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The Effects of Irrigation and Climate on the High Plains Aquifer: A County-level Econometric Analysis

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Research Impact Statement: Results show the average net effect of irrigation in the High Plains Aquifer is a reduction in groundwater level of 0.47 feet per year. Climate change could significantly increase the rate of change.

ABSTRACT: The High Plains Aquifer (HPA) underlies parts of eight states and 208 counties in the central area of United States (US). This region produces more than 9% of US crops sales and relies on the aquifer for irrigation. However, these withdrawals have diminished the stock of water in the aquifer. In this paper, we investigate the aggregate county-level effect on the HPA of groundwater withdrawal for irrigation, of climate variables, and of energy price changes. We merge economic theory and hydrological characteristics to jointly estimate equations describing irrigation behavior and a generalized water balance equation for the HPA. Our simple water balance model predicts, at average values for irrigation and precipitation, an HPA-wide average decrease in the groundwater table of 0.47 feet per year, compared to 0.48 feet per year observed on average across the HPA during this 1985-2005 period. The observed distribution and predicted change across counties is in the (-3.22, 1.59) and (-2.24, 0.60) feet per year range, respectively. The estimated impact of irrigation is to decrease the water table by an average of 1.24 feet per year, while rainfall recharges the level by an average of 0.76 feet per year. Relative to the past several decades, if groundwater use is unconstrained, groundwater depletion would increase 50% in a scenario where precipitation falls by 25% and the number of degree days above 36°C doubles.

(KEYWORDS: High Plains Aquifer; water resource economics; water use; climate variability/change; irrigation, energy.)

INTRODUCTION

The High Plains Aquifer (HPA) underlies parts of eight states and 208 counties in the central area of United States, an area which produces nearly ten percent of U.S. crop value (National Agricultural Statistics Service, 2017). The HPA is the primary source of water for irrigation (Hutson et al., 2000) in these states. While irrigation can increase crop production by up to 50% in some counties in the HPA (García Suárez et al., 2019), these withdrawals have contributed to HPA depletion. Since the 1950s, HPA groundwater storage has declined eight percent, or 266 million acre-feet (McGuire, 2014).

The effect of groundwater withdrawal for irrigation on local areas of the HPA has been investigated by several papers that consider both hydrological characteristics and economic modelling (Brozović et al., 2010; Hendricks and Peterson, 2012; Pfeiffer and Lin, 2012; Kuwayama and Brozović, 2013; Palazzo and Brozović, 2014; Pfeiffer and Lin, 2014). These studies examine individual well data to quantify the effect of water pumping on depth to water and the effect of energy prices on the amount of water pumped and the area irrigated. Although these papers deliver important insights about the link between economic behavior and aquifer depletion they apply to small geographic areas of the aquifer. Yet for a resource stretched across eight states and accounting for an additional $3 billion in crops each year (García Suárez et al., 2019), it is also important to have an aquifer-wide assessment of the impact of irrigation behavior, prices, and climate. In the current paper, our objective is to use a hydro-economic framework to provide economic insights about the motivations for, and effect of user behavior on the aquifer at the scale of the entire HPA aquifer.

In this paper, we merge economic theory and hydrological information to jointly estimate a water balance equation and irrigation behavior, including the amount of water applied (the intensive margin) and the fraction of the surface area irrigated (the extensive margin). Our primary goal is to estimate economic behavior (irrigation decisions), while incorporating the hydrological response of the aquifer. We estimate these relationships using county level data from 183 counties over the entire HPA, during the 1985-2005 period. Our results allow conclusions about factors affecting water withdrawals at both intensive (per-acre irrigation water demand) and extensive (acres irrigated) margins. We use these results to examine the response of water levels to irrigation withdrawals as well as to adverse climate scenarios and energy price changes. These results complement previous studies and add new estimates of the potential effect of adverse climate on the HPA.

Our results indicate that relative to a no-irrigation scenario, at average conditions for the data set, irrigation has decreased the groundwater table by 1.24 feet per year while precipitation recharges it by 0.76 feet per year. We estimate that in a scenario where precipitation decreases by 25% and the amount of time at temperatures higher than 36^{o}C doubles, HPA depletion would increase by 50% relative to the average change during the past several decades if groundwater use is not constrained. The estimated price elasticity of water demand suggests that an increase of 25% in energy prices would decrease water withdrawn by 9%.

THE HIGH PLAINS AQUIFER

The High Plain Aquifer comprises more than 112 million acres under the states of Nebraska, Colorado, South Dakota, Kansas, Oklahoma, Texas, New Mexico and Wyoming, with water storage of 2.92 billion acre-feet in 2013 (McGuire, 2014). HPA counties in the states of Nebraska, Kansas, and Texas were responsible for 90% of the crop sales in the HPA region in

2016 (NASS/USDA, 2017). Irrigation has increased production dramatically in this region and the HPA has been the primary source of water for irrigation (Hutson et al., 2000).

In the northern area of the HPA both groundwater and surface water are jointly used to irrigate. In 2010, the state of Nebraska applied 4.8 million acre-feet from groundwater and 1.5 million acre-feet surface water (Maupin et al., 2014). Little or no depletion has been observed in counties where there is an interaction between ground and surface water and/or high levels of precipitation. Figure 1 displays our estimates of the accumulated county-level groundwater change from 1980 to 2010. To obtain these estimates we have summed yearly groundwater level change, which we measured using county averages of observed annual changes in wells' depth-to-water. The geographical distribution of our results resembles those presented in McGuire (2014) and Haacker et al. (2016). As shown in Figure 1, the highest levels of depletion have been observed in western Kansas, Texas, and New Mexico.

[Figure 1]

There are several reasons for the observed differences in county depletion rates across the HPA. There is a wide range of climatic and hydrological characteristics that affect both irrigation behavior and recharge rates. The eastern portion of the HPA receives higher annual precipitation, while the northern portion receives recharge from hydrologically connected surface water. The southern portion has more shallow saturated thickness (a measure of the vertical thickness of the aquifer), which affects the rate at which water can be withdrawn (Haacker et al. 2016). These factors led to irrigation disparities such as Nebraska counties in 2005 irrigating 44% of the surface area, while South Dakota counties irrigated less than 1%.

Groundwater recharge in the HPA has been modeled in the hydrological literature using different approaches. Sophocleous (2005) provides an extensive literature review on groundwater recharge for the HPA, including a discussion of differences across states. Szilagyi et al. (2003, 2005) investigate groundwater recharge in Nebraska using a water-balance approach. Szilagyi et al. (2003) focused on the estimation of the base recharge, the difference between total recharge and evapotranspiration. Szilagyi et al. (2005) estimate a mean annual total recharge in Nebraska from 3 to 163 mm per year, with a state average of 48 mm per year.

Another commonly used method is the chloride mass balance (CMB) approach, which estimates the chloride flux in-out looking at the chloride inputs (precipitation, irrigation, fertilizer). Scanlon et al. (2012) provide aquifer-scale analyses for the High Plains and California Valley using the CMB approach and MODFLOW, respectively. As in our paper, they use USGS wells data to estimate groundwater recharge for the High Plains. They estimate that total recharge for the HPA is 12 km^3 per year (8.6, 0.77, and 1.17 km^3 per year for Nebraska, Kansas, and Texas, respectively) and that average total depletion is 5.66 km^3 per year for the entire HPA.

Butler et al. (2016) use the simple water balance concept (water volume change is equal to the difference between inflow and pumping) to estimate the pumping level that would lead to a stable average water level (water volume change is zero). They use this approach in a small area of the HPA in Kansas, and argue that this approach is well-suited for areas where the aquifer is fairly deep. They find that a reduction in pumping of 22% (relative to actual pumping) between 1996 and 2013 would have led to an average stable water level in Kansas.

RELATED ECONOMIC LITERATURE

Papers in the literature have used theoretical modeling, simulations, and *ad hoc* specifications to investigate the relationship between irrigation behavior and groundwater level change. Brozović, Sunding and Zilberman (2010), Kuwayama and Brozović (2013), Palazzo and Brozović (2014) and Pfeiffer and Lin (2012) focused on spatial patterns of water levels due to interaction among well users.

Pfeiffer and Lin (2012) examined the effects of irrigation on groundwater level change over a small portion of the HPA in Kansas. They found that 100 acre-feet of water pumped induces an increase of 0.30 to 0.48 feet in depth-to-water, and they estimated rates of spillovers among well users (i.e. the impact of the *ith* unit’s withdrawals on the *jth* unit's depth-to-water). In a simpler setup, Rubin, Perrin and Fulginiti (2014) estimated a water balance equation for a set of 32 counties along the 41^{o} parallel in Nebraska using county data for the period from 1987 to 2008. Four alternative water balance equations were estimated, indicating that if a given area were converted from dryland to irrigated agriculture, under median precipitation in 2007, the water level would recede between 1.23 and 1.81 feet.

