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# The Effects of Irrigation and Climate on the High Plains Aquifer:

## An econometric analysis of groundwater levels and irrigation behavior

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# The Effects of Irrigation and Climate on the High Plains Aquifer:

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**ABSTRACT**

*The High Plains Aquifer (HPA) underlies parts of eight states and 208 counties in the central area of the United States. This region produces more than 9% of U.S. crops and relies on the aquifer as the primary source of irrigation water, which can increase crop production by up to 50%. However, these withdrawals have diminished the stock of water in the aquifer. In this paper, we investigate the effect of groundwater withdrawal for irrigation on the HPA. We merge economic theory and hydrological characteristics to jointly estimate a generalized water balance equation for the HPA and equations describing irrigation behavior. Our results predict a decrease in the groundwater table of 0.78 feet per year at the mean application rate of 0.89 acre-feet per acre per year and average land irrigated of 32%. Groundwater depletion would increase 42% with a scenario where precipitation falls by 25% and the number of days with temperature higher than 30$^{o}$C doubles. We estimate that a 25% increase in pumping costs would decrease the water withdrawn for irrigation by 8.9%.*



**Key words:** High Plains Aquifer, Groundwater Depletion, Irrigation.

**JEL:** Q51, Q54, C61.

## INTRODUCTION

The High Plains Aquifer (HPA) covers parts of eight states and 208 counties in the central area of United States, which produces more than 9% of U.S. crops sales (U.S. Department of Agriculture – USDA, 2016). The HPA is the primary source of water for irrigation (Hutson *et al.*, 2000), which can increase crop production up to 50% (Suarez, 2013). These withdrawals have contributed to HPA depletion; for instance, since the 1950s, HPA groundwater storage has declined 8% (or 266 million acre-feet), and this depletion is still occurring (McGuire, 2014).

The effect of groundwater withdrawal for irrigation on the HPA has been investigated by a few papers aligning aquifer hydrological characteristics and economic modelling. These papers exploit theoretical modeling and simulations (e.g. Brozović *et al.*, 2010), and wells data available only for a small area of the HPA region (i.e. Pfeiffer and Lin, 2012; Kuwayama and Brozović, 2013; Palazzo and Brozović, 2014; Pfeiffer and Lin, 2014). However, the outcome of these studies does not allow an analysis of the effects of irrigation, climate change and water price for the entire HPA.

In this study, we merge economic theory and hydrological characteristics to jointly estimate a water balance equation and irrigation behavior, at the extensive and intensive margins, for the entire HPA. Our analysis includes climate variables and energy price to predict the impact of climate change and price changes on groundwater depletion. We include 183 counties on the HPA over the period from 1985 to 2005. Our results will allow to draw conclusions about the effect of climate change and price changes on the groundwater table, important to design policies that seek to preserve the HPA and incentivize agriculture.

Our preliminary results predict a decrease in the groundwater table of 0.78 feet per year at the mean values of 0.89 acre-feet per year per acre and 32% of the land irrigated. Results suggest that groundwater depletion will rise due to possible adverse climate environment and it will lower with increases on energy price. Depletion will increase by 42% with a scenario where precipitation is reduced by 25% and the number of days with temperature higher than 30$^{o}$C doubles. A 25% increase in the marginal cost of pumping decreases water withdrawn for irrigation by 8.9%.

## HIGH PLAINS AQUIFER

The High Plains Aquifer comprises more than 112 million acres in 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). Counties in the states of Nebraska, Kansas and Texas are the largest crop producers, responsible for 90% of the crop sales in this region in 2016. Irrigation has been essential to increase crop productivity in this region. In 2000, the state of Nebraska[1] withdrew 7,420 million gallons per day for irrigation, equivalent to 94% of total water withdrawn in Nebraska and 90% of the water used with irrigation in that state (Hutson *et al*., 2000).

In the HPA region, 70% of the counties have land area irrigated both by ground and surface water. Crop production in this region relies greatly on the former source of water but in the northern area both sources of water are jointly used to irrigate. These withdrawals have intensified groundwater depletion. Less or no depletion has been observed in counties where there is an interaction between ground and surface water and/or high level of precipitation. Figure 1 displays the accumulated[2] 1980-2010 county level groundwater change in the HPA

[1] On average for 2008, each county in Nebraska over the HPA region had 39% of surface irrigated, where only 15% of the counties had no irrigation surface and 5% of the counties had more than 80% of the surface irrigated.
[2] To measure accumulated groundwater change we have summed yearly groundwater level change (measure on change on wells depth to water in feet) over the period 1980-2010.

region. While Figure 1 is based on county-level measures from our data, it resembles what McGuire (2014)[3] and Haacker *et al.* (2015)[4] find. Some areas have had an increase in the amount of groundwater in the aquifer, primarily due to surface water recharge. Portions of the HPA, particularly in Texas, New Mexico, and southwest Kansas, have high levels of depletion.

**[Figure 1]**

Two factors contribute to differences in depletion level between counties. First, a wide range of climate and hydrological characteristics (i.e. precipitation, saturated thickness, soil moisture and specific yields) directly affect recharge and depletion rates. Annual precipitation rates are greater in the eastern portion of the HPA, and the southern portion of the HPA has a low saturated thickness[5], which determines the rate at which water can be withdrawn (Haacker *et al.* 2015). The HPA region has a wide range of specific yields[6], which partially explains differences in the depletion level across the region.

Irrigation behavior, the second factor, is heterogenous across the region. For example, Tripp County in South Dakota did not have any irrigated land in 2005, while Phelps County in Nebraska had irrigation on more than 90% of the county area. On average, 44% of the county area was irrigated in Nebraska while less than 1% in South Dakota in 2005 (Suarez, 2013; obtained from National Agricultural Statistical Service – United States Department of Agriculture – NASS/USDA). On average, counties in Nebraska irrigated 100,000 acres, adding

[3] The author has considered the period from predevelopment (about 1950) to 2013 (in hers figure 1).
[4] Haacker *et al.* (2016) suggests that the eastern part of the HPA has greater chances of being depleted by 2025 (in Figure 10), especially the Southern and Central part of the HPA.
[5] Saturated thickness of the aquifer is used to measure the groundwater volume.
[6] The specific yield is the ratio of the depth of a given quantity of water on the surface versus the same quantity in the soil. McGuire (2014) argues that the specific yields ranges by state, from 0 to 30%. McGuire, Lund and Densmore (2012) progides estimates of the average specific yields by state: Colorado (16.3), Kanas (16.1), Nebraska (15.1), New Mexico (14.3), Oklahoma (18.4), South Dakota (9.1), Texas (15.3) and Wyoming (8.1).

up to more than 8 million acres in 2005; Texas counties also irrigated an average of 100,000 acres in 2005, adding up to 4.7 million acres (United States Geological Services – USGS, 2016).

In the literature, papers have exploited different approaches to investigate irrigation behavior and groundwater level change in the HPA region, such as theoretical modeling, simulations and *ad hoc* empirics. Each paper focuses on a small portion of the aquifer and/or on specific hydrological characteristics of the aquifer instead of investigating these issues for the entire HPA. For instance, Brozović, Sunding and Zilberman (2010), Kuwayama and Brozović (2013), Palazzo and Brozović (2014) and Pfeiffer and Lin (2012) consider the spatial interaction among adjacent irrigation wells. The interaction between ground and surface water is investigated by Sophocleous (2002), Burt, Baker and Helmers (2002), Kuwayama and Brozovic (2013) and Cobourn (2015). Additionally, Pfeiffer and Lin (2012), Hendricks and Peterson (2012), Kuwayama and Brozović (2013), Palazzo and Brozović (2014), Pfeiffer and Lin (2014) investigate groundwater depletion and irrigation behavior for a specific region. However, in this paper we are interested on a broader analysis that can identify the effects of irrigation, weather change and water price on groundwater change for the entire HPA.

Regarding the effects of irrigation on groundwater level change, Pfeiffer and Lin (2012) focus on a portion of the HPA in Kansas, where data is available at the irrigation well level. They incorporate the lateral movement of water using Darcy's law[7] into a groundwater equation of motion. Results suggest that 100 acre-feet pumped from a given well induces an increase of 0.39 feet in the depth to water[8], and smaller increases among nearby wells.

[7] Pfeiffer and Lin (2012) describes this law as "an equation describing the physical movement of a liquid through a porus material" (page 24).
[8] In this literature, groundwater table change is consistently measured as change in well depth to water.

