# The Economic Cost of Aquifer Depletion in the High Plains

Gabriela Perez-Quesada, Nathan P. Hendricks, and David R. Steward *

**Abstract**

Groundwater depletion is constraining agricultural production and could cause economic distress in regions that strongly rely on groundwater for irrigation. Identifying how changes in the stock of groundwater—or any natural resource—impact economic outputs is challenging due to bias from feedback effects from irrigation behavior affecting current resource conditions. In this paper, we estimate how changes in groundwater stocks affect the returns to agricultural land in the High Plains Aquifer of the central US. We address feedback effects by exploiting hydrologic variation in pre-development saturated thickness that was determined by natural processes in a previous geological era. We find that 63% of the economic impact of a decrease in the stock of groundwater corresponds to adjustment through reduced irrigated acreage (extensive margin) and 37% occurs through reduced irrigated rental rates (intensive margin) when saturated thickness is less than 70 feet and nearly all of the response is at the extensive margin when saturated thickness is larger. The simulation results reveal that average annual returns to land are expected to decrease in the High Plains region by $120.6 million in 2050, and by $250.5 million in 2100. The most severe decreases in returns to land are expected to occur in Texas, Kansas, and Colorado.

*Keywords*: Groundwater, depletion, irrigation, feedback effects.
*JEL codes*: Q15, Q25, Q30.

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# 1 Introduction

Groundwater is a critical input for agriculture in many arid regions around the world. Expansion of groundwater use for irrigation has offered a substantial source of water to supplement insufficient growing season rainfall. However, the extraction of groundwater for irrigation at higher rates than natural recharge has led to persistent aquifer depletion in many countries (Richey et al., 2015). This stressed aquifer condition is critically important in the central and southern portion of the High Plains Aquifer (HPA) in the United States where water levels have been declining rapidly (Scanlon et al., 2012; Steward and Allen, 2016).

Groundwater irrigation has played an essential role in the development of the agricultural economy in the High Plains region. The HPA supplies over 30% of the total groundwater used for irrigation in the US and annually adds an additional revenue of about $3 billion to agricultural production (Steward et al., 2013; Garcia-Suarez et al., 2019). The access to groundwater has also increased agricultural land values. Hornbeck and Keskin (2014) estimate that the value of Ogallala groundwater peaked at $25 billion in 1964 as a result of consistently higher land values in the 1950s in Ogallala counties. Sampson et al. (2019) find that agricultural land values are about 53% higher for irrigated parcels than nonirrigated parcels in the Kansas portion of the HPA. Furthermore, Fenichel et al. (2016) estimate that between 1996 and 2005, the present value of profits generated by the aquifer in Kansas—the value as natural capital— decreased by $110 million annually due to aquifer depletion.

Although our empirical analysis focuses on groundwater resources, the identification of causally interpretable effects of how varying the stock of natural resource impacts economic outputs is relevant to many other natural resource settings. The existence of feedbacks across social and environmental dimensions of complex systems makes it difficult to support assumptions about excludability and absence of interference required for causal inference (Ferraro et al., 2019). For example, current aquifer conditions depend on the behavior of users because as farmers increase groundwater extraction, the saturated thickness—a measure of resource stock— decreases.

Our paper quantifies the economic impacts of a decrease in the stock of groundwater avoiding bias from the feedback of irrigation behavior affecting the current resource conditions. We address this source of endogeneity by exploiting hydrologic variation in pre-development saturated thickness that is unrelated to irrigation behavior. Pre-development saturated thickness was determined by the structure and features of the eroded pre-Ogallala surface roughly 24 to 5 million years ago, which leads to variation in the availability of groundwater across the HPA today. Intuitively, our empirical strategy compares counties within the same state for a given year, with similar climatic, soil, and aquifer characteristics that have a different amount of current saturated thickness because of differences in pre-development saturated thickness.