Water price, which typically refers to the cost of extracting groundwater and/or any irrigation district payments, affects irrigation pumping at both the intensive margin (water applied) and the extensive margin (acres irrigated). A number of papers have studied these price responses. Moore, Gollehon and Carey (1994) developed and estimated a system of equations that includes price response at the extensive and intensive margins, based on a land-constrained profit maximization approach. They found that the marginal effect of the price of water varies across regions of the U.S. and by crop produced. For the Central Plains (Colorado, Kansas, Nebraska and Wyoming), their results indicated that an increase of $1.00 in energy price would reduce applied water by 5.0 acre-feet per farm for alfalfa, but would increase applied water by 4.5 acre-feet per farm for corn (average water applied is 503 and 1,224 acre-feet per farm for alfalfa and corn, respectively). However, the only statistically significant short-run own-price demand elasticity for water they were able to obtain (for dry beans in the Central Plains), was of the wrong sign, equal to 0.21. Given the prevalence of positive estimates of short-run price elasticity, their results for this region are not plausible. Mullen and Hoogenboom (2009) have used this theoretical framework in farms in the southern region of the United States that produce corn, cotton, peanuts and soybeans. They present a negative water demand own-price elasticity for all crops but only for corn is own-price elasticity is statically significant, -0.17. Adusumilli, Rister and Lacewell (2011) found a statistically significant own-price elasticity for water demand only for soybean of -0.106 using the same theoretical framework applied to the Texas High Plains.

In western Kansas, Pfeiffer and Lin (2014) estimated an own-price water application elasticity of -0.26. For the same region, Hendricks and Peterson (2012) found an overall own-price water demand elasticity of -0.10, mainly driven by changes at the intensive margin, which has an elasticity of -0.09. However, Mieno and Brozović (2016) argued that measurement error has led to biased estimation of own-price elasticities and marginal effects in much of the previous work on groundwater demand. Schoengold, Sunding and Moreno (2006) found a direct own-price elasticity of -0.41 for surface water in a portion of California.

Precipitation affects the HPA directly through aquifer recharge and indirectly through water demand. Hendricks and Peterson (2012) and Pfeiffer and Lin (2012) found that an inch of precipitation decreases applied water by 0.28 acre-inches per acre and 3.7 acre-feet per farm, respectively. Pfeiffer and Lin (2012) also found a decrease in the depth to groundwater of around 0.20 feet per inch of precipitation. An adverse climate scenario in which yearly average precipitation decreases and/or average temperatures increase would generate higher demand for water (Hendricks and Peterson, 2012; Pfeiffer and Lin, 2012) and thus increase depth to groundwater (Pfeiffer and Lin, 2012). Trindade et al. (2011) and García Suárez et al. (2019)

found that crop damage from high temperatures is mitigated by irrigation, thus increasing the effect of warming on demand for aquifer water.

In this paper we estimate a simple county-level water balance equation for the entire HPA, a short-run water application demand, and a long-run demand for acres under irrigation. We followed the economic literature to estimate the water balance using econometric models incorporating the intensive and extensive margin effects of irrigation, and the effect of precipitation. This framework allows to estimate the effect of irrigation withdrawals on groundwater levels and make inferences about the effects of both climate change and price changes on irrigation withdrawals and groundwater levels in the HPA region.

THE MODEL

The groundwater balance equation is based on simple concepts of recharge and depletion. Precipitation represents groundwater recharge. Depletion is comprised of two components, water applied per acre irrigated (changes in water use at the intensive margin), and the proportion of the county area irrigated (changes in water use at the extensive margin). We represent year-to-year average groundwater level change across a county (δ) as

$$\delta = f(x_1, z_1, z_2) \tag{1}$$

where x_1 is quantity of water applied per acre irrigated in the county, z_1 is fraction of the surface irrigated, and z_2 is county precipitation.

We represent the farm technology and farmer irrigation behavior with a restricted profit function $\pi(\boldsymbol{p}, \boldsymbol{z})$. This function represents the maximum profit that can be obtained per acre of land given the vector of prices $\boldsymbol{p}$ for outputs $\boldsymbol{y}$ and inputs $\boldsymbol{x}$**,** and a vector **z** of other variables not under the control of individual decision makers (either exogenous such as weather, or quasi-fixed variables that are difficult to change within the crop year, such as the share of the land irrigated).

The input demands can be found using Hotelling's lemma

$$\frac{\partial \boldsymbol{\pi}(\boldsymbol{p},\boldsymbol{z})}{\partial p_i} = -x_i(\boldsymbol{p},\boldsymbol{z}) \tag{2}$$

where p_i represents the price of input x_i, indicating that the quantity demanded will depend on exogenous factors such as input and output prices, quasi-fixed factors, and weather. We accommodate the possibility that there may be a contemporaneous effect of price changes on the number of acres irrigated, implying a relaxation of the short-run constraint. Following Hendricks and Peterson (2012), we can express the effect of p_i, or any other element of $(\boldsymbol{p},\boldsymbol{z})$, on groundwater in terms of total water response elasticity as

$$\frac{\partial^2 \boldsymbol{\pi}(\boldsymbol{p},\boldsymbol{z}^*)}{\partial p_i \partial p_i}\frac{p_i}{x_i} = -\left[\frac{\partial x_i(\boldsymbol{p},\boldsymbol{z}^*)}{\partial p_i} + \frac{\partial x_i(\boldsymbol{p},\boldsymbol{z}^*)}{\partial z_j^*}\frac{\partial z_j^*}{\partial p_i}\right]\frac{p_i}{x_i} \tag{3}$$

where (3) represents the elasticity that incorporates the quasi-fixed input adjustments given the optimum level of z_j^*. The first term within the brackets represents the short-run price effect: the price effect at the intensive margin. The second term within the brackets incorporates the adjustments made in the fraction of land irrigated, a quasi-fixed input.

We are also interested in how prices and weather affect the HPA. The variable z_1 (fraction of surface irrigated) is a quasi-fixed input that depends on exogenous factors, $z_1 = h(\boldsymbol{p},\boldsymbol{z})$. In the literature, changes in $x_1(\boldsymbol{p},\boldsymbol{z})$ and $z_1(\boldsymbol{p},\boldsymbol{z})$ are commonly referred to as responses at the intensive and extensive margins, respectively. Denoting the price of water as p_1, we can decompose the effect of a change in the water price on the change in groundwater level as

$$\frac{\partial \delta}{\partial p_1} = \underbrace{\frac{\partial \delta}{\partial x_1(\boldsymbol{p},\boldsymbol{z}^*)}\frac{\partial x_1(\boldsymbol{p},\boldsymbol{z}^*)}{\partial p_1} + \frac{\partial \delta}{\partial z_1^*}\frac{\partial z_1^*}{\partial p_1}}_{\text{Direct Price Effect}} + \underbrace{\frac{\partial \delta}{\partial x_1(\boldsymbol{p},\boldsymbol{z}^*)}\frac{\partial x_1(\boldsymbol{p},\boldsymbol{z}^*)}{\partial z_1^*}\frac{\partial z_1^*}{\partial p_1}}_{\text{Indirect Effect}}\ , \tag{4}$$

where the first two terms represent the short-run or direct price effect and the second term represents the long-run or indirect effect i.e., changes at the extensive margin on per-acre water demand.

Regarding the effect of weather on the HPA, precipitation and other weather variables may affect groundwater level directly through recharge, and indirectly by changing the demand for irrigation. We denote precipitation as z_2 and temperature as z_3. Their impacts on aquifer water level can be decomposed as

$$\frac{\partial\delta}{\partial z_2} = \frac{\partial\delta}{\partial x_1(\boldsymbol{p},\boldsymbol{z}^*)}\left[\frac{\partial x_1(\boldsymbol{p},\boldsymbol{z}^*)}{\partial z_2} + \frac{\partial x_1(\boldsymbol{p},\boldsymbol{z}^*)}{\partial z_2}\frac{\partial z_1^*}{\partial z_2}\right] + \frac{\partial\delta}{\partial z_1}\frac{\partial z_1^*}{\partial z_2} + \frac{\partial\delta}{\partial z_2} \tag{5'}$$

$$\frac{\partial\delta}{\partial z_3} = \frac{\partial\delta}{\partial x_1(\boldsymbol{p},\boldsymbol{z}^*)}\left[\frac{\partial x_1(\boldsymbol{p},\boldsymbol{z}^*)}{\partial z_3} + \frac{\partial x_1(\boldsymbol{p},\boldsymbol{z}^*)}{\partial z_1}\frac{\partial z_1^*}{\partial z_3}\right] + \frac{\partial\delta}{\partial z_1}\frac{\partial z_1^*}{\partial z_3} \tag{5''}$$

where equation (5’) represents the precipitation effect and (5’’) the temperature effect on change in water levels. We expect that an increase in precipitation will decrease the rate of depletion, while an increase in temperature will have the opposite effect.

EMPIRICAL STRATEGY

Data

For the 208 counties that overlay the High Plains Aquifer, we obtained annual data on output and input prices, and acres irrigated for the 1980-2010 period from the National Agricultural Statistical Service (NASS/USDA) and the Economic Research Service (ERS/USDA). We obtained estimates of county-level water use from the U.S. Geological Survey (USGS), which are determined every five years (USGS, 2017). Because depth-to-water was not available for all years in all counties, the dataset we analyze includes 183 counties[1] in 1985, 1990, 1995, 2000 and 2005, giving us 915 observations. . Table 1 displays descriptive statistics of the variables for this balanced panel. The 25 counties excluded are distributed across the states as follows: Colorado (4), Kansas (5), New Mexico (1), Oklahoma (1), South Dakota (1), Texas (9), and Wyoming (4). The average water applied (share of land irrigated) in these counties is about 8% (28%) lower than the average of the counties included in the analysis.