In a simpler setup, Rubin, Perrin and Fulginiti (2015) estimate a water balance equation for a subset of 32 counties in the 41$^{o}$ parallel in Nebraska using county data for the period 1987-2008. They find that conversion of a rain fed county to an entire irrigated county increases the depth to water by 1.23 feet, on average. None of these papers have considered all counties comprised by the High Plains Aquifer.

In terms of irrigation water demand, water (energy) own and cross-price elasticities are relevant to the outcome of potential water restrictive policies. Several studies have tried to identify these elasticities but they have not achieved a consensus. Pfeiffer and Lin (2014) investigate the effect of irrigation costs (energy prices) on groundwater extraction in the western region of the state of Kansas. Their results confirm an inverse relationship between energy prices and irrigation water demand at the intensive (more water applied per acre) and extensive (expending irrigated crop area) margins. They find an estimate own-price elasticity at -0.26. For the same region, Hendricks and Peterson (2012) has also estimated an irrigation water demand. They find an own-price elasticity of -0.10, which is mainly driven by the intensive margin, -0.09 (the change in the amount of water applied).

Moore, Gollehon ad Carey (1994) develop and estimate a system of equations that includes water demand at the extensive and intensive margins, based on profit maximization given a land constraint[9]. They find that the marginal effect of the price of water, or pumping costs, varies across regions of the U.S. and by crop produced. For the Central Plains (Colorado, Kansas, Nebraska and Wyoming), results suggest that an increase of US$ 1.00 in pumping costs (dollars

[9] Mullen and Hoogenboom (2009) have used this theoretical framework on 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 corn own-price elasticity was 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 portion.

per acre-foot) would induce a decrease of 5 acre-feet per farm of water use in alfalfa and an increase of 4.5 acre-feet per farm in corn. However, only for dry beans was the short-run water own-price elasticity statistically significant and positive (equal to 0.21).

Schoengold, Sunding and Moreno (2006) estimate a direct own-price elasticity of -0.41 for a portion of the state of California. Hendricks and Peterson (2012) and Pfeiffer and Lin (2014) also find inelastic responses, -0.08 and -0.26 respectively. Hendricks and Peterson (2012)[10] find that an increase of US$ 1.00 in pumping cost per acre-inch would lead to a decrease in 1.34 inch reduction in the water applied per acre while Pfeiffer and Lin (2014) find that an increase in energy price of US$ 1.00 per million *btu* decreases the quantity of water pumped by 5.15 acre-feet. Examining irrigation water demand by crop[11], Moore, Gollehon and Carey (1994) find positive pumping cost marginal effects for corn, dry beans and wheat in the Central Plains.

We propose to estimate a single, generalized water balance equation for the HPA and the irrigation behavior for the entire High Plains Aquifer. This will allow us to consider the implications of climate change and price changes for the entire region. Hydrological characteristics such as recharge and depletion as well as economic information such as input and output prices are considered in the analysis.

## THE MODEL

Our model merges hydrological principles and economic behavior. The groundwater balance equation is based on simple concepts of recharge and depletion. Precipitation represents

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[10] We follow Hendricks and Peterson (2012) to build our pumping cost, proxy for the water price. See our Data section to understand how they estimate pumping cost.

[11] In Moore, Gollehon and Carey (1994) water demand is estimated by crop (alfalfa, barley, corn, dry beans and wheat). They do not present an aggregate own-price elasticity. On the other hand, Hendricks and Peterson (2012) estimate a crop-aggregate water demand including crop explanatory variables for corn, soybean, wheat, sorghum and other.

groundwater recharge. Depletion is comprised of two components, water withdrawn for irrigation at the intensive margin (changes in water per acre), and the extensive margin (the proportion of the county area irrigated). We represent year-to-year average groundwater level change ($\delta_{it}$) in county *i* and year *t* (subscripts for county and time are suppressed hereafter for simplicity) as

$$\boldsymbol{\delta} = \boldsymbol{\Gamma}'\boldsymbol{\beta} \tag{1}$$

where $\boldsymbol{\Gamma} = [x_1, z_1, z_2]$, $\boldsymbol{\beta}$ is a vector of coefficients which does not include a constant, $x_1$ is quantity of water applied per acre irrigated, $z_1$ is share of the land irrigated and $z_2$ is precipitation.

We represent the farm technology and farmers' irrigation behavior, at a county scale, 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 $\boldsymbol{z}$ of quasi-fixed variables (either exogenous such as weather, or those difficult to change within the crop year, such as the share of the land irrigated).

Economic behavior is captured by input demands that are 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, and quasi-fixed factors. For example, share of the land irrigated is considered a quasi-fixed input which we allow to modify the water demand [$x_i(\boldsymbol{p}, \boldsymbol{z})$] through partial adjustments. In this framework we consider a contemporaneous price effect on the share of the land irrigated but we acknowledge that there may be some non-contemporaneous effect of the price. We can express the effect of $p_i$ on water demand in terms of water response elasticity as

$$\frac{\partial^2 \boldsymbol{\pi}(\boldsymbol{p},\boldsymbol{z}^*)}{\partial p_i^2}\frac{p_i}{x_i} = -\left[\frac{\partial x_i(\boldsymbol{p},\boldsymbol{z}^*)}{\partial p_i} + \frac{\partial x_i(\boldsymbol{p},\boldsymbol{z}^*)}{\partial z_1^*}\frac{\partial z_1^*}{\partial p_i}\right]\frac{p_i}{x_i} \tag{3}$$

where (3) represents the elasticity of the demand at both the intensive margin and the quasi-fixed inputs adjustments of the optimum level of $z_1^*$, (demand at the extensive margin).

To evaluate the effect of water price on groundwater depletion, let $x_1$ [from equations (1) and (2)] represents the quantity of water demanded, and that $p_1$ is the water price. Also let $z_1$ represent irrigation demand at the extensive margin. $z_1$ is a quasi-fixed input that depends on exogenous factors, $z_1 = f(\boldsymbol{p},\boldsymbol{z})$. Using this information we can estimate the water price effect on groundwater level change as

$$\frac{\partial \delta}{\partial p_1} = \frac{\partial \delta}{\partial x_1(\boldsymbol{p},\boldsymbol{z}^*)}\left[\frac{\partial x_1(\boldsymbol{p},\boldsymbol{z}^*)}{\partial p_1} + \frac{\partial x_1(\boldsymbol{p},\boldsymbol{z}^*)}{\partial z_1^*}\frac{\partial z_1^*}{\partial p_1}\right] + \frac{\partial \delta}{\partial z_1^*}\frac{\partial z_1^*}{\partial p_1} \tag{4}$$

where (4) represents the price effect on groundwater level at the intensive margin (first term) and extensive margin (second term). An increase on water price is expected to decrease groundwater depletion given that it would decrease water demand.

We are also interested in how weather affects the HPA. Precipitation affects groundwater level directly through recharge, and indirectly by changing the demand for water for irrigation. The effects of temperature and precipitation are obtained in a similar way. Assume that precipitation is $z_2$ [from equations (1) and (2)] while temperature is measured as $z_3$. Their impacts on aquifer water level are estimated 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 effect of a change on precipitation rate on groundwater depletion while (5'') is the effect of increasing temperatures. An increase in precipitation (temperature) is expected to decrease (increase) groundwater depletion.

## EMPIRICAL STRATEGY

### *Data*

We use data from Suarez (2013) obtained from the National Agricultural Statistical Service – United States Department of Agriculture (NASS/USDA) and Economic Research Service (ERS/USDA) to obtain output and input prices, and acres irrigated for the 208 counties that overlap the High Plains Aquifer during the period of 1980-2010. We only observe water use (quantity) for irrigation for five years. We do not observe wells' depth to water for all counties and all years. The dataset used in estimation consists of 183 counties over five years (1985, 1990, 1995, 2000 and 2005), or a balanced panel with 915 observations. Table 1 displays the overall descriptive statistics.

Fertilizer and chemicals price indexes are also from Suarez (2013) for the United States as a whole, and thus vary only by year[12]. Suarez (2013) estimates the output price index as the value of all biomass produced in the county, divided by the total amount of biomass produced in the county in a given year. We divide other prices by the chemicals price to obtain normalized prices. In Table 1 we present average normalized output and input prices.