We estimate two-stage least square (2SLS) models of irrigated acres and irrigated cash rental rates on saturated thickness, controlling for other confounders. Pre-development saturated thickness is used as an instrument for current saturated thickness. We provide support for the validity of the exclusion restriction by conducting a falsification test to evaluate if pre-development saturated thickness is correlated with unobserved land productivity. We use annual data at the county-level on irrigated area from the US Census of Agriculture and irrigated cash rental rates for cropland from the National Agricultural Statistics Service (NASS). We combine these data with hydrological characteristics of the HPA, climatic, and soil characteristics. The parameter estimates are then used to simulate the projected economic impacts of future aquifer depletion. The simulation results reveal that the average annual returns to land are expected to decrease in the High Plains region by $120.6 million in 2050 and by $250.5 million in 2100. However, the economic impact of the projected decrease in saturated thickness varies significantly across regions of the HPA.

Our paper provides two main contributions. First, we estimate the economic impacts of varying resource stocks by using initial resource conditions as an instrument to reduce potential bias from users' behavior. Previous studies measure the economic impact of access to groundwater but do not quantify the economic impact of differences in the stock of groundwater. As a result, they are not able to estimate the impact of a projected decrease in the stock of groundwater. Hornbeck and Keskin (2014) compare counties over the HPA aquifer with nearby similar counties to estimate the impact of access to water. They show that access to the HPA increased agricultural land values and decreased initial sensitivity to drought but had no effect on long-term resilience to drought. By contrast, Hornbeck and Keskin (2015) show that access to the HPA has not generated a significant long-term expansion in non-agricultural activities. Blakeslee et al. (2020) compare households in India whose first borewell failed to those for whom it is still working, within the same village to estimate the impact of groundwater access on different outcomes. The unique setting of Blakeslee et al. (2020)'s study allows the authors to exploit variation in long-term loss of water that occurs within villages that are smaller and closer spatial units than counties used by Hornbeck and Keskin (2014).

Second, we estimate the economic impact of a projected decrease in the stock of groundwater across the HPA region using observed farmer responses to varying groundwater conditions. Previous studies have focused on the extent of the HPA depletion and projected aquifer conditions in the future but without estimating economic impacts (Scanlon et al., 2012; Steward et al., 2013; Haacker et al., 2016). Another related literature uses programming models to simulate the economic impact of aquifer depletion but is not validated with real-world data on farmer behavior (Ding and Peterson, 2012; Foster et al., 2014, 2015, 2017).

## 2 Background

Being one of the world's largest aquifers, the HPA comprises 118.8 million acres over portions of eight states in the U.S—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (McGuire, 2017). The HPA supplies over 30% of the total groundwater used for irrigation in the US (Steward et al., 2013), and it is the principal source of irrigation in a major agricultural producing region where crop yields are limited by precipitation (McGuire et al., 2003). However, the extraction of groundwater for irrigation at higher rates than natural recharge has led to persistent aquifer depletion as in many other parts of the world (Scanlon et al., 2012; Richey et al., 2015; Steward and Allen, 2016)

A rapid and substantial increase in groundwater irrigation occurred after the adoption of center pivot technology during the 1960s. Estimated groundwater withdrawals increased from 4 to 19 million acre-feet between 1949 and 1974, while estimated irrigated acreage increased from 2.1 million acres in 1940 to 13.7 million acres in 1980 (McGuire et al., 2003). Water-level declines began in some areas of the HPA soon after this substantial increase in groundwater irrigation. By 1980, water levels had declined by more than 100 ft in portions of Kansas, New Mexico, Oklahoma, and Texas (McGuire et al., 2003). Depletion is much greater in the Central and Southern High Plains compared to depletion in the Northern portions. For instance, average water-level change from pre-development to 2015 ranged from a decline of 41.1 feet in Texas to a decline of only 0.9 feet in Nebraska (McGuire, 2017).