The county output price for a given year, from García Suárez et al. (2019), was calculated as the market value of all crops produced in the county, divided by the total tons of biomass produced. This output price considers the major crops in the HPA: barley, beans, corn, hay, oats, potato, rye, sorghum, soybeans, sugar beets, sunflower and wheat. We divide input prices by the output price to obtain normalized prices (table 1). Fertilizer and chemical price indexes obtained from García Suárez et al. (2019), are for the United States as a whole, and thus vary only by year.

Water price was calculated as shown in Eq. 6, which is an adaption of the cost of lifting the water from the aquifer in Hendricks and Peterson (2012), adapted so as to match the definition of dynamic cost of lifting given by Mieno and Brozović (2016):

$$p_1 = \sum_{f=1}^{3} s_f * c_f * w_f * (33.05 + 1.07 * h_i) \tag{6}$$

where p_1 is the water price, or marginal cost of pumping water, s_f is the share of fuel f in the energy used (natural gas, electricity and diesel), c_f is a constant for fuel f from Rogers and Alan (2006), w_f is fuel price and h_i is county average well depth to water. The term in brackets captures the dynamic cost of lifting, where the pumping depth is actually greater than the depth to the water table, h_i. The two constants, 33.05 and 1.07, were obtained from a regression of static well depth on pumping well depth using the groundwater wells database collected by the Nebraska Department of Natural Resources, which includes all groundwater irrigation wells in Nebraska (Nebraska Department of Natural Resources, 2018). Rogers and Alan (2006) estimate that the fuel required to lift one acre-foot of water one foot in height is 1.551 kWh for electricity, 0.0223 mmbtu for natural gas, 0.1098 gallons for diesel and 0.1993 cubic feet for propane. We calculate the shares of each fuel, s_f, using FRIS data on the number of acres irrigated from each fuel type. We follow Hendricks and Peterson (2012) and use the fuel prices for the industrial sector from the United States Energy Information Administration (EIA) as the proxy for energy price. Mieno and Brozović (2016) find that error in measurement of this variable leads to bias in the estimate of water price elasticity. We recognize this limitation, but data to correct this only exists for limited areas, and not for the full HPA region, so we make no such correction to this measure of energy price.

[Table 1]

Average well depth-to-water, available for thousands of wells from the USGS NWIS database (United States Geological Survey, 2017), is used to develop our proxy for average annual groundwater change in the county. We take the average of *changes* in depth-to-water from individual wells to obtain a county average estimate of change in depth-to-water. This process, explained in detail in Sims (2017), followed a four-step procedure.

1. Wells selected were those for which depth to water was measured during the non-irrigation season (i.e., between October of year *t* and May of year *t+1*) for two successive seasons. The algorithm we use requires that observations in successive years be within

one month of each other (e.g., an October observation can be matched with a November observation, but not with a December or January observation).

2. If the well was monitored more than once in each period, observations were averaged.
3. For each well the change in water level (the negative of change in depth to water) during period *t* was calculated as $\delta_{jt} = -(h_{jt} - h_{jt-1})$, where h_{jt} refers to the depth to water in well *j* period *t* and where *t* refers to measurements taken after crop year *t*.
4. The average water level change (δ_{it}) per county was calculated; for county *i* we obtained $\delta_{it} = \sum_{j=1}^{K} \delta_{jt}/K$, where *K* is the number of wells per county (the number of wells per county, *K*, ranged from 1 to 351, with an average of 43).

We recognize that a larger number of wells are more likely to provide a representative measure of the average water level change for the county. Unfortunately, in some counties only a few observations were available. In our dataset (915 observations), in fewer than 50 observations was water level change based on fewer than four wells, and for 18 observations the variable was constructed using only one well. Since our methodology requires a balanced sample, dropping observations constructed with less than four wells would reduce our sample from 183 to 163 counties. Thus, we choose to keep all observations. As a robustness check we estimate the full system of equations for the 163 counties with at least four wells in every period. Results were quite similar to the full sample. For example, the own-price elasticity of water demand is almost the same (-0.385 vs -0.379).

A negative value of δ_{it} indicates depletion of the aquifer, while a positive value indicates recharge. Figure 1 displays the calculated accumulated groundwater change using this method ($\sum_{t=1}^{T'} \delta_{it}$, where T' is the number of years in the period 1981-2010). The average accumulated groundwater change from 1981 to 2010 is -6.74 feet (Figure 1). By way of comparison, McGuire

(2014) estimates the HPA average water level change to be -15.4 feet from predevelopment (before 1950) to 2013. USGS (2017) reports a depletion of -9.9 feet from predevelopment to 1980, and an additional -2.39 feet from 1980 to 1995. McGuire (2011) reports an HPA average annual water level change of -0.1 and -0.3 feet for the individual years 2007/08 and 2008/09, respectively, whereas our calculations indicate changes of -0.1 and -0.2 feet respectively for these two years. Using the sample years 1985, 1990, 1995, 2000, and 2005, we calculate an average annual groundwater depletion of 0.48 feet for our study area. Using the same years, counties in New Mexico, Texas, and Kansas have annual average depletions of 1.35 feet, 0.57 feet and 0.51 feet, respectively.

We calculate the water applied per acre based on the total quantity of water used for irrigation by county from the USGS, reported by Maupin et al. (2014) for 1985, 1990, 1995, 2000 and 2005. The area irrigated is also available from the USGS based on Maupin et al. (2014). We normalize the area irrigated by the total planted area of a county to calculate the fraction of the county surface area that is irrigated (range of [0, 1]). Figure 2 displays 2005 levels of both of these variables. Counties in Texas, northeast New Mexico, and the eastern part of Nebraska have higher fractions of area irrigated while counties in the western part of the HPA have higher rates of application.

[Figure 2]

Weather variables at the county level are from Trindade (2011) and García Suárez et al. (2019), who used a spatial averaging technique for daily weather data from the five reporting stations closest to the county center. A daily index for each of the 208 counties was built using weights equal to the inverse distances of the center of the county to the station. We use their estimates of precipitation and degree days. Degree days are the amount of time (measured in days) during the growing season that the crops were exposed to a particular degree interval. In our empirical analysis we measure temperature as the number of degree days over 36°C, because García Suárez et al. (2019) showed a rapid yield decline in this region due to temperatures above this threshold. Figure 3 displays precipitation and degree days above 36°C for 2005. Not surprisingly, counties in the eastern part of the HPA have higher levels of precipitation. A relatively high number of degree days above 36°C is observed in both the southern and eastern portions of the HPA.

[Figure 3]

Estimation

The equation we estimate for groundwater change is:

$$\delta = \beta_{1,x_1} x_1 + \beta_{1,z_1} z_1 + \beta_{1,z_2} z_2 + \epsilon_1 \tag{7}$$

where subscripts *i* for counties and *t* for time are dropped for simplicity. δ represents groundwater level change, x_1 represents water applied per acre, z_1 represents fraction of land irrigated and z_2 represents precipitation. The parameters, β_{1,x_1}, β_{1,z_1} and β_{1,z_2} are to be estimated and ϵ_1 are idiosyncratic errors. The coefficients β_{1,x_1}, β_{1,z_1} and β_{1,z_2} represent the marginal effect of water applied, share of land irrigated, and precipitation on groundwater change. For instance, an increase of one inch of precipitation would increase the groundwater level by β_{1,z_2}. Equation (7) does not have a constant, since including a constant would imply that groundwater level change is non-zero, even in a situation with no precipitation ($z_2 = 0$), no water applied per acre ($x_1 = 0$) and no land irrigated ($z_1 = 0$). The formulation of Eq. (7) defines the groundwater change as a function of these factors and a random error, ϵ_1. Following the literature, we did not consider a direct effect of temperature, z_3, on groundwater change.

However, it affects groundwater change indirectly through the amount of water applied per acre and share of land irrigated (see Eq. (8) and (9)). All variables are defined explicitly in Table 1.

Our estimation of the groundwater change equation uses explanatory variables from the same period as the change in groundwater level. We recognize that the precipitation that falls in a particular year may not be the same physical water as the water that reaches the aquifer. However, for our approach that is not necessary. What is necessary is that there exists a high correlation between precipitation and aquifer recharge, after ignoring the effect on irrigation behavior. Recent work (Whittemore et al, 2016) has analyzed the empirical relationship between weather variables and groundwater level changes in Kansas. They find that irrigation behavior is a significant factor in explaining the correlation, but that the correlation exists even for non-growing season measures, and suggests a physical relationship between groundwater level and precipitation (specifically, SPI) that is distinct from the effect on irrigation behavior. In addition, other theoretical work, as documented in the UFZ package for MODFLOW (Niswonger et al, 2006) shows that recharge is frequently modeled as an event that pushes water through the vadose zone to the groundwater table. Finally, we have empirically tested our data and estimated the change in groundwater level as a function of current season precipitation and lags of precipitation. The addition of lagged measures had no measurable change in the coefficient on current season precipitation, and a negligible effect on overall model fit.