Water price is estimated as in Hendricks and Peterson (2012), it is a measure of the cost of lifting the water from the aquifer

$$p_1 = \theta * w_f * h_i$$

[12] Fertilizer (Chemicals) price index is 98 (90) in 1985, 97 (95) in 1990, 120 (116) in 1995, 110 (12) in 2000 and 162 (123) in 2005.

where $p_1$ is the water price, or marginal cost of pumping water, $\theta$ is a constant (.0223 mcf to lift one acre-foot by one foot of elevation) available from Roger and Alan (2006) [13], $w_f$ is fuel price and $h_i$ is the county average well depth to water from Haacker (2017)[14]. Following Hendricks and Peterson (2012) we have used the natural gas price for the industrial sector as the energy price[15].

**[Table 1]**

Well depth to water is used as a proxy to groundwater level, obtained from the United States Geological Services (USGS). Fulginiti et al. (2014) aggregated individual well information to obtain a county average measure of change in depth to water. To aggregate this information they followed a five-step procedure[16].

1. They selected wells for which depth to water has been measured out of the crop season, from October to May.
2. Given that a well could have been monitored more than once in a single season, they averaged each well by season.
3. They selected those wells for which we have measurements in two consecutive seasons.
4. For the selected wells they calculate change in water level (the negative of change in depth to water) during period *t* as $\delta_{jt} = -(h_{jt} - h_{jt-1)}$, where $h_{jt}$ refers to the depth to water in well *j* period *t*, where *t* refers to measurements following crop year *t* (i.e., between Oct of year t and May of year *t+1*).

[13] This study suggests that the pumping fuel units required for lifting 1 acre-foot of water from a 1 foot in height varies with type fuel (i.e. 1.551 for electricity, 0.0223 for natural gas, 0.1098 for diesel and 0.1993 for propane).
[14] We would like to thank Erin Haacker and the Water Center at the University of Nebraska, for making this information available to us.
[15] The United States Energy Information Administration (EIA) made available prices only for the period from 1997 to 2016. To obtain natural gas prices for 1985, 1990 and 1995 we have extrapolated using the average geometric growth rate per state from 1997 to 2016.
[16] We thank John Sims for his work on the construction of this variable.

5. They calculate the average water level change ($\delta_{jt}$) per county; for county *i* we obtain $\delta_{it} = \sum_{j=1}^{K} \delta_{jt}/K$, where there are *K* wells per county (the number of wells per county, K, ranged from 1 to 381, with an average of 43).

A negative value of $\delta_{it}$ indicates that the aquifer has been depleted, while a positive value indicates a recharge. Figure 1 displays the accumulated groundwater change using this information ($\sum_{t=1}^{T\prime} \delta_{it}$, where *T'* is the number of years within the period 1981-2010). Our county average estimate of accumulated groundwater change (Figure 1) for the period 1981-2010 is -6.74 feet. McGuire (2014) estimates the HPA average water level change to be -15.4 feet from predevelopment (before 1950) to 2013, and USGS (2017) reports a depletion of -9.9 feet from predevelopment to 1980 and of -2.39 feet from 1980 to 1995. Our study implies an annual rate of groundwater change for this period of -0.58 feet, whereas USGS (2017) reports an annual change of -0.66 feet from 1994 to 1995. McGuire (2011) reports an average annual water level change of -0.1 and -0.3 feet for the years 2007/08 and 2008/09, respectively, whereas our estimates indicate changes of -0.1 and 0.17 feet respectively for these two years.

For the period from 1981 to 2010, counties in Wyoming and Nebraska have shown the largest average depletion, 2.17 and 1.37 feet, respectively, while counties in South Dakota have experienced, on average, a recharge of 0.11 feet. Figure 2 presents a histogram of the county average groundwater change during the whole period (1981-2010). Except for a few observations, the bulk of the distribution is around the average.

**[Figure 2]**

Water application rate is the quantity demanded per acre, referred to as demand at the intensive margin in the literature. To construct this variable we use data on water quantity for irrigation by county from the United States Geological Services (USGS, 2016) for 1985, 1990, 1995, 2000 and 2005. This variable is in million gallons per day (Mgal/day), which we convert to acre-feet per year using a conversion factor of 1.121 (1 Mgal/day x 1.121 = acre-feet per year). To construct the application rate, water quantity in acre-feet per year was divided by area irrigated (in acres), which is also available from USGS (2016).

We use the fraction of the county area irrigated (range of [0,1]) as a proxy for demand for water at the extensive margin. Figure 3 displays quantities demanded at both intensive and extensive margins for 2005. Counties in the eastern part of Nebraska have a higher fraction of area irrigated while counties in the western part of the HPA have a higher rate of application.

**[Figure 3]**

Weather variables at the county level are from Suarez (2013) who uses a spatial averaging technique for the five reporting stations closest to the county center[17]. Growing season (March to August) precipitation and degree days are from this source. Degree days are the amount of time (measured in days) during the growing season that the crops were exposed to a particular degree interval starting at -5°C. We considered two Degree Days intervals: the amount of time between 20°C and 30°C and amount of time with temperatures higher than 30°C. Figure 4 displays both precipitation and Degree Days>30°C for 2005. Counties in the eastern part of the HPA face higher levels of precipitation and in the southern part face higher number of hotter days.

**[Figure 4]**

*Estimation*

Our groundwater equation is based on a water balance approach, equation (1), considering recharge, represented by precipitation, and depletion, represented by demand at the intensive and

[17] Following Trindade (2011) 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.

extensive margins. Groundwater level ($\delta_{it}$) in county *i* (*i* = 1, ..., 183) and year *t* (*t* = 1, …, 5), where subscripts for county and time are suppressed hereafter for simplicity, is given by

$$\boldsymbol{\delta} = \boldsymbol{\Gamma_1}'\boldsymbol{\beta_1} + \boldsymbol{\epsilon_1} \quad (6)$$

where $\boldsymbol{\delta}$ is a vector of groundwater level change, $\boldsymbol{\Gamma}_1 = [\boldsymbol{x_1} \;\; \boldsymbol{z_1} \;\; \boldsymbol{z_2}]$ is a matrix of information variables: water demand, extensive margin and precipitation; $\beta_1$ is a vector of parameters which does not include a constant, and $\epsilon_1$ a vector of errors. We do not include a constant in this equation, given that we believe that our system incorporates the variables that affect changes in groundwater levels. There are 915 observations.

The quantity of irrigation water applied per acre, $x_1$, is represented by equation (2). We assume a quadratic flexible form for the normalized restricted profit function, which is second order Taylor expansion on output and input prices, and quasi-fixed inputs. To satisfy homogeneity of degree one in prices, output and input prices should be normalized by one of the prices. Given the quadratic specification of the restricted profit function, the input demands (equation 7) will be linear in normalized input and output prices, and in quasi-fixed inputs:

$$\boldsymbol{x_1} = \boldsymbol{\Gamma_2}'\boldsymbol{\beta_2} + \boldsymbol{\epsilon_2} \quad (7)$$

where $\boldsymbol{x_1}$ is a vector of observed quantities of water demanded, $\boldsymbol{\Gamma_2} =$ $[p_1 \;\; p_2 \;\; p_3 \;\; z_1 \;\; z_{21} \;\; z_{22} \;\; z_{23} \;\; z_{24} \;\; z_{31} \;\; z_{32}]$ is a matrix of explanatory variables, $p_1$, $p_2$ and $p_3$ are normalized water, fertilizer and output prices (price of chemicals was use for normalization); $z_1$is extensive margin; $z_{21}$, $z_{22}$, $z_{23}$ and $z_{24}$ refers to quarterly precipitation; and $z_{31}$ and $z_{32}$ refers to degree days between 20-29$^{o}$C and higher than 30$^{o}$C; $\boldsymbol{\beta_2}$ is of vector of parameters which includes a constant; and $\boldsymbol{\epsilon_2}$ is a vector of errors. We also include state fixed effects. Monotonicity in prices of the restricted profit function implies non-negative derived demands and convexity in prices imply non-positive own derived demand effects $\partial x_1/\partial p_1 \leq 0$.