Saturated thickness is a measure of the vertical distance between the water table and the base of the aquifer, and thus reflects the resource stock. Current saturated thickness is mainly explained by pre-development saturated thickness, aquifer recharge, and extraction for irrigation. Pre-development saturated thickness is the estimated saturated thickness that existed before any effects imposed by human activity, and in our study, it is represented by a measure of saturated thickness in 1930[1]. The pre-development thickness of the Ogallala formation—the principal geologic unit of the HPA—was determined by the structure and features of the eroded pre-Ogallala surface roughly 24 to 5 million years ago, and the greatest thickness occurs where sediments have filled previously eroded drainage channels (NPGCD, 2021). Therefore, the pre-development saturated thickness was shaped by the structure of the eroded pre-Ogallala surface that existed long before human settlement which makes it unrelated to human activity.

By looking at figure 1, it is apparent that the geographic patterns of saturated thickness in 2017 resemble the pattern of pre-development saturated thickness in 1930. In general, the greatest contemporaneous saturated thickness occurs in those areas where the initial saturated thickness was also the largest.

[1] See Haacker et al. (2016) for more discussion on the pre-development date.

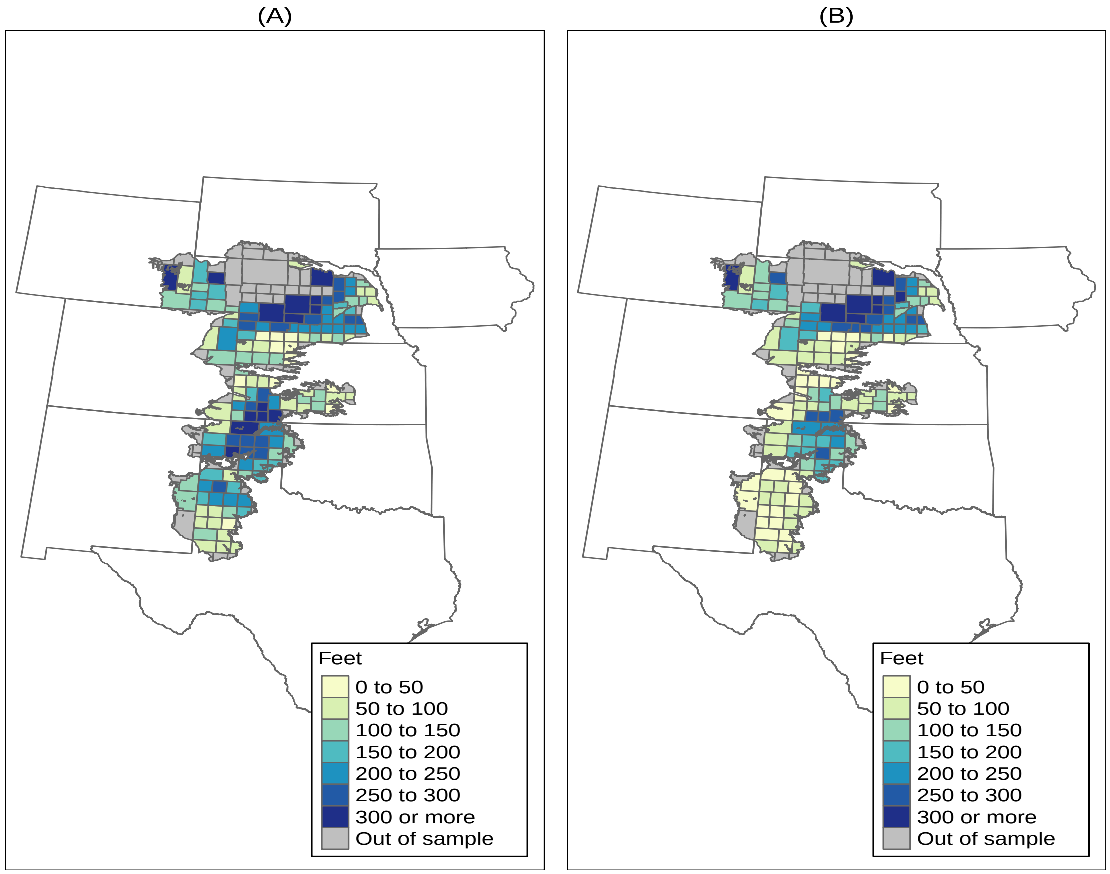


Figure 1: (A) Saturated thickness in 1930 (B) Saturated thickness 2017

The variability in current saturated thickness is also driven by variations in groundwater recharge from precipitation (Scanlon et al., 2012). Recharge is the natural movement of water into an aquifer and is mainly determined by climate, soil, vegetation, land use, and depth to the water table (Sophocleous, 2005). The HPA is commonly divided into three sub-regions with different recharge rates. The Northern area of the aquifer consists of renewable groundwater formations with large rates of recharge. The Central and Southern parts of the aquifer, however, consist of nonrenewable or fossil groundwater with little recharge (Scanlon et al., 2012).