For behavioral relationships, we specify a quadratic restricted profit function, which yields input demands (equation 8) that are linear in normalized input prices, quasi-fixed inputs and weather variables. We estimate:

$$x_1 = \beta_{2,c} + \beta_{2,p_1}p_1 + \beta_{2,p_2}p_2 + \beta_{2,p_3}p_3 + \beta_{2,z_1}z_1 + \sum_{q=1}^{4} \beta_{2,z_{2q}} z_{2q} + \beta_{2,z_3}z_3 + \boldsymbol{\beta_2} + \epsilon_2 \qquad (8)$$

where p_1, p_2 and p_3 are normalized water, fertilizer and chemicals prices, z_{2q} represents precipitation in q = 4 quarters (the last quarter of year $t-1$ and the first three quarters of year t), z_3 represents temperature (degree days), $\boldsymbol{\beta_2}$ is a vector of parameters, including county fixed effects, ϵ_2 are idiosyncratic errors, and all other variables are defined previously.

For the quasi-fixed factor, we estimate the demand for fraction of surface land under irrigation:

$$z_1 = \beta_{3,c} + \beta_{3,p_1}p_1 + \beta_{3,p_2}p_2 + \beta_{3,p_3}p_3 + \beta_{3,z_2}z_2 + \beta_{3,z_3}z_3 + \boldsymbol{\beta_3} + \epsilon_3 \tag{9}$$

where $\boldsymbol{\beta_3}$ is a vector of estimated parameters, including county fixed effects, and ϵ_3 are idiosyncratic errors. Note that z_2 is annual precipitation (the fourth quarter of the year $t-1$ and the first three quarters of year t). We estimate equations (7), (8) and (9) jointly using Seemingly Unrelated Regression, to take advantage of potential contemporaneous correlation among error terms. The county-level fixed effects that are included in equations (8) and (9) will account for county-level differences that are fixed over time. This will account for some of the differences in governance (e.g., irrigation district, state).

Changes in groundwater due to changes in irrigation at the intensive and extensive margins are identified as

$$\frac{\partial \delta}{\partial x_1} = \beta_{1,x_1}, \qquad \frac{\partial \delta}{\partial z_1} = \beta_{1,z_1}, \qquad \frac{\partial \delta}{\partial z_1^*} = \beta_{1,z_1} + \beta_{1,x_1}\beta_{2,z_1} \tag{10}$$

where the first and second expressions represent the direct (short-run) effect of the intensive and extensive margins on groundwater level. The last expression represents the total extensive margin effect, which incorporates adjustment effects through the intensive margin (water demand), $x_1(\boldsymbol{p}, \boldsymbol{z}^*)$. The total (long-run) effect of irrigation on groundwater level is calculated by adding the first and third expressions evaluated at a specific level of these variables.

The effect of water price on groundwater levels are obtained by evaluating equation (4) using the estimated coefficients and parameter values, as shown in equations (11') and (11'').

$$\frac{\partial \delta}{\partial p_1} = \frac{\partial \delta}{\partial x_1(\boldsymbol{p}, \boldsymbol{z}^*)}\left[\frac{\partial x_1(\boldsymbol{p}, \boldsymbol{z}^*)}{\partial p_1} + \frac{\partial x_1(\boldsymbol{p}, \boldsymbol{z}^*)}{\partial z_1^*}\frac{\partial z_1^*}{\partial p_1}\right] + \frac{\partial \delta}{\partial z_1^*}\frac{\partial z_1^*}{\partial p_1} \tag{11'}$$

$$= \{\beta_{1,x_1}[\beta_{2,p_1} + \beta_{2,z_1}\beta_{3,p_1}] + \beta_{1,z_1}\beta_{2,p_1}\}. \tag{11''}$$

Economic theory requires that $\beta_{2,p_1} < 0$ (i.e., an increase in the lifting cost will lead to a decrease in water applied per acre). Aquifer characteristics require that $\beta_{1,x_1} < 0$ and $\beta_{1,z_1} < 0$, which implies that increasing water applied per acre and land irrigated leads to a increase in groundwater depletion. We expect that $\beta_{3,p_1} \leq 0$, or that an increase in contemporaneous cost of lifting does not increase the share of land irrigated. The coefficient may be zero if an irrigator has limited foresight about energy prices and limited ability to adjust the land under irrigation after energy prices are observed. The sign of β_{2,z_1} is ambiguous. Overall, we expect $\partial\delta/\partial p_1 > 0$, which means that an increase on water price would save groundwater, that is, decrease groundwater depletion.

Although the most interesting results of this paper relate to the impact of irrigation withdrawals and of prices on groundwater depletion, we illustrate the usefulness of the approach by estimating weather effects. These are evaluated as in equations (5') and (5'') using the parameters estimated by the system of equations (7) to (9). The marginal effect of a change in precipitation on groundwater is captured by

$$\frac{\partial \delta}{\partial z_2} = \left\{\frac{\partial \delta}{\partial z_2} + \frac{\partial \delta}{\partial x_1(\boldsymbol{p}, \boldsymbol{z}^*)}\left[\frac{\partial x_1(\boldsymbol{p}, \boldsymbol{z}^*)}{\partial z_2} + \frac{\partial x_1(\boldsymbol{p}, \boldsymbol{z}^*)}{\partial z_1^*}\frac{\partial z_1^*}{\partial z_2}\right] + \frac{\partial \delta}{\partial z_1^*}\frac{\partial z_1^*}{\partial z_2}\right\} \tag{12'}$$

$$= \{\beta_{1,z_2} + \ \beta_{1,x_1}[\beta_{2,z_2} + \beta_{2,z_1}\beta_{3,z_2}] + \beta_{1,z_1}\beta_{3,z_2}\} \tag{12''}$$

where the first term on the right captures the direct effect of precipitation through groundwater recharge, the second term is an indirect effect through increased irrigation (the intensive margin), and the third term is an additional indirect effect through an increase in area irrigated (the extensive margin). While the estimation allows us to separate these factors, a reduction in precipitation is expected to lead to higher depletion overall, given that it will decrease recharge and increase water demand.

The marginal effect of higher temperatures on groundwater level, as captured by a change in degree days, is

$$\frac{\partial \delta}{\partial z_3} = \frac{\partial \delta}{\partial x_1(\boldsymbol{p}, \boldsymbol{z}^*)}\left[\frac{\partial x_1(\boldsymbol{p}, \boldsymbol{z}^*)}{\partial z_3} + \frac{\partial x_1(\boldsymbol{p}, \boldsymbol{z}^*)}{\partial z_1}\frac{\partial z_1^*}{\partial z_3}\right] + \frac{\partial \delta}{\partial z_1}\frac{\partial z_1^*}{\partial z_3} \tag{13'}$$

$$= \left\{\beta_{1,x_1}\left[\beta_{2,z_3} + \beta_{2,z_1}\beta_{3,z_3}\right] + \beta_{1,z_1}\beta_{3,z_3}\right\} \tag{13''}$$

where the first term is the effect of higher temperatures through higher irrigation rates (the intensive margin) and the second is the effect through change in area irrigated (the extensive margin).

RESULTS AND DISCUSSION

We jointly estimate the groundwater balance equation, water demand, and the proportion of area irrigated using Seemingly Unrelated Regression (SUR). We also estimate Equations (7), (8) and (9) separately and, then, clustered the errors at state level. Estimated parameters differ slightly from the SUR estimation given that these equations are first estimated separately and assume no correlation among errors of the equations. The Breusch-Pagan (BP) test, with a calculated value of 9.79, indicates that the disturbance covariance matrix is not diagonal at 5% level of significance leading to the contemporaneously correlated error structure in the seemingly unrelated regression choice. Thus, we present the estimated parameters from the SUR estimation in Table 2.

[Table 2]

As expected, increases in irrigation at the intensive and extensive margins deplete the aquifer and precipitation recharges the aquifer. Our findings suggest that an increase of one inch of precipitation would lead to a decrease in groundwater depletion of 0.036 feet, everything else constant (see Table 2). At the average value of 21.25 inches per year, the effect of precipitation is to increase groundwater level by 0.76 feet per year (= 0.036 x 21.25 inches). Our estimate of the water balance equation predicts an average decrease in the groundwater table across the HPA of 0.47 feet per year (at the average application rate and irrigated area), compared to the observed rate of 0.48 feet per year across the time period, however, there is significant variation in these measures. Figure A1 in the Appendix provides a scatterplot of the predicted versus observed change. The best fit line is close to the 45 degree line, with a slope of 0.896 and an intercept of -0.066. However, there is significant variance in the estimate, with estimated values generally in the [-2.5, 1] range, while actual values are in the [-9, 9] range. However, the number of observations with a large absolute value is small (only 40 out of 915 observations have an absolute value over 3), so the fit is reasonably good for more typical values of groundwater change.

The combined effect of current irrigation application rate and current area irrigated is to reduce the groundwater level by 1.24 feet per year. Precipitation, especially in the first two quarters, also affects water applied per acre. An increase of one inch in each of the first two quarters reduces water applied by 0.06 acre-feet per acre. On the other hand, an increase of one degree day over 36°C increases water applied by 0.073 acre-feet per acre. Below we discuss the marginal effects described in the previous section. The empirical results presented in Table 3, along with the formulas presented in Table A1, complement this interpretation.