Pfeiffer and Lin (2014), observing choices on individual fields, estimate separate equations for demand at the extensive and intensive margins, including irrigated crop choice and area planted. Their model of demand at the extensive margin includes contemporaneous energy and outputs prices, precipitation and hydrological characteristics variables such as evapotranspiration. Hendricks and Peterson (2012), also observing choices on individual parcels, estimate separate demands at the intensive and extensive margin using a fixed effect panel methodology. Both papers investigate parcels in western Kansas. In light of this discussion, we add an equation for demand at the extensive margin:

$$\boldsymbol{z_1} = \boldsymbol{\Gamma_3}'\boldsymbol{\beta_3} + \boldsymbol{\epsilon_3} \tag{8}$$

where $\boldsymbol{z_1}$ is the proportion of the county area irrigated, $\boldsymbol{\Gamma}_3 = [p_1\ \ p_2\ \ p_3\ \ \ z_2\ \ z_{31}\ \ z_{32}]$ is a matrix of explanatory variables, $p_1$, $p_2$ and $p_3$ are normalized water, fertilizer and output prices (price of chemicals was use for normalization); $z_2$ refers to precipitation; and $z_{31}$ and $z_{32}$ refers to degree days between 20-29$^{o}$C and higher than 30$^{o}$C; $\beta_3$ is a vector of estimated parameters which includes a constant, $\boldsymbol{\epsilon_3}$ is vector of errors. Equation (8) is estimated including county fixed effects.

We estimate equations (6), (7) and (8) as the system

$$\begin{bmatrix} \boldsymbol{\delta} \\ \boldsymbol{x_1} \\ \boldsymbol{z_1} \end{bmatrix} = \begin{bmatrix} \boldsymbol{\Gamma_1}' & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{\Gamma_2}' & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{\Gamma_3}' \end{bmatrix} \begin{bmatrix} \boldsymbol{\beta_1} \\ \boldsymbol{\beta_2} \\ \boldsymbol{\beta_3} \end{bmatrix} + \begin{bmatrix} \boldsymbol{\epsilon_1} \\ \boldsymbol{\epsilon_2} \\ \boldsymbol{\epsilon_3} \end{bmatrix} = \boldsymbol{\Gamma}'\boldsymbol{\beta} + \boldsymbol{\epsilon}, \tag{9}$$

using *Iterated Seemingly Unrelated Regressions* (ISUR), to take advantage of potential correlation among error terms. A Breusch-Pagan test will allow us to test the significance of such correlations.

Estimated parameters are used to evaluate the impact of irrigation, prices and weather on the HPA. Groundwater level change due to changes on irrigation at the intensive margin and at the extensive margin (coefficients are presented in Table 2) are

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

where the first term incorporates the extensive margin partial adjustment effect on water quantity per acre demanded ($x_1$). Price effects on groundwater levels are obtained evaluating equation (4)

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

$$= \left\{\beta_{1,x_1}\left[\beta_{2,p_1} + \beta_{2,z_1}\beta_{3,p_1}\right] + \beta_{1,z_1}\beta_{2,p_1}\right\} * \Delta p_1 \tag{11''}$$

where equation (11') repeats (4), and on equation (11'') $\beta_{1,x_1} = \partial\delta/\partial x_1(\boldsymbol{p}, \boldsymbol{z}^*)$, $\beta_{2,p_1} = \partial x_1(\boldsymbol{p}, \boldsymbol{z}^*)/\partial p_1$, $\beta_{2,z_1} = \partial x_1(\boldsymbol{p}, \boldsymbol{z}^*)/\partial z_1^*$, $\beta_{3,p_1} = \partial z_1^*/\partial p_1$, $\beta_{1,z_1} = \partial\delta/\partial z_1^*$, $\beta_{2,p_1} = \partial z_1^*/\partial p_1$, and $\Delta p_1$ represents a change in the normalized price of water; i.e. 0.10 for 10% change. $\beta_{2,p_1}$ is non-positive as a result of convexity of the restricted profit function. $\beta_{1,x_1}$ and $\beta_{1,z_1}$ are negative due to hydrological characteristics of the HPA. $\beta_{2,p_1}$ and $\beta_{1,z_1}$could be either positive or negative. Overall, we expect $\partial\delta/\partial p_1 > 0$, which means that an increase in water price would increase groundwater level, that is will decrease groundwater depletion.

Weather effects on groundwater change are obtained evaluating equations (5). To illustrate the effects of precipitation on groundwater we will consider a reduction of 25% on the average precipitation rate. The negative of equation (5') captures this effect, repeated in equation (12'):

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

$$= -\left\{\beta_{1,x_1}\left[\beta_{2,z_2} + \beta_{2,z_1}\beta_{3,z_2}\right] + \beta_{1,z_1}\beta_{2,z_2} + \beta_{1,z_2}\right\} * \Delta z_2 \tag{12''}$$

where $\Delta z_2$ represents this change in precipitation. There are three components to this impact. A direct effect of precipitation through the groundwater recharge ($\partial\delta/\partial z_2$), and two indirect effects through intensive and extensive margins

Global warming is expected to cause an increase on the number of days with high temperatures. For instance, consider an increase of 50% on the average amount of time with temperature higher than 30°C. Equation (13'') represents these effects

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

$$=\left\{\beta_{1,x_1}\left[\beta_{2,z_3}+\beta_{2,z_1}\beta_{3,z_3}\right]+\beta_{1,z_1}\beta_{2,z_3}\right\}*\Delta z_3 \quad (13'')$$

where equation (13') repeats equation (5'') and $\Delta z_3$ represents this change in number of days with high temperatures, $\Delta z_3 = 0.5$.

We used Stata 14, commands *sureg* and *nlcom*, to estimate the system in (9), the marginal effects (10), (11''), (12'') and (13''). Standard errors for these equations were obtained using the delta method (see *nlcom*) evaluated at the mean of the observations used in the estimation of (9).

## RESULTS AND DISCUSSION

Estimates of the parameters of the system in equation (9) are reported in Table 2[18]. Our estimated groundwater water balance equation complies with hydrological aspects of the HPA. Irrigation intensive and extensive margins deplete the groundwater aquifer and precipitation recharges the aquifer. Parameter estimated are displayed in Table 2[19]. A Breusch-Pagan test, with a calculated

[18] As a robustness check we have estimated the system considering a reduced form for $x_1$, specifying that water demand be linear in all prices and other exogenous variables. The water price is not statistically significant. We also estimate the system in equation (9), for a structural or a reduced form of $x_1$, considering the water price as only the natural gas price (without multiplying by the conversion measure and the county average wells depth to water). In both cases, the coefficient of the natural gas price is negative.
[19] Monotonicity of the profit function in prices was evaluated after estimation with violations in 33 observations out of 915.

value of 8.50, supports a seemingly unrelated econometric approach as it suggests that the disturbance covariance matrix is not diagonal at 5% level of significance.

We calculate the direct own-price elasticity[20] of water to be -0.0997, and -0.1019 including the indirect, extensive margin effect. Both elasticities are statistically significant at 1%. Hendricks and Peterson (2012) reported a 0.10 own-price elasticity for irrigation, though their observations were field-level data for some counties in Kansas. Our estimate is half the size of the elasticity estimated by Pfeiffer and Lin (2014), which is -0.26, also based on field-level observations in Kansas.

**[Table 2]**

In Table 3 we evaluate marginal effects at the average values of intensive ($x_1$) and extensive margin ($z_1$) for counties that have adopted irrigation (respectively 0.8925 acre-feet per acre and fraction 0.3222 of the county area irrigated). At these averages, irrigation generates an annual water level reduction of 0.78 feet. At this average application rate, conversion of a rain-fed county to an irrigated county (100% of the area) increases the depth to water in 1.82 feet[21]. Rubin, Perrin and Fulginiti (2015) have found a depletion of 1.23 feet.

Pfeifer and Lin (2012) data imply an average application rate of 1.05 acre-feet per acre, 18% higher than our data estimates. At this application rate, their results imply an average annual groundwater depletion that ranges from 0.43 to 0.70 feet[22]. Adjusting our extensive margin to this discrepancy, 0.38 (= 0.32*1.18), and using their average application rate, we find[23] a depletion of 0.91 feet.

[20] Water demand is very responsive to fertilizer price (2.8) and has an almost unitary elastic with respect to output price (0.89). Both elasticities are statistically significant at 1%.
[21] It is found using the estimated parameters: $\beta_{1,x_1} * \overline{x_1} + \beta_{1,z_1}$= -0.3137*0.8925 – 1.5397.
[22] We have calculated this range using only the parameter associated with own pumping (excluding the indirect effect of neighbors' water withdrawn).
[23] This calculation did not include the extensive margin effect through the intensive margin variable.