# 3 Conceptual Model

Reductions in groundwater availability affect farmers' economic benefits through two main mechanisms: decreasing the well yield and increasing the cost of pumping. The well yield controls the maximum rate of groundwater extraction and is determined by the saturated thickness and hydraulic conductivity. The cost of pumping increases as the aquifer depletes because it requires more energy to pump the water from a greater distance to the surface. The overall economic impact of a change in groundwater availability can be analyzed using the relationship between saturated thickness and the returns to land.

$$B_{it}(ST_{it}) = \Phi_{it}^{irr}(ST_{it})R_{it}^{irr}(ST_{it}) + (1 - \Phi_{it}^{irr}(ST_{it}) - \Phi_{it}^{past})R_{it}^{non} + \Phi_{it}^{past}R_{it}^{past}, \tag{1}$$

where $B_{it}$ is the return to land per acre of the county overlying the aquifer for county $i$ in year $t$, $\Phi_{it}^{irr}$ is the proportion of acres in the county that are irrigated, $\Phi_{it}^{past}$ is the proportion of acres in the county that are pastureland, $(1 - \Phi_{it}^{irr} - \Phi_{it}^{past})$ is the proportion of acres in the county that are nonirrigated, $R_{it}^{irr}$, $R_{it}^{non}$ and $R_{it}^{past}$ are the irrigated, nonirrigated and pastureland cash rental rates, and $ST_{it}$ is the saturated thickness.

We assume that the area of pastureland does not depend on saturated thickness. This assumption implies that when water scarcity increases, farmers switch to nonirrigated cropland as the next most productive use of land after irrigated cropland. As a result, we may underestimate the extensive margin response if some farms convert from irrigated cropland to pasture. Deines et al. (2020) estimate that 87% of lost irrigated area through 2100 could support nonirrigated crop production and 13% was better suited to pasture use. Therefore, the assumption that irrigated cropland converts to nonirrigated cropland rather than pasture is reasonable for our study area and is unlikely to substantially affect our results.

A change in returns to land due to an exogenous change in saturated thickness is expressed as:

$$\frac{\partial B_{it}}{\partial ST_{it}} = \underbrace{\frac{\partial \Phi_{it}^{irr}}{\partial ST_{it}}(R_{it}^{irr} - R_{it}^{non})}_{\textbf{Extensive Margin}} + \underbrace{\frac{\partial R_{it}^{irr}}{\partial ST_{it}}\Phi_{it}^{irr}}_{\textbf{Intensive Margin}}. \tag{2}$$

Farmers may respond to increased water scarcity along adjustments in the extensive and intensive margins. On the extensive margin, the farmer decides what proportion of the field to plant with nonirrigated and irrigated crops. The intensive margin reflects changes in economic value due to changes in the irrigated cash rental rate. The intensive margin response captures two main adjustments: a reduction in water intensity for the proportion of the field that is irrigated and a switch from relatively water intensive crops (e.g., corn) towards less water-intensive crops (e.g., wheat).

The objective of our empirical model is to estimate nonlinear functions in saturated thickness of $\Phi_{it}^{irr}(ST_{it})$ and $R_{it}^{irr}(ST_{it})$ controlling for other explanatory variables, and then use equation 2 to simulate the economic impact of different scenarios of aquifer depletion. We allow a nonlinear relationship between saturated thickness on the output of interest based on recent studies which show that declines in well yield may have negative nonlinear impacts on irrigated area. Foster et al. (2014) and Foster et al. (2015) predict large reductions in irrigated area when well yield is limiting due to intraseasonal groundwater supply constraints. Intuitively, when saturated thickness is above a certain level, then well yield is not a binding constraint and different levels of saturated thickness may have minimal impact on producer behavior. But for lower saturated thickness where well yields become constraining, then producers adjust their behavior by either reducing acres irrigated or reducing irrigation intensity.