We find a negative own-price response in the water demand estimation. Using Equation (3) and the results in Table 2, we estimate the own-price elasticity of water demand to be -0.367 at the intensive margin, and -0.378 after incorporating the extensive margin. Both elasticities are statistically significant at the 1% level. These elasticities are larger than estimates reported by Hendricks and Peterson (2012) and Pfeiffer and Lin (2014). However, our study area of 183 counties over the entire HPA covers a significantly larger region than previous work, and these studies have not incorporated the dynamic cost of lifting water**.**

$$\frac{\partial^2 \boldsymbol{\pi}(\boldsymbol{p}, \boldsymbol{z}^*)}{\partial p_i \partial p_i} \frac{p_i}{x_i} = -\left[\frac{\partial x_i(\boldsymbol{p}, \boldsymbol{z}^*)}{\partial p_i} + \frac{\partial x_i(\boldsymbol{p}, \boldsymbol{z}^*)}{\partial z_j^*} \frac{\partial z_j^*}{\partial p_i}\right] \frac{p_i}{x_i}$$
$$= -[3.679 + 0.146 * 0.708] * \left(\frac{0.112}{1.122}\right) \cong -0.378$$

Revisited Eq. (3)

The estimated coefficients of our model reflect relationships among variable levels that occurred over the 1985-2005 time period, and thus the model results are most useful for predicting marginal effects within those ranges. Our estimates of the marginal effects of irrigation on groundwater at the intensive and extensive margins are in Table 3. Using the notation from equations (7), (8), and (9), the formulas used to calculate the values in Table 3 are in Appendix Table A1.

[Table 3]

Results show that a 10% reduction in average application rate, from 1.12 feet to 1 foot, is predicted to reduce the rate of groundwater level decline by 1 inch per year, with precipitation and area irrigated unchanged (this is calculated by evaluating (1.12-1.0)*0.741=0.088 feet, or approximately, 1 inch). Similarly, a 10% decrease in area irrigated, with application rate and precipitation unchanged, is predicted to reduce the rate of groundwater level decline by 1.5 inches (0.127 feet) per year. Empirical results predict that a full conversion of cropland in a county from rain-fed to irrigated production (the extensive margin) would increase the rate of groundwater level decline by 1.27 feet per year, when evaluated at mean values of other variables.

The full effect of precipitation on groundwater change is calculated using equation (12'). The total marginal effect of an additional inch of precipitation is a reduction in groundwater depletion of 0.041 feet per year. The direct and indirect marginal effects are 0.036 feet and 0.004 feet, respectively. Thus our total recharge estimates for individual counties, multiplying equation (12') by the observed average precipitation by county, range from 0.03 to 1.95 feet per year. USGS (2017) suggests that potential recharge from precipitation and irrigation return ranges from 0.38 inches in the western portion of the HPA to 6 inches in the eastern portion of the HPA.

Temperature changes will affect groundwater level through water demand (intensive margin) and proportion of land under irrigation (extensive margin) as in equation (13'). Our estimate of the total marginal effect of temperature is that an extra 24 hours of temperature above 36^{o}C would lead to an additional 0.056 feet of depletion per year.

Climate Change

The Third National Climate Assessment (Shafer et al., 2014) suggests that climate change will cause lower precipitation rates and higher temperatures (resulting in a higher level of evapotranspiration) in the Southern High Plains, which will drive an increase in irrigation demand. Shafer et al. (2014) project that hotter days (over 100^{o}F) will double in the northern portion of the Great Plains and will quadruple in the southern portion of the Great Plains by mid-century. Kunkel et al. (2013) forecasted an increase of more than 20 days with maximum temperatures higher than 95^{o}F in the southeast area of the Great Plains and a smaller increase, of

10 days or less, in the northern area, by 2055. Over the entire region, this report predicts for 2041-2070 an average increase of 20 days with a maximum temperature higher than 90^{o}F, under their high emission scenario. Overall, these studies suggest an increase in hotter days and a decrease in precipitation for this region. The impact of climate change on agricultural production has been analyzed in a range of economic studies as well. However, many of those studies (e.g., Schlenker, Hanemann, and Fisher, 2006; Schlenker and Roberts, 2009) focus on rain-fed agricultural production. In regions that use surface water irrigation, decreased availability of irrigation water under climate change is also expected to reduce agricultural production (Schlenker, Hanemann, and Fisher, 2007). There is significant evidence (e.g., Trindade, 2015) that when irrigation is available (such as with groundwater), it can mitigate the impact of climate change on agricultural productivity.

We model potential impacts of climate change by predicting the effects of a hotter and drier climate on irrigation use and groundwater levels. Three scenarios were designed, all of which are consistent with potential impacts of climate change outlined in Bathke et al. (2014):

Scenario 1: 50% increase in the average amount of time with temperature higher than 36^{o}C, with average precipitation.

Scenario 2: 50% increase in the average amount of time with temperature higher than 36^{o}C and a decrease of 25% in average precipitation.

Scenario 3: 100% increase in the average amount of time with temperature higher than 36^{o}C and a decrease of 25% in average precipitation. This is consistent with predicted changes in temperature (Bathke et al., 2014).

For each of these scenarios we evaluate how irrigation behavior (intensive and extensive margins) and groundwater level change under a uniform change in temperature and precipitation for all counties in the HPA. Table 4 presents the results of this analysis, which we illustrate using the results from *Scenario 2*, using formulas shown in Appendix Table A2. To obtain the effect of a 50% increase in the number of degree days above 36ºC, we use equation (13”) and increase the observed degree days above 36ºC in all counties and all years by 50%. This induces an increase in water demanded. A similar approach is used for precipitation using equation (12”) and a decrease in precipitation of 25%. A decrease in precipitation reduces recharge and increases water demanded. We stress that these results are an upper bound on the impact of climate change, as they assume that there are no new constraints imposed on groundwater extraction. Likely constraints that might be enacted under this scenario include both physical (e.g., well yield) and policy (e.g., allocations) limitations.

[Table 4]

Our results predict a potentially severe effect of climate change on groundwater levels. We estimate an increase in the annual rate of groundwater depletion of 0.02 feet, 0.22 feet, and 0.24 feet under Scenarios 1, 2, and 3, respectively. Scenarios 2 and 3 predict fairly significant impacts when compared to the average groundwater change of 0.48 feet per year for our study period. These estimates incorporate changes at both the extensive and intensive margins. For Scenario 1, an increase of 50% in degree days above 36C, keeping precipitation constant, increases average water applied (x_1) by 2.% (= 0.022/1.12) and land irrigated (z_1) by less than 1%. This implies an increase in depletion of 0.017 feet per year, which is a 3.5% (= 0.017/0.48) increase in the annual average groundwater change. In Scenario 2, groundwater depletion increases to 45% (= 0.22/0.48) of the annual average groundwater change. Groundwater depletion increases by 50% (0.24 feet) in Scenario 3 where the number of days with temperature higher than 36ºC double and precipitation decreases 25%.

To obtain a measure of the climate change effect on the volume of water across the entire High Plains Aquifer, we note that the HPA comprises 112 million acres (McGuire, 2014). Using the Scenario 2 results and an average specific yield of 15%, climate change would increase the rate of depletion by an additional 0.22 feet per year, for a total of about 3.7 million acre-feet per year (= 0.22 feet per year x 0.15 x 112 million acres). This is about 20 percent of the total 18.5 million acre-feet (USGS, 2017) extracted for HPA irrigation in 2005.

Energy price effects on groundwater depletion

We model potential impacts of water price changes on groundwater using equation (11'') and the average price of water. Three different scenarios were considered: a 10%, a 25%, and a 50% increase in the average water price. Table 5 displays the outcome of this analysis. A 10% increase in water price is expected to decrease the average rate of annual depletion by 0.031 feet. The total effect, which includes the extensive margin, would decrease depletion by 0.042 feet per county per year.

[Table 5]

Changes in water price affect the cost of production and producer surplus. This change has two components. First, a movement along the demand schedule for water applied, and second, a shift of that schedule caused by an extensive margin (share of land irrigated) adjustment. Both effects are captured by the estimated elasticity of -0.378. The welfare impact is calculated for each county by identifying the reduction in irrigators' surplus.

To approximate the irrigators' welfare impact of a price increase we use the average county area irrigated of 92,176 acres and the average water price of US$ 10.06 in 2005. The average loss in irrigators' surplus per county can be calculated using Eq. (14), which is measured as the size of the area under the derived demand between the new and old price:

$$Av\ County\ Loss = \left[\Delta p_1 * x_1 + \frac{\Delta p_1 * \Delta x_1}{2}\right] * (Av\ irrigated\ acres) \tag{14}$$

We estimate the total welfare loss as $HPA\ Loss = Av\ County\ Loss * 183\ counties$. This is the dollar value of the total loss in irrigators' surplus over the entire HPA. For a water price increase of 25%, the average size county would lose $242,618 in surplus, while the HPA region would lose $44,399,094 (an amount less than 1% of the estimated crop revenue in 2005). We estimate that a water price increase of 25% would reduce groundwater depletion by 1,747,200 acre-feet per year (= 0.104 x 0.15 x 112 million acres), or about 9.4% (= 1,747,200/18,554,714) of the water withdrawn for irrigation in 2005 (USGS, 2017). Note that our estimates assume that farmers do not adopt new technologies and strategies to overcome the higher cost of lifting (prices). Therefore, the welfare loss we calculate due to this price increase is an upper bound.