**[Table 3]**

From equation (12'), the average precipitation effect on groundwater is 0.414 feet, decomposed into direct and indirect effects of 0.35 feet and 0.064 feet, respectively. Our recharge estimate, equation (12') calculated for each county ranges from 0.05 to 0.92 feet per year. USGS (2017) suggests a potential recharge from precipitation and irrigation return that ranges from 0.03 feet (0.038 inches) in the western portion of the HPA to 0.5 feet (6 inches) in the eastern portion of the HPA. Our average annual recharge rate, 0.414, falls within this range.

*Impacts of Weather Change on the HPA*

The Intergovernmental Panel on Climate Change (IPCC, 2014) predicts that climate change in the southern Plains will result in lower precipitation rates and higher temperatures (higher evapotranspiration), which will drive an increase in irrigation demand. Shafer *et al* (2014) project that the number of 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) predict an increase of more than 20 days with high temperature above 95$^{o}$F in the southeast part of the Great Plains while a smaller increase, of 10 days or less, on the far north of the region. For the entire region, this report predicts an average increase of 20 such days using a high $CO_2$ emissions scenario for the period 2041-2070. Overall, these studies suggest an increase on hotter days and a decrease on precipitation for this region.

We model potential impacts of climate change on the HPA by predicting the effects of a hotter and drier climate on irrigation use and groundwater levels. Three *scenarios* were used:

***Scenario 1***: 50% increase in the average amount of time the crop is exposed to temperature above 30$^{o}$C, with average precipitation.

***Scenario 2***: 50% increase in the average amount of time the crop is exposed to temperature higher than 30°C and a decrease of 25% on average precipitation.

***Scenario 3***: 100% increase in the average amount of time the crop is exposed to temperature above 30°C and a decrease of 25% on average precipitation.

Table 4[24] presents the results of this analysis. The *scenario 2* calculation[25] is as follows. We evaluated Equation (13'') to obtain the effect of temperature on groundwater, where $\Delta z_3$ is 0.50 times the average amount of days with temperature higher than 30°C or 8.61 number of days. A negative value for (13'') is expected, given that it would increase water demand. To obtain the effect of a 25% decrease in precipitation on groundwater level, we evaluated equation (12''), with $\Delta z_2$ = 0.25 times the average precipitation rate, which is 21.25 inches.

**[Table 4]**

Our preliminary results predict a severe effect of climate change on groundwater levels. We calculate a 10% increase in the rate of groundwater depletion with *scenario 1*, another 21% under scenario 2, and an additional increase of 11% under *scenario 3*. For *scenario 1*, an increase of 50% on hotter days, keeping precipitation constant, causes an increase of 10% on the water demand ($x_1$) and of 4.5% in irrigation at the extensive margin ($z_1$). This implies an increase on depletion of 0.048 feet a year, which is 10% of annual average groundwater change. In *scenario 2*, irrigation demand does not change dramatically but groundwater depletion increases 31% of the annual average. Groundwater depletion reaches an increase of 42% (0.2

[24] These estimates assume a uniform effect of climate change on temperature and precipitation over the entire HPA. They also assume that the average observed number of days with temperature higher than 30°C and precipitation represents the entire HPA. These assumptions were made to simplify the analysis.

[25] Instead of calculating a base scenario where the effect of climate variables is evaluated on the average temperature and precipitation and then subtract scenario 2 inputting a $\Delta z_3$ of 1.5 and a $\Delta z_2$ of 0.75 we estimate the effect of the change directly.

feet) in *scenario 3* where the number of days with temperature higher than 30°C doubles 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). Under *scenario 2*, for example, climate change would increase the rate of depletion by 31%, or an additional 0.15 ft/yr, for a total of about 17 million acre-feet per year. This is about equal to the 18.5 million acre-feet used for HPA irrigation in 2005 for the 183 counties used in our estimation. Thus, these weather conditions would essentially double the annual amount of water withdrawn for irrigation.

*Energy price effects on groundwater depletion*

We model potential impacts of water price changes on groundwater by evaluating equation (11'') at the overall mean. We considered three different *scenarios*: a 10%, a 25% and a 50% increase on the average water price. Table 5 displays the outcome of this analysis. For a 10% increase on average water price[26] we expect the direct intensive margin effect to reduce depletion by 0.00279 feet/year, with a combined total reduction of 0.006 feet per year.

**[Table 5]**

Changes in water price affect cost of production, and producer surplus. This change can be decomposed in two components. First, a movement along the water demand, and second, a shift of the water demand caused by adjustments at the extensive. Both effects are represented in the elasticity of -0.10. To approximate the welfare impact of this price change for the entire region (183 counties) we use the average county area irrigated of 92,176.07 acres, and the average water

[26] To calculate this value, we have use 10% of the normalized price of water, *p1*.

price of US$ 6.02 in 2005. The surplus loss for the irrigators can be identified by calculating the size of the area underneath the demand and between new and old prices:

$$AvLoss = \left[\Delta p_1 * x_1' + \frac{\Delta p_1 * \Delta x_1}{2}\right] * (Irrigated\ acres)$$

$$Loss = AvLoss * N$$

where $AvLoss$ represents the average loss, at county level, for irrigators and $Loss$ is the aggregated regional loss for the irrigators. For a water price increase of 25%, we find that the average county would lose US$ 150,417, and for the entire HPA region a total of US$ 27,526,310 (an amount less than 1% of the crop revenue in 2005[27]).

The amount of groundwater saved due to an increase of 25% on water price is obtained using information on the HPA area plus the county level average change in groundwater level of 0.01390 (Table 5). An annual decrease in groundwater depletion of 1,556,916[28] acre-feet per year (= 112 million acres x 0.01390) would be observed. This translates to a reduction of 8.39% of the water withdrawn for irrigation in the 183 counties considered in our study for 2005.

## CONCLUSIONS

This paper identifies the effect of irrigation, changes in temperatures and precipitation due to climate change and energy prices on the rates of groundwater depletion across the entire High Plains Aquifer (HPA), by estimating a county-level system of equations. The system includes a groundwater water balance equation, an equation for water demand per acre, and a reduced form equation for irrigation at the extensive margin. To estimate this system, we merged hydrologic,

[27] To find total revenue we first estimate each county revenue as biomass quantity by biomass price and then we sum over all counties. For 2005, we find a revenue of 6,968 billion dollars.

[28] This value is statistically significant at 1% and its 95% confidence interval is [821,074.2, 2,292,758].

climatic and economic information for 183 counties over the period 1985-2005. This system was estimated using *Iterated Seemingly Unrelated Regression* (ISUR).

Our preliminary results predict an average decrease in the groundwater table of 0.78 feet per year, when evaluated at the mean values of 0.89 acre-feet applied per acre and 32% of the land irrigated. The results of our simple water balance equation are very close to those of Pfeiffer and Lin (2012). Our estimate of the total water own-price elasticity of demand, -0.102, is also virtually the same as the Hendricks and Peterson (2012) elasticity of 0.10. These comparisons suggest that our county-level analysis provides results, at the mean, similar to previous estimates from individual well data in small subregions of the HPA. Our estimates also comply with theoretical properties derived from the restricted profit function and with hydrological characteristics of the aquifer.

While water withdrawn for irrigation has played a major role in groundwater depletion, potential impacts of changing weather due to global warming are also of concern. Our results indicate that the rate of groundwater depletion could rise by as much as 42% due to possible adverse changes in climate. The rate of groundwater depletion would fall by as much as 3% with a 25% rise in pumping costs, due to a decrease of 8.9% on the application rate. This 25% rise would reduce water irrigators' welfare surplus by somewhat less than 1% of crop revenues in this region.

Our estimates of potential changes in temperatures and precipitation due to climate change on groundwater depletion should be interpreted with caution. They are based on hypothetical and somewhat arbitrary predictions of changes in temperature and precipitation, and are evaluated at the mean of the observations across the HPA. In future research, we intend to explore and report individual outcomes across the HPA consistent with IPCC forecasts of changes in weather variables for the region.