It is important to note that we do not have data available on depth to water table—vertical distance from the land surface to water table—to explicitly control for differences in the cost of pumping. If saturated thickness and depth to water table are perfectly or highly correlated, the estimated impact of saturated thickness on the outputs reflects the total impact of depletion through changes in well yields and cost of pumping. However, if these two variables are not highly correlated we would most likely underestimate the impact of depletion since we do not fully account for the impact of increasing pumping costs. A large literature examines how pumping costs affect water use indicating that the price elasticity of irrigation water demand is, in general, inelastic (e.g., Scheierling et al., 2006; Schoengold et al., 2006; Hendricks and Peterson, 2012; Pfeiffer and Lin, 2014; Mieno and Brozović, 2017). Recent studies have shown how reductions in well yield have a large negative impact on economic outputs (e.g., Foster et al., 2014, 2015, 2017; Manning and Suter, 2019; Rouhi-Rad et al., 2020). In particular, Foster et al. (2015) suggest that well yield has larger impacts on irrigated production areas and profits than depth to groundwater and pumping costs which cast doubt on the assumption that depth to water is the main hydrogeological variable determining farmers' decisions.

# 4 Empirical Strategy

The objective of our econometric model is to estimate the impact of a change in saturated thickness on irrigated acres and irrigated cash rental rates. Even after controlling for relevant confounders, our estimates are subject to potential bias from feedback effects between saturated thickness and irrigation behavior. The feedback effect is evident between irrigated acres and saturated thickness which would bias our estimates downward—as farmers expand irrigated acres, extraction of groundwater increases and saturated thickness decreases. We propose to use pre-development saturated thickness as an instrument to obtain a source of plausibly exogenous variation in saturated thickness.

## 4.1 Econometric Model

We estimate two-stage least square (2SLS) models of irrigated acres and irrigated cash rental rates on saturated thickness. We model the nonlinear relationship between saturated thickness on the output of interest using linear spline regression which is a piecewise linear function that fits a line in each segment of the saturated thickness space defined by the knots while requiring continuity at the knot (Harrell, 2001).

The second-stage equation that we estimate is:

$$Y_{it} = \beta_0 + \beta_1[(1 - D_{it})ST_{it} + D_{it}K] + \beta_2 D_{it}(ST_{it} - K) + \alpha X_{it} + \delta_g + \gamma_{rt} + \varepsilon_{it}, \qquad (3)$$

where $K$ is the location of spline knot and

$$D_{it} = \begin{cases} 0 & \text{if } ST_{it} < K \\ 1 & \text{if } ST_{it} \geq K. \end{cases}$$

$Y_{it}$ reflects either the percentage of acres irrigated of the total county area over the aquifer—note that we scale the dependent variable to $\Phi_{it}^{irr} \times 100$ for ease of interpreting marginal effects[2]—or the irrigated rental rate ($R_{it}^{irr}$) in county $i$ at time $t$; $ST_{it}$ is the average saturated thickness in the county; $[(1-D_{it})ST_{it}+D_{it}K]$ and $D_{it}(ST_{it}-K)$ are linear spline functions of saturated thickness; $X_{it}$ is a vector of controls (i.e., climatic variables, aquifer characteristics, and soil suitability for corn and soybeans); $\delta_g$ is the fraction of county area in each soil group; $\gamma_{rt}$ are state-by-year fixed effects for state $r$ and year $t$; and errors ($\varepsilon_{it}$) are clustered at the agricultural district level to adjust for heteroskedasticity, within-county correlation over time and spatial correlation between counties in a district.

[2]Even though our dependent variable (percentage of acres irrigated) is expressed in percentage, we use a 2SLS model given its values are inside the range (0, 1). See table 1.