CONCLUSIONS

This paper contributes to knowledge necessary for management of groundwater in the High Plains Aquifer (HPA). We provide aquifer-scale estimates, not previously available, of the effects of irrigation, climate change and energy prices on the rates of groundwater depletion, by county across the entire HPA. We achieve this by estimating a system of equations that includes a groundwater water balance equation, a demand equation for water applied per acre irrigated, and a demand equation for the fraction of land irrigated. Since our results are estimated with a consistent methodology across the entire HPA, and allow us to separate the effects of climate from irrigation behavioral responses, they provide a useful picture of where policymakers may expect to observe changes in groundwater levels and groundwater irrigation if no additional policies are enacted. To estimate this system, we merged hydrologic, climatic, and economic information for 183 counties over the period 1985-2005. The estimates of changes in HPA water levels using this HPA-wide econometric analysis correspond well to comparable estimates from the hydrological literature.

Our results indicate that under current circumstances, the HPA groundwater table is decreasing on average at the rate of 0.47 feet per year, with considerable variation across counties over the HPA. We estimate that under average conditions a 10% increase in the average application rate, ceteris paribus, would result in a one-inch annual decline in the water table, while a 10% increase in irrigated surface area would result in a 1.5 inch annual decline. We estimate a long-run water demand elasticity of -0.378. To demonstrate the usefulness of predictions from the model, we estimate that climate change projections to 2050 could increase the rate of depletion of HPA groundwater by as much as 50% if irrigators have no additional constraints on groundwater pumping. Any pumping limitations are likely to come at either the irrigation district or state level, and not cover the entire aquifer. Because we assume that the climate change conditions we consider would engender constraints on pumping, our estimates are an upper bound on the impact of climate change, but they are reasonable estimates for portions of the aquifer that lack the political motivation to implement new groundwater use restrictions.

A contribution of our work is that the structural estimation with limited location-specific variables allows a comparison of expected changes in groundwater levels and irrigation behavior across a large area with intensive irrigated agricultural production. However, we recognize that the methodology precludes us from incorporating some of the location-specific variables that are important for understanding irrigation behavior at a highly disaggregated level. For example, our analysis does not incorporate differences across the region in well yield, although there is evidence that managing well yield is an important factor in some areas of the HPA. Our analysis also lacks an analysis of institutional changes that occurred at local level, as our methodology does not allow us to incorporate time-varying and specific localized changes during the period analyzed (1985 to 2005). However, this period precedes many of the recent groundwater policies that have been enacted in states across the HPA (see Guerrero et al. 2017 and Schoengold and Brozović, 2018 for a review of these changes), and the methodology does incorporate geographical factors that are constant over time (e.g., soil measures) through the use of county fixed effects. Thus, we do not expect a significant bias in our results due to changes in local policies during the study period, and we leave the detailed analysis of local policies for future work.

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FIGURES AND TABLES

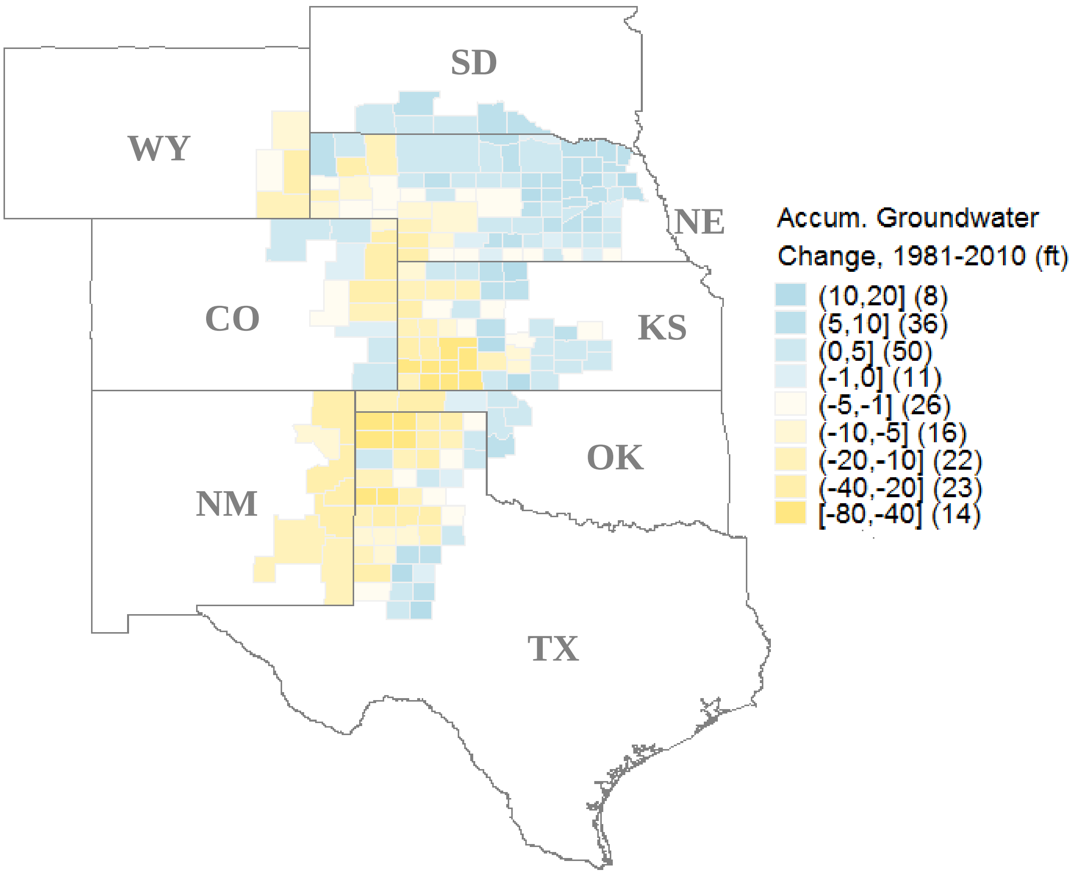

Figure 1. Accumulated groundwater change (in feet) in the High Plains aquifer from 1981 to 2010 as calculated by this study, based on county averages of change in well depth to water. The numbers in parentheses are the number of counties in each category.

Table 1. Mean, standard deviation, minimum and maximum of the variables used to estimate the system of equations (6) to (8) for the High Plains aquifer for years 1985, 1990, 1995, 2000, and 2005.

Variable	Units	Variable	Mean	Std. Dev.	Min	Max
Annual Groundwater Change	Feet	δ	-0.49	1.39	-9.17	8.83
Application Rate[a]	Acre-feet	x_1	1.12	0.48	0.00	3.87
Fraction of land irrigated [b]	Proportion [0,1]	z_1	0.32	0.22	0.00	0.91
Water price	$/acre-foot	p'_1	6.20	2.76	2.43	22.24
Fertilizer price	Price index	p'_2	117.40	23.86	97.00	162.00
Output price	$/ton	p'_3	58.54	13.69	29.89	147.06
Chemicals price	Price Index	p'_4	108.80	13.59	90.00	123.00
Normalized Water price	$/acre-foot	p_1	0.11	0.06	0.02	0.45
Normalized Fertilizer price	Price Index	p_2	2.08	0.53	0.75	3.68
Normalized Chemicals price	Price Index	p_3	1.93	0.40	0.73	4.01
Annual precipitation	Inches	z_2	21.25	5.38	2.04	40.41
Precipitation Quarter 1	Inches	z_{21}	3.12	1.57	0.15	11.17
Precipitation Quarter 2	Inches	z_{22}	8.48	3.41	0.09	23.57
Precipitation Quarter 3	Inches	z_{23}	6.74	2.57	0.06	18.86
Lag Precipitation Quarter 4	Inches	z_{24}	3.09	2.34	0.10	12.29
Degree Days > 36^{o}C	24-hour days [c]	z_3	0.61	0.50	0.00	2.89

[a] Application rate per acre
[b] Share of cropland irrigated
[c] Hours of temperature in excess of 36^{o}C, divided by 24