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**FIGURES AND TABLES**

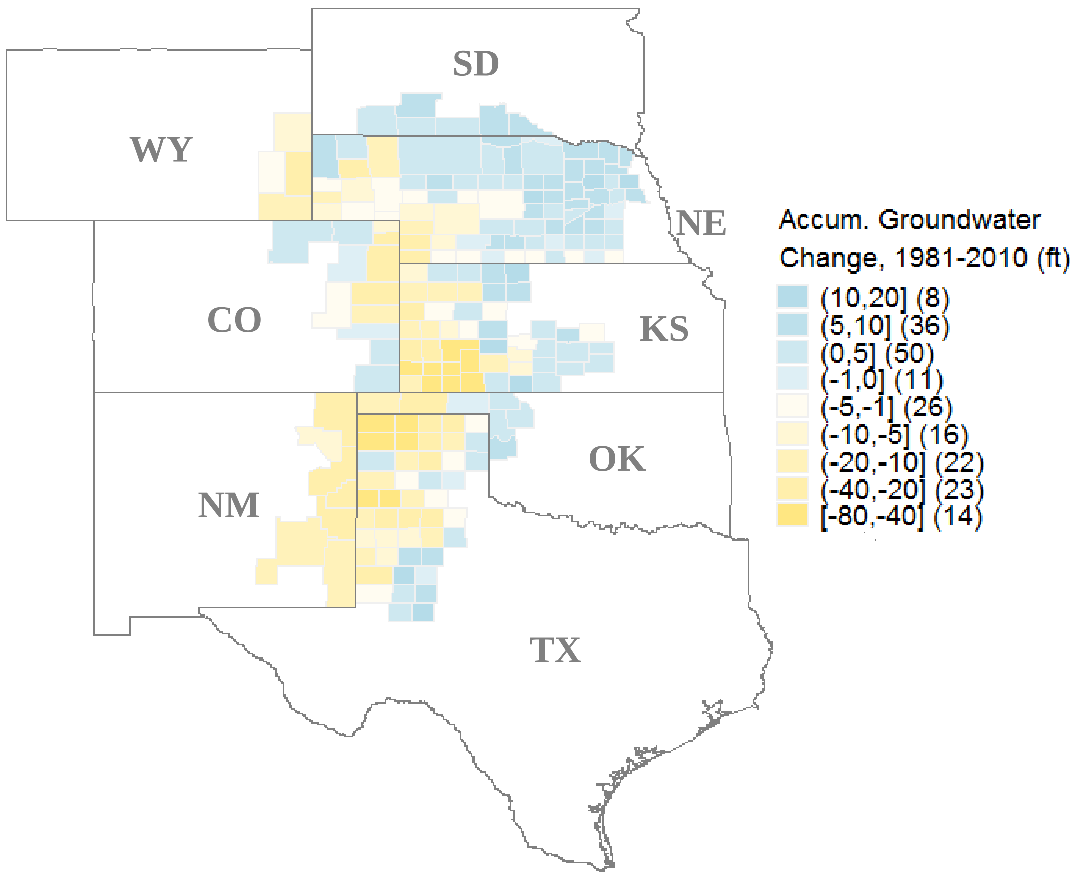


**Figure 1.** Accumulated groundwater change in the HPA from 1981 to 2010 using county averages of well depth to water (in feet).

**Table 1**. Descriptive statistics, HPA.

| Variable | Units | Variable | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|---|
| Groundwater Change | Feet | $\delta$ | -0.485572 | 1.386464 | -9.165833 | 8.826579 |
| Water Demand [a] | Acre-feet per acre | $x_1$ | 0.8857664 | 0.6250053 | 0 | 3.866581 |
| Extensive Margin [b] | Proportion [0,1] | $z_1$ | 0.3175842 | 0.2180257 | 0 | 0.9060403 |
| Water price | US$ per acre-foot | $p'_1$ | 2.979159 | 2.416475 | 0.1753838 | 15.97582 |
| Fertilizer price | US$ | $p'_2$ | 117.4 | 23.85922 | 97 | 162 |
| Biomass price | US$ | $p'_3$ | 58.53674 | 13.69157 | 29.8885 | 147.0588 |
| Chemicals price | US$ | $p'_4$ | 108.8 | 13.59272 | 90 | 123 |
| Normalized Water price | US$ | $p_1$ | 0.0264063 | 0.0191768 | 0.0019487 | 0.1298847 |
| Normalized Fertilizer price | US$ | $p_2$ | 1.075633 | 0.1330477 | 0.9166667 | 1.317073 |
| Normalized Biomass price | US$ | $p_3$ | 0.5427636 | 0.1251941 | 0.2490708 | 1.361524 |
| Precipitation | Inches | $z_2$ | 21.25157 | 5.375303 | 2.041784 | 40.40593 |
| Precipitation Quarter 1 | Inches | $z_{21}$ | 3.116999 | 1.568829 | 0.1520972 | 11.16564 |
| Precipitation Quarter 2 | Inches | $z_{22}$ | 8.482586 | 3.410687 | 0.089171 | 23.56762 |
| Precipitation Quarter 3 | Inches | $z_{23}$ | 6.741764 | 2.572145 | 0.0618973 | 18.85972 |
| Lag Precipitation Quarter 4 | Inches | $z_{24}$ | 3.092942 | 2.342933 | 0.095788 | 12.29037 |
| Degree Days 20$^o$C – 29$^o$C | Units | $z_{31}$ | 59.44709 | 13.10966 | 16.61745 | 97.85526 |
| Degree Days > 30$^o$C | Units | $z_{32}$ | 8.607493 | 3.880383 | 0.32143 | 20.9862 |

**Note:** [a] Application rate and [b] Share of land irrigated.

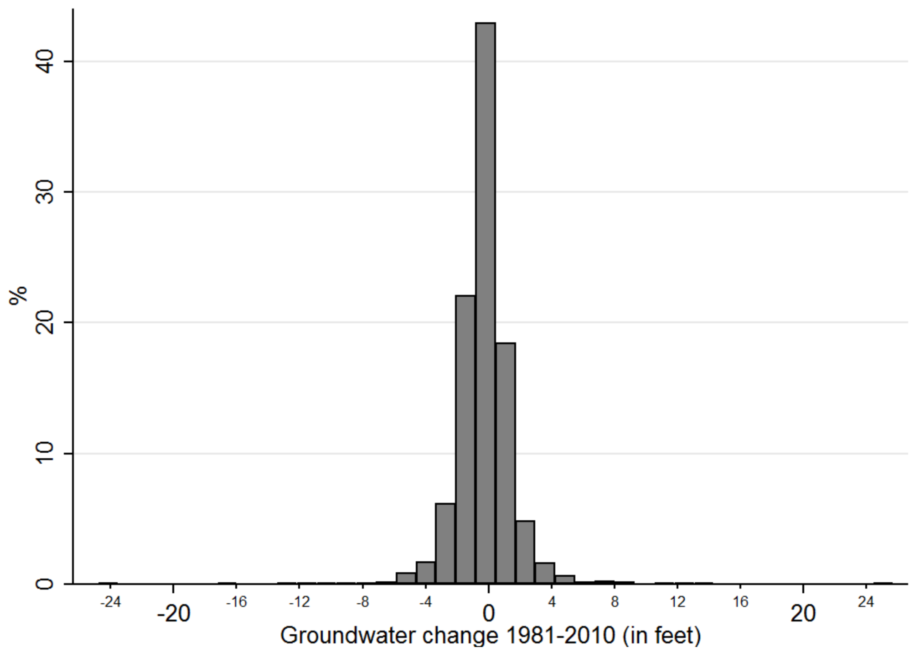


**Figure 2.** Histogram of cumulative groundwater change for the HPA from 1981 to 2010 using county averages well depth to water data (in feet).

