating climate data will not capture these relationships. Understanding if precipitation occurred in June or August will change a producer's expected water withdrawals; understanding if a heat wave occurred early in the growing season or late in the growing season will have similar impacts. Of course, in arid, water-scarce areas like the URNRD, producers will always need groundwater to irrigate their crops. Those who irrigate in coarse soil are much less efficient since the ground will not hold as much water, both from precipitation and from irrigation. Precipitation over these soils will do less to alleviate water stress and cause producers to pump more groundwater.

Additionally, economic drivers change the incentive for irrigation. As corn price increases, the relative importance of costs to use additional groundwater diminish and this is clearly reflected in our results. An increase of 1 dollar per bushel in the price of corn increases irrigation application by 0.21 inches per acre, while an increase in the depth to groundwater of 100 feet reduces irrigation application by 1.1 inches per acre.

Economies of scale are also important in determining a producer's groundwater pumping decisions. The rate at which they pump, the number of certified acres, and the presence or absence of double cropping and multiple fields all significantly affect water use. The more water a well can pump per minute, the more water per acre will be applied. Conversely, the more irrigated acres there are, the less water is applied per acre. The former may be a reflection of necessity or capability: larger wells are needed for less efficient, water-intensive acres, or larger wells let producers water more per minute and so they water more because it is possible. The latter suggests producers are either satisfied with lower intensive yields in favor of extensive growth, or that there is some economy of scale in producing corn in larger fields. Double cropping and shared wells show similar patterns, and both reduce the demand for irrigation on a per-acre basis.

Water use depends on a number of variables, but at the margin, climate can substantially increase or decrease a producer's total water use. In areas dependent on groundwater to make up for this climatic volatility, especially when groundwater is scarce, declining, or limited as is the case in the Republican River watershed, accumulations of fractions of inches per acre necessary to correct for climate volatility can add up to substantial increases in groundwater withdrawals.

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Table 1: Variable Descriptions

Variable Name	Description
Cooling degree-days	Each month has the total number of cooling degree-days using a 65 degree Fahrenheit base and measured in degrees Celsius per average day
Precipitation	Each month has the monthly total precipitation measured in centimeters
Soil type	A dummy variable to indicate whether field soil is coarse, medium, or fine
Pumping water level	Describes the depth from the surface to groundwater level, measured in feet
Pumping rate	Describes the rate at which a particular well extracts groundwater, measured in gallons per minute
Certified acres	The number of acres in a field with an irrigation allocation
Corn price	The price of corn in real USD (1983 base)
Oil price	The price of US crude oil in real USD (1983 base)
Double-cropping	A dummy variable to indicate whether a second crop is listed for a field in a given year
Shared well	A dummy variable to indicate whether a second field is irrigated by a single well

Table 2. Summary Statistics

	Observations	Mean	Standard Deviation	Min	Max
Usage	65783	13.427	5.105	0.000	62.180
Mar. Precipitation	65177	2.470	1.809	0.004	14.418
Apr. Precipitation	65000	5.003	2.839	0.002	15.228
May Precipitation	65220	7.103	4.145	0.219	20.770
June Precipitation	65000	7.482	3.702	0.363	29.843
July Precipitation	65223	7.827	3.599	0.185	25.145
Aug. Precipitation	65223	6.250	4.334	0.095	28.666
Sept. Precipitation	65223	3.430	2.192	0.001	12.192
Oct. Precipitation	65223	3.689	2.729	0.001	17.589
Winter Precipitation	65783	10823.800	11365.460	0.000	196342.700
Mar. CDD	65230	0.002	0.005	0.000	0.045
Apr. CDD	65377	0.071	0.099	0.000	0.656
May CDD	65230	0.739	0.395	0.000	2.301
June CDD	65318	3.292	1.266	0.334	7.426
July CDD	65230	5.947	1.277	1.230	10.147
Aug. CDD	65230	4.916	1.278	1.169	9.001
Sept. CDD	65230	1.713	0.829	0.114	4.347
Oct. CDD	65230	0.097	0.118	0.000	0.933
Winter CDD	65230	0.001	0.011	0.000	0.328
Adjusted Corn Price	65783	1.747	0.554	1.004	3.277
Adjusted Fuel Price	63337	35.174	20.606	12.700	86.610
Pumping Rate	65783	1565.480	734.435	25.000	3600.000
Pumping Water Level	65775	138.652	68.831	8.000	440.000
Certified Acres	65770	144.191	51.785	0.000	702.900
Double-cropped	65783	0.085	0.279	0.000	1.000
Shared well	65783	0.002	0.145	0.000	1.000

Table 3. The Effects on Groundwater Use

Dependent Variable: Groundwater use, in acre-in per acre		
	Coefficient	Standard Error
Mar. CDD	-2.232082	2.792
Apr. CDD	-1.347***	0.169
May CDD	0.254***	0.037
June CDD	0.275***	0.014
July CDD	0.290***	0.019
Aug. CDD	0.185***	0.017
Sept. CDD	0.525***	0.020
Oct. CDD	-1.264***	0.120
Winter CDD	-20.311***	1.222
Mar. Precipitation	-0.092***	0.014
Mar. Precipitation x S_1	-0.084***	0.017
Mar. precipitation x S_2	-0.122***	0.017
Apr. Precipitation	-0.080***	0.009
Apr. Precipitation x S_1	-0.025**	0.012
Apr. precipitation x S_2	-0.044***	0.012
May Precipitation	-0.256***	0.006
May Precipitation x S_1	0.034***	0.008
May precipitation x S_2	0.042***	0.008
June Precipitation	-0.176***	0.007
June Precipitation x S_1	0.001	0.009
June precipitation x S_2	-0.002	0.009
July Precipitation	-0.326***	0.007
July Precipitation x S_1	0.056***	0.009
July precipitation x S_2	0.053***	0.010
Aug. Precipitation	-0.284***	0.006
Aug. Precipitation x S_1	-0.001	0.008
Aug. precipitation x S_2	0.0127	0.008
Sept. Precipitation	0.057***	0.010
Sept. Precipitation x S_1	-0.082***	0.014
Sept. precipitation x S_2	-0.040***	0.014
Oct. Precipitation	0.040***	0.009

Oct. Precipitation x S_1	-0.001	0.012
Oct. precipitation x S_2	0.022*	0.012
Winter Precipitation	-0.000004*	0.000
Winter Precipitation x S_1	-0.00001	0.000
Winter precipitation x S_2	0.00001*	0.000
Adjusted Corn Price	0.210***	0.042
Adjusted Fuel Price	0.001	0.001
Pumping Rate	0.0003***	0.000
Pumping Water Level	-0.011***	0.001
Certified Acres	-0.007***	0.001
Double-cropped	-0.871***	0.055
Shared well	-0.865***	0.255

Notes: Significance at the 0.01, 0.05, and 0.1 levels denoted by ***, **, and * respectively

Table 4. Marginal Effects of Soil and Precipitation

Dependent Variable: Groundwater use, in acre-in per acre		
	Coefficient	Standard Error
Mar. Precipitation	-0.161	0.009
Apr. Precipitation	-0.103***	0.006
May Precipitation	-0.230***	0.004
June Precipitation	-0.176***	0.005
July Precipitation	-0.290***	0.005
Aug. Precipitation	-0.281***	0.004
Sept. Precipitation	0.0153**	0.007
Oct. Precipitation	-1.264***	0.006
Winter Precipitation	-1.79e-06	0.000
Medium Soil Type	-0.141	0.113
Coarse Soil Type	1.529***	0.114

Notes: Significance at the 0.01, 0.05, and 0.1 levels denoted by ***, **, and * respectively