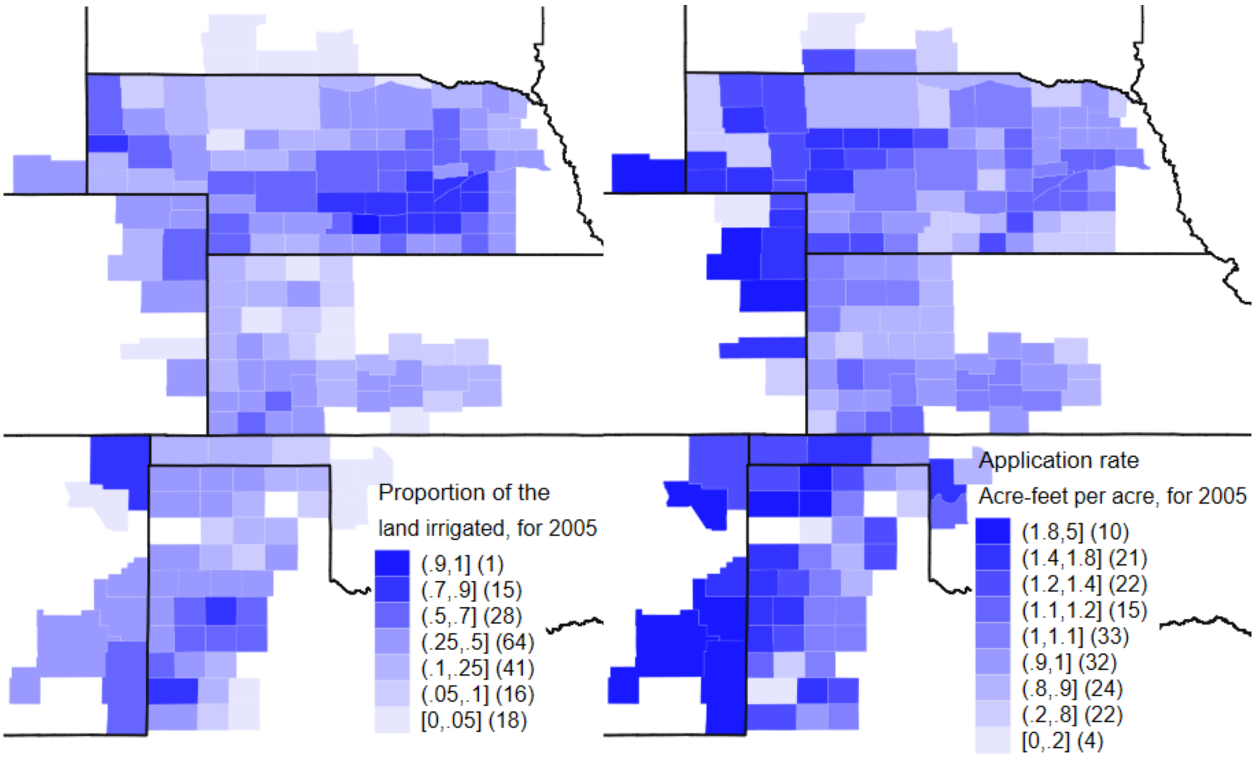

Figure 2. Proportion of the land irrigated (NASS/USDA) and water application rate (in acre-feet, USGS) by county over the High Plains aquifer in 2005.
Note: The numbers in parentheses are the number of counties in each category.

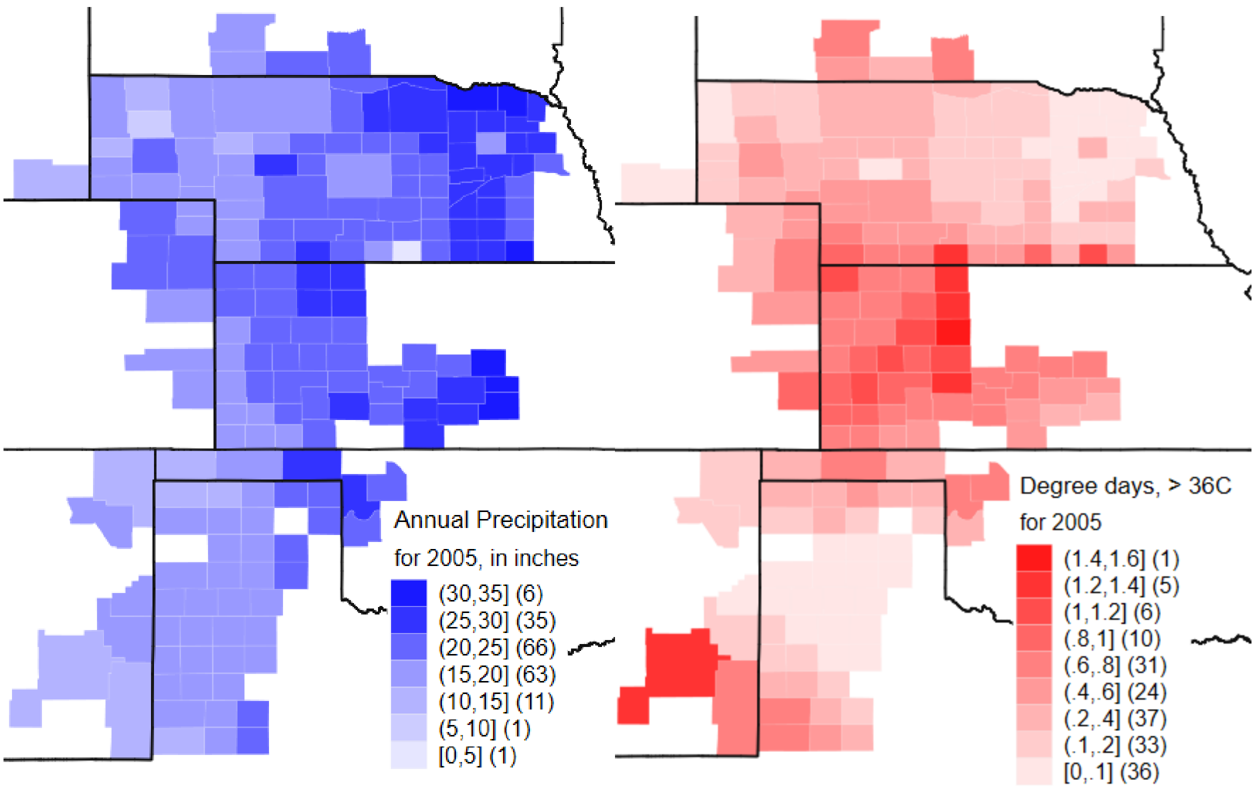

Figure 3. Annual precipitation (in inches) and degree days during the growing season (hours with temperatures above 36ºC, measured in days) by county in the High Plains aquifer for 2005 developed using information from the United States Historical Climatology Network. The numbers in parentheses are the number of counties in each category. We note that the data showed a much wider range for the degree days variable in 2000 (0 to 5.74) than shown here for 2005.

Table 2. SUR parameter estimates for the system of equations (6), (7) and (8) for 183 counties over the High Plain Aquifer, 1985-2005.

	Coefficient	Estimate	Standard Error
Eq 6: Annual change in groundwater water level (feet)			
Precipitation (z_2)	β_{1,z_2}	0.036***	0.004
Application rate (x_1)	β_{1,x_1}	-0.741***	0.069
Fraction of land irrigated (z_1)	β_{1,z_1}	-1.271***	0.185
Eq 7: Annual water demand, (acre-feet per acre, x_1)			
Normalized water price (p_1)	β_{2,p_1}	-3.679***	0.562
Normalized fertilizer price (p_2)	β_{2,p_2}	0.239***	0.061
Normalized chemicals price (p_3)	β_{2,p_3}	0.122**	0.055
Precipitation quarter 1 (z_{21})	$\beta_{2,z_{21}}$	-0.041***	0.010
Precipitation quarter 2 (z_{22})	$\beta_{2,z_{22}}$	-0.019***	0.004
Precipitation quarter 3 (z_{23})	$\beta_{2,z_{23}}$	0.005	0.005
Lag precipitation quarter 4 (z_{24})	$\beta_{2,z_{24}}$	0.010*	0.006
Degree Days > 36^{o}C (z_3)	β_{2,z_3}	0.073*	0.039
Fraction of land irrigated (z_1)	β_{2,z_1}	0.146	0.187
Constant	$\beta_{2,c}$	1.988***	0.163
County fixed effects	*Yes*		
Eq 8: Fraction of land irrigated (z_1)			
Normalized water price (p_1)	β_{3,p_1}	-0.708***	0.091
Normalized fertilizer price (p_2)	β_{3,p_2}	0.077***	0.010
Normalized chemicals price (p_3)	β_{3,p_3}	0.001	0.008
Precipitation (z_2)	β_{3,z_2}	-0.001*	0.001
Degree Days > 36^{o}C (z_3)	β_{3,z_3}	0.002	0.006
Constant	$\beta_{3,c}$	-0.075***	0.027
County fixed effects	*yes*		

Note: *** for p-value smaller than 0.01, ** smaller than 0.05, and * smaller than 0.1.

Table 3. Marginal direct and indirect effects of irrigation, precipitation and temperature on the rate of change in groundwater levels (in feet) in the High Plains Aquifer for years 1985, 1990, 1995, 2000, and 2005.

Effects	**Estimated effect (in feet per year)**	**Standard Error**
Irrigation		
Direct Effect: intensive margin	-0.741***	0.069
Direct Effect: extensive margin	-1.271***	0.185
Indirect Effect: extensive margin	-0.108	0.139
Precipitation (per inch)		
(P.1) Direct Effect	0.036***	0.004
(P.2) Indirect Effect	0.0045*	0.002
Total Effect	0.041***	0.005
Temperature (per degree day)		
(D.1) Intensive Margin	-0.054*	0.029
(D.2) Extensive Margin	-0.002	0.008
Total Effect	-0.056*	0.031

Note: *** for p-value smaller than 0.01, ** smaller than 0.05, and * smaller than 0.1. In **(P.2)** we consider the average marginal effect of an extra inch of precipitation across the four quarters. Standard Errors were calculated using the delta method. See Appendix table A1 for equivalences between marginal effects and coefficients in equations (6), (7), and (8).

Table 4. Estimated climate change effects on the rate of change in groundwater levels across the High Plains Aquifer for years 1985, 1990, 1995, 2000, and 2005 (averaged over all observations).