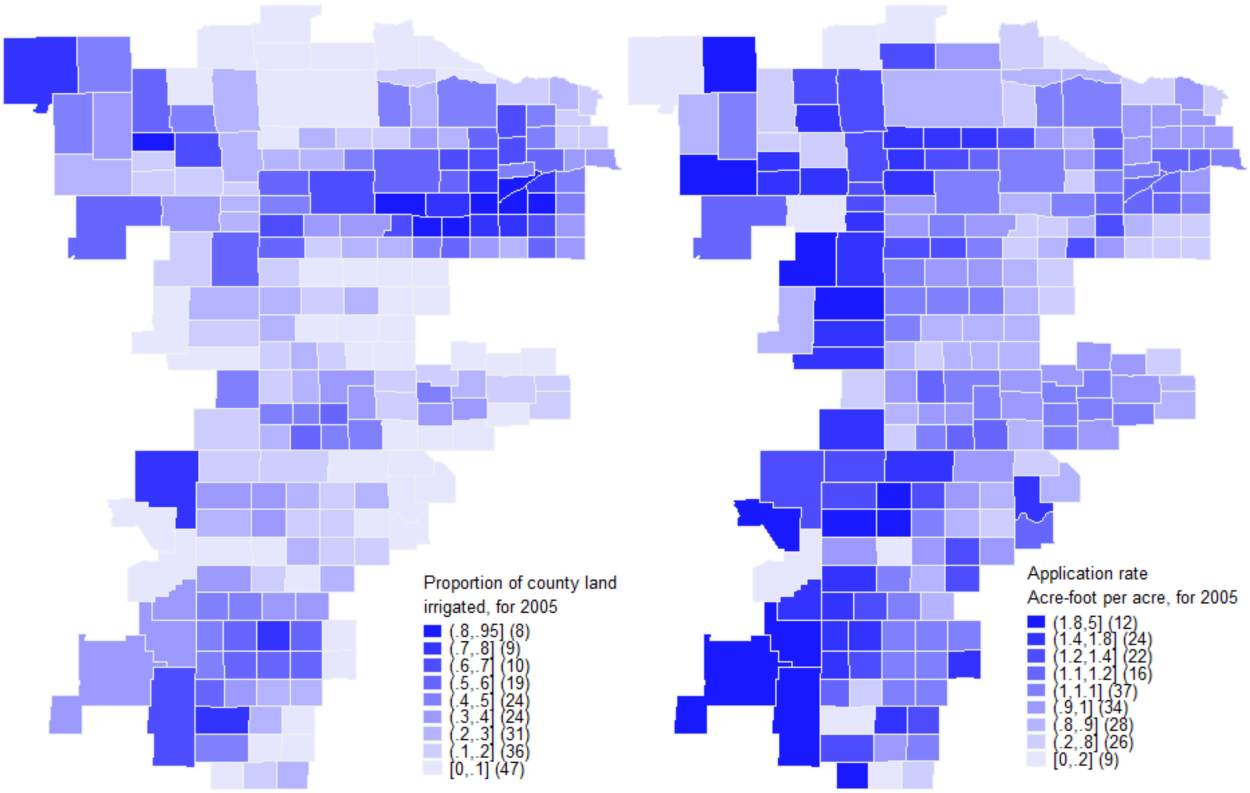


**Figure 3.** Proportion of the county land that is irrigated in 2005 using NASS/USDA data and application rate (in acre-feet per acre) for 2005 using USGS data.

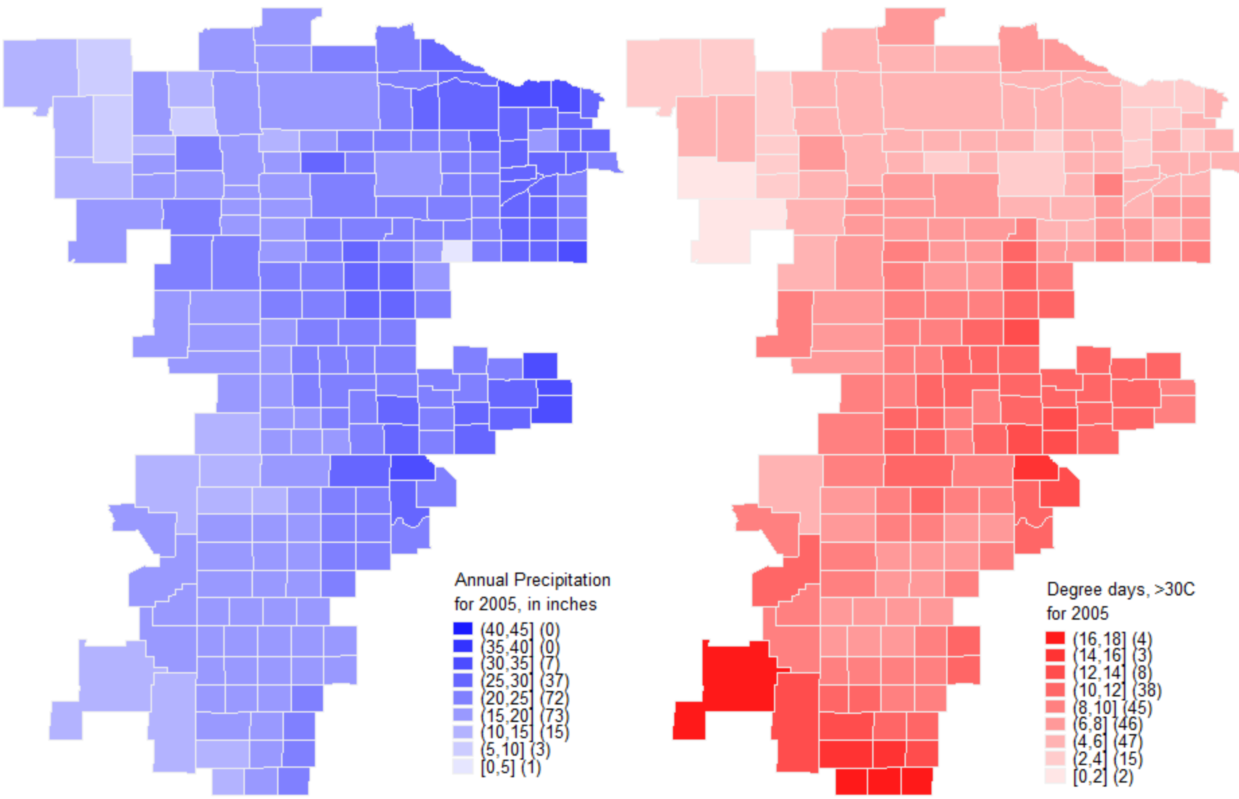


**Figure 4.** Annual precipitation (in inches) and degree days (hours with temperature above 30$^{o}$C, measured in days) for 2005 using information from the United States Historical Climatology Network.

**Table 2.** ISUR parameter estimates for the system of equations in (7) that includes a groundwater water balance equation, a water demand per acre and a reduced form demand for share of area irrigated, for 183 counties over the High Plain Aquifer, 1985-2005.

| | **Variable** | **Coefficient** | **Parameter** | **Standard Error** | **z** |
|---|---|---|---|---|---|
| *Groundwater water balance* | | | | | |
| Precipitation | $z_2$ | $\beta_{1,z_2}$ | 0.0165 | 0.0040 | 4.1600 |
| Intensive margin | $x_1$ | $\beta_{1,x_1}$ | -0.3137 | 0.0655 | -4.7900 |
| Extensive margin | $z_1$ | $\beta_{1,z_1}$ | -1.5397 | 0.1887 | -8.1600 |
| *Water demand ($x_1$)* | | | | | |
| Normalized Water price | $p_1$ | $\beta_{2,p_1}$ | -3.3716 | 1.0520 | -3.2000 |
| Normalized Fertilizer price | $p_2$ | $\beta_{2,p_2}$ | 2.3298 | 0.1462 | 15.9300 |
| Normalized Biomass price | $p_3$ | $\beta_{2,p_3}$ | 1.4767 | 0.1454 | 10.1600 |
| Precipitation Quarter 1 | $z_{21}$ | $\beta_{2,z_{21}}$ | -0.0652 | 0.0111 | -5.9000 |
| Precipitation Quarter 2 | $z_{22}$ | $\beta_{2,z_{22}}$ | -0.0092 | 0.0052 | -1.7700 |
| Precipitation Quarter 3 | $z_{23}$ | $\beta_{2,z_{23}}$ | 0.0325 | 0.0067 | 4.8600 |
| Lag Precipitation Quarter 4 | $z_{24}$ | $\beta_{2,z_{24}}$ | -0.0142 | 0.0078 | -1.8100 |
| Degree Days 20$^o$C – 29$^o$C | $z_{31}$ | $\beta_{2,z_{31}}$ | -0.0178 | 0.0024 | -7.5000 |
| Degree Days > 30$^o$C | $z_{32}$ | $\beta_{2,z_{32}}$ | 0.0190 | 0.0084 | 2.2700 |
| Extensive margin | $z_1$ | $\beta_{2,z_1}$ | 0.1067 | 0.0736 | 1.4500 |
| Constant | $c$ | $c$ | -1.4077 | 0.1990 | -7.0700 |
| State fixed effect | *yes* | | | | |
| *Extensive Margin ($z_1$)* | | | | | |
| Normalized Water price | $p_1$ | $\beta_{3,p_1}$ | -0.666 | 0.179 | -3.730 |
| Normalized Fertilizer price | $p_2$ | $\beta_{3,p_2}$ | 0.100 | 0.019 | 5.280 |
| Normalized Biomass price | $p_3$ | $\beta_{3,p_3}$ | -0.059 | 0.024 | -2.460 |
| Precipitation | $z_2$ | $\beta_{3,z_2}$ | -0.001 | 0.001 | -1.780 |
| Degree Days 20$^o$C – 29$^o$C | $z_{31}$ | $\beta_{2,z_{31}}$ | 0.001 | 0.001 | 1.520 |
| Degree Days > 30$^o$C | $z_{32}$ | $\beta_{2,z_{32}}$ | 0.003 | 0.001 | 2.600 |
| Constant | $c$ | $c$ | -0.104 | 0.046 | -2.270 |
| County fixed effect | *yes* | | | | |