The coefficients of interest throughout the paper are $\beta_1$ and $\beta_2$. The estimated $\beta_1$ can be interpreted as the effect of saturated thickness on agricultural outcomes when the level of saturated thickness is less than $K$, while the estimated $\beta_2$ is the effect of saturated thickness on agricultural outcomes when the level of saturated thickness is greater than $K$. Based on exploratory analysis of our data and previous studies described above, we allow for one spline knot location ($K = 70$).

The linear spline functions of saturated thickness in equation 3 are treated as endogenous and we use linear spline functions of pre-development saturated thickness as instruments. The first stage regressions are defined as:

$$\begin{aligned}[(1-D_{it})ST_{it}+D_{it}K] = \theta_0^1 + \theta_1^1[(1-D_{it}^{'})ST1930_{it}+D_{it}^{'}K^{'}] + \theta_2^1 D_{it}^{'}(ST1930_{it}-K^{'}) + \\ + \phi^1 X_{it} + \delta_g^1 + \gamma_{rt}^1 + v_{it}^1,\end{aligned} \tag{4}$$

$$\begin{aligned}(ST_{it}-K) = \theta_0^2 + \theta_1^2[(1-D_{it}^{'})ST1930_{it}+D_{it}^{'}K^{'}] + \theta_2^2 D_{it}^{'}(ST1930_{it}-K^{'}) + \\ + \phi^2 X_{it} + \delta_g^2 + \gamma_{rt}^2 + v_{it}^2,\end{aligned} \tag{5}$$

where $K^{'}$ is the spline knot and

$$D_{it}^{'} = \begin{cases} 0 & \text{if } ST_{it} < K^{'} \\ 1 & \text{if } ST_{it} \geq K^{'}. \end{cases}$$

It is important to note that we have two endogenous explanatory variables ($[(1-D_{it})ST_{it} + D_{it}K]$ and $(ST_{it} - K)$). We can apply the standard 2SLS estimator using as instruments $[(1-D_{it}^{'})ST1930_{it}+D_{it}^{'}K^{'}]$ and $D_{it}^{'}(ST1930_{it}-K^{'})$. $ST1930_{it}$ is pre-development saturated thickness, and $[(1-D_{it}^{'})ST1930_{it}+D_{it}^{'}K^{'}]$ and $D_{it}^{'}(ST1930_{it}-K^{'})$ are linear spline functions of pre-development saturated thickness with $K = 90$. Since pre-development saturated thickness is larger than current saturated thickness, the selected knot ($K = 90$) also results larger.

For the statistical inference, standard errors are clustered at the agricultural district level to adjust for heteroskedasticity, within-county correlation over time and spatial correlation between counties within a district. Bester et al. (2011) propose clustering by large spatial groups as a simple and flexible method to account for spatial correlation, under the assumption that in large groups most observations are far from borders and uncorrelated with observations in other groups. Bester et al. (2011) show that clustering results in valid inference if cluster-level averages are approximately independent.

## 4.2 Controlling for Potential Confounders

We explicitly include several variables to account for cross-sectional heterogeneity between counties in equation 3. To account for the effect of dry or wet years on the agricultural outcomes, we include the contemporaneous cumulative measures for precipitation and reference evapotranspiration demand within the growing season (April 1 - September 30). For example, a drought could induce some farmers to irrigate more acres than in previous years. We also include four long-run climate variables to describe the climate in each county: average precipitation, average reference evapotranspiration, the average number of growing degree days between 10°C and 30°C, and the average number of degree days greater than 32°C. The average number of growing degree days between 10°C and 30°C measures the exposure to heat within a range of temperatures considered beneficial to crop growth, and the average number of degree days greater than 32°C measures the exposure to heat levels that are detrimental to crop growth (Schlenker et al., 2006).

To account for the aquifer's characteristics in each county we include three variables: hydraulic conductivity, specific yield and natural recharge. Hydraulic conductivity is a measure of the rate at which water can move laterally, and specific yield is the