Effects	**Estimated effect (in feet per year)**	**Standard Error**
***Scenario 1**: 50% increase in the average amount of time with temperature higher than 36^{o}C, with an average precipitation*		
(A.1) Water application rate	0.022*	0.011
(B.1) Fraction of land irrigated	0.0004	0.002
(C.1) Groundwater level change	-0.017*	0.009
***Scenario 2:** 50% increase in the average amount of time with temperature higher than 36^{o}C, with a 25% decrease on the average precipitation*		
(A.2) Water application rate	0.034**	0.013
(B.2) Fraction of land irrigated	0.005	0.003
(C.2) Groundwater level change	-0.222***	0.027
***Scenario 3:** 100% increase in the average amount of time with temperature higher than 36^{o}C, with a 25% decrease on the average precipitation*		
(A.3) Water application rate	0.056**	0.024
(B.3) Fraction of land irrigated	0.005	0.004
(C.3) Groundwater level change	-0.239***	0.033

Note: *** for p-value smaller than 0.01, ** smaller than 0.05, and * smaller than 0.1. Standard Errors were calculated using the delta method (see footnote 21).

Table 5. Direct and indirect effects of three levels of change in water price on the rate of change in groundwater levels for the High Plains Aquifer, evaluated at the overall mean of the data.

Effects	**Calculation**	**Estimated effect (in feet per year)**	**Standard Error**
A 10% increase on average water price			
(E.1) Direct Effect: intensive margin	$\frac{\partial\delta}{\partial x_1}\frac{\partial x_1}{\partial p_1} * 0.1 * \overline{p_1}$	0.031***	0.005
(E.2) Indirect Effect: extensive margin	$\frac{\partial\delta}{\partial x_1}\frac{\partial x_1}{\partial z_1}\frac{\partial x_1}{\partial p_1} * 0.1 * \overline{p_1} + \frac{\partial\delta}{\partial z_1}\frac{\partial z_1}{\partial p_1} * 0.1 * \overline{p_1}$	0.011***	0.002
Total Effect	$(\boldsymbol{E.1}) + (\boldsymbol{E.2})$	0.042***	0.0075
A 25% increase on average water price			
Total Effect	$(\boldsymbol{E.1}) + (\boldsymbol{E.2})$ *for a 0.25 change*	0.104***	0.014
A 50% increase on average water price			
Total Effect	$(\boldsymbol{E.1}) + (\boldsymbol{E.2})$ *for a 0.5 change*	0.208***	0.027

Appendix

Table A1. Equivalence between derivatives of the model and coefficients of equations (6), (7) and (8) in Table 3.

Effects	**Model derivatives**	**Derivatives**
Irrigation		
Direct Effect: intensive margin	$\frac{\partial \delta}{\partial x_1}$	β_{1,x_1}
Direct Effect: extensive margin	$\frac{\partial \delta}{\partial z_1}$	β_{1,z_1}
Indirect Effect: extensive margin	$\frac{\partial \delta}{\partial x_1}\frac{\partial x_1}{\partial z_1}$	$\beta_{1,x_1}\beta_{2,z_1}$
Precipitation		
(P.1) Direct Effect	$\frac{\partial \delta}{\partial z_2}$	β_{1,z_2}
(P.2) Indirect Effect	$\sum_{i=1}^{4}\frac{\partial \delta}{\partial x_1^*}\frac{\partial x_1^*}{\partial z_{2,i}}S_{z_{2,j}} + \frac{\partial \delta}{\partial x_1^*}\frac{\partial x_1^*}{\partial z_1^*}\frac{\partial z_1^*}{\partial z_2}$	$\beta_{1,x_1}\sum_{j=1}^{4}\beta_{2,z_{2,j}}S_{z_{2,j}} + \beta_{1,x_1}\beta_{2,z_1}\beta_{3,z_2} + \beta_{1,z_1}\beta_{3,z_2}$
Total Effect	$(\boldsymbol{P.1}) + (\boldsymbol{P.2})$	$(\boldsymbol{P.1}) + (\boldsymbol{P.2})$
Temperature (degree days)		
(D.1) Intensive Margin	$\frac{\partial x_1^*}{\partial z_3}$	β_{2,z_3}
(D.2) Extensive Margin	$\frac{\partial x_1^*}{\partial z_1^*}\frac{\partial z_1^*}{\partial z_3} + \frac{\partial z_1^*}{\partial z_3}$	$\beta_{2,z_1}\beta_{3,z_3} + \beta_{3,z_3}$
Total Effect	$(\mathbf{D.1}) + (\mathbf{D.2})$	$(\mathbf{D.1}) + (\mathbf{D.2})$

Note: $x_1^* = x_1(\boldsymbol{p}, \boldsymbol{z}^*)$. In **(P.2)** we use the average precipitation in the four quarters given that we want to capture the effect of one extra inch per year.

Table A2. Derivatives in Table 4.

Effects	**Calculation**
Scenario 1*: 50% increase in the average amount of time with temperature higher than 36ºC, with an average precipitation*	
(A.1) Water application rate	$\frac{\partial x_1^*}{\partial z_3} * 0.5 * z_3$
(B.1) Fraction of land irrigated	$\frac{\partial z_1}{\partial z_3} * 0.5 * z_3$
(C.1) Groundwater level change	$\frac{\partial \delta}{\partial x_1}(\boldsymbol{A.1}) + \frac{\partial \delta}{\partial z_1}(\boldsymbol{B.1})$
Scenario 2: *50% increase in the average amount of time with temperature higher than 36ºC, with a 25% decrease on the average precipitation*	
(A.2) Water application rate	$\frac{\partial x_1^*}{\partial z_3} * 0.5 * z_3 - \sum_j^4 \frac{\partial x_1^*}{\partial z_{2j}} * S_{z_{2,j}} * 0.25 * z_{2j}$
(B.2) Fraction of land irrigated	$\frac{\partial z_1}{\partial z_3} * 0.5 * z_3 - \frac{\partial z_1}{\partial z_2} * 0.25 * z_2$
(C.2) Groundwater level change	$\frac{\partial \delta}{\partial x_1}(\boldsymbol{A.2}) + \frac{\partial \delta}{\partial z_1}(\boldsymbol{B.2}) - \frac{\partial \delta}{\partial z_2} * 0.25 * z_2$
Scenario 3: *100% increase in the average amount of time with temperature higher than 36ºC, with a 25% decrease on the average precipitation*	
(A.3) Water application rate	$\frac{\partial x_1^*}{\partial z_{32}} * 1 * z_3 - \sum_j^4 \frac{\partial x_1^*}{\partial z_{2j}} * S_{z_{2,j}} * 0.25 * z_2$
(B.3) Fraction of land irrigated	$\frac{\partial z_1}{\partial z_3} * 1 * z_3 - \frac{\partial z_1}{\partial z_2} * 0.25 * z_2$
(C.3) Groundwater level change	$\frac{\partial \delta}{\partial x_1}(\boldsymbol{A.3}) + \frac{\partial \delta}{\partial z_1}(\boldsymbol{B.3}) - \frac{\partial \delta}{\partial z_2} * 0.25 * z_2$

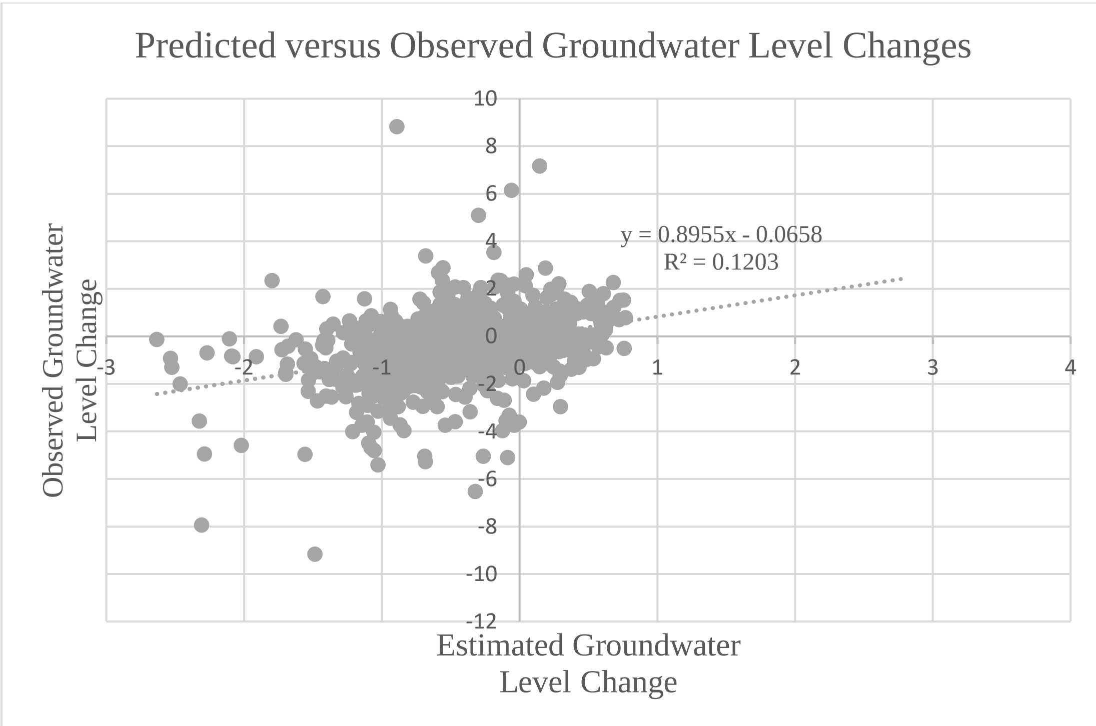

Figure A1. Scatterplot of Predicted and Observed Groundwater Level Changes