**Table 3.** Direct and indirect effects of irrigation (intensive and extensive margin) and precipitation on groundwater levels for the HPA, evaluated at the overall mean.

| Effects | Derivatives | Parameter | Std. Err. | z | P > z |
|---|---|---|---|---|---|
| *Irrigation* | | | | | |
| Direct intensive margin effect | $\partial\delta/\partial x_1$ | -0.280 | 0.058 | -4.790 | 0.000 |
| Direct extensive margin effect | $\partial\delta/\partial z_1$ | -0.496 | 0.061 | -8.160 | 0.000 |
| Indirect extensive margin effect | $\frac{\partial\delta}{\partial x_1}\frac{\partial x_1}{\partial z_1}$ | -0.011 | 0.008 | -1.390 | 0.166 |
| Total Effect | $\partial\delta/\partial x_1 + \partial\delta/\partial z_1^*$ | -0.787 | 0.081 | -9.710 | 0.000 |
| *Precipitation* | | | | | |
| Direct Effect | $\partial\delta/\partial z_2$ | 0.350 | 0.084 | 4.160 | 0.000 |
| Indirect Effect | $\frac{\partial\delta}{\partial x_1^*}\frac{\partial x_1^*}{\partial z_2} + \frac{\partial\delta}{\partial x_1^*}\frac{\partial x_1^*}{\partial z_1^*}\frac{\partial z_1^*}{\partial z_2}$ | 0.064 | 0.028 | 2.250 | 0.024 |
| Total Effect | $\frac{\partial\delta}{\partial z_2} + \frac{\partial\delta}{\partial x_1^*}\frac{\partial x_1^*}{\partial z_2} + \frac{\partial\delta}{\partial x_1^*}\frac{\partial x_1^*}{\partial z_1^*}\frac{\partial z_1^*}{\partial z_2}$ | 0.414 | 0.095 | 4.380 | 0.000 |

**Note**: $x_1^* = x_1(\boldsymbol{p}, \boldsymbol{z}^*)$

**Table 4.** Climate change effects on groundwater levels for the HPA, evaluated at the overall mean.

| Effects | Derivatives | Parameter | Std. Err. |
|---|---|---|---|
| ***Scenario 1**: 50% increase in the average amount of time with temperature higher than 30ºC, with an average precipitation* | | | |
| **(A.1)** Water application rate | $\frac{\partial x_1^*}{\partial z_{32}} * 0.5 * \overline{z_{32}}$ | 0.0834** | 0.0362 |
| **(B.1)** Extensive Margin | $\frac{\partial z_1}{\partial z_{32}} * 0.5 * \overline{z_{32}}$ | 0.0143*** | 0.0055 |
| **(C.1)** Groundwater level change | $\frac{\partial \delta}{\partial x_1}(\boldsymbol{A}) + \frac{\partial \delta}{\partial z_1}(\boldsymbol{B})$ | -0.0482*** | 0.0156 |
| ***Scenario 2:** 50% increase in the average amount of time with temperature higher than 30ºC, with a 25% decrease on the average precipitation* | | | |
| **(A.2)** Water application rate | $\frac{\partial x_1^*}{\partial z_{32}} * 0.5 * \overline{z_{32}} - \sum_j^4 \frac{\partial x_1^*}{\partial z_{2j}} * 0.25 * \overline{z_{2j}}$ | 0.1105*** | 0.0353 |
| **(B.2)** Extensive Margin | $\frac{\partial z_1}{\partial z_{32}} * 0.5 * \overline{z_{32}} - \frac{\partial z_1}{\partial z_2} * 0.25 * \overline{z_2}$ | 0.0191*** | 0.0059 |
| **(C.2)** Groundwater level change | $\frac{\partial \delta}{\partial x_1}(\boldsymbol{A}) + \frac{\partial \delta}{\partial z_1}(\boldsymbol{B}) - \frac{\partial \delta}{\partial z_2} * 0.25 * \overline{z_2}$ | -0.1517*** | 0.0313 |
| ***Scenario 3:** 100% increase in the average amount of time with temperature higher than 30ºC, with a 25% decrease on the average precipitation* | | | |
| **(A.3)** Water application rate | $\frac{\partial x_1^*}{\partial z_{32}} * 1 * \overline{z_{32}} - \sum_j^4 \frac{\partial x_1^*}{\partial z_{2j}} * 0.25 * \overline{z_{2j}}$ | 0.1939*** | 0.0695 |
| **(B.3)** Extensive Margin | $\frac{\partial z_1}{\partial z_{32}} * 1 * \overline{z_{32}} - \frac{\partial z_1}{\partial z_2} * 0.25 * \overline{z_2}$ | 0.0334*** | 0.0111 |
| **(C.3)** Groundwater level change | $\frac{\partial \delta}{\partial x_1}(\boldsymbol{A}) + \frac{\partial \delta}{\partial z_1}(\boldsymbol{B}) - \frac{\partial \delta}{\partial z_2} * 0.25 * \overline{z_2}$ | -0.1999** | 0.0434 |

**Note**: $x_1^* = x_1(\boldsymbol{p}, \boldsymbol{z}^*)$, so $\frac{\partial x_1^*}{\partial z_{32}} = \frac{\partial x_1}{\partial z_{31}} + \frac{\partial x_1}{\partial z_1}\frac{\partial z_1}{\partial z_{31}}$, and $z_{32}$ represents number of days with more than 30ºC

**Table 5.** Direct and indirect effects of water price changes on groundwater levels for the HPA, evaluated at the overall mean for three different price change scenarios.

| Effects | Derivatives | Param. | Std. Err. | z | P > z |
|---|---|---|---|---|---|
| *A 10% increase on average water price* | | | | | |
| Intensive margin Effect | $\frac{\partial \delta}{\partial x_1}\frac{\partial x_1}{\partial p_1}$ | 0.00279 | 0.001 | 2.670 | 0.008 |
| Extensive margin Effect | $\frac{\partial \delta}{\partial x_1}\frac{\partial x_1}{\partial z_1}\frac{\partial x_1}{\partial p_1}+\frac{\partial \delta}{\partial z_1}\frac{\partial z_1}{\partial p_1}$ | 0.00277 | 0.001 | 3.400 | 0.001 |
| Total Effect | $\frac{\partial \delta}{\partial x_1}\frac{\partial x_1}{\partial p_1}+\frac{\partial \delta}{\partial x_1}\frac{\partial x_1}{\partial z_1}\frac{\partial x_1}{\partial p_1}+\frac{\partial \delta}{\partial z_1}\frac{\partial z_1}{\partial p_1}$ | 0.00556 | 0.001 | 4.150 | 0.000 |
| *A 25% increase on average water price* | | | | | |
| Total Effect | $\frac{\partial \delta}{\partial x_1}\frac{\partial x_1}{\partial p_1}+\frac{\partial \delta}{\partial x_1}\frac{\partial x_1}{\partial z_1}\frac{\partial x_1}{\partial p_1}+\frac{\partial \delta}{\partial z_1}\frac{\partial z_1}{\partial p_1}$ | 0.01390 | 0.003 | 4.150 | 0.000 |
| *A 50% increase on average water price* | | | | | |
| Total Effect | $\frac{\partial \delta}{\partial x_1}\frac{\partial x_1}{\partial p_1}+\frac{\partial \delta}{\partial x_1}\frac{\partial x_1}{\partial z_1}\frac{\partial x_1}{\partial p_1}+\frac{\partial \delta}{\partial z_1}\frac{\partial z_1}{\partial p_1}$ | 0.02780 | 0.007 | 4.150 | 0.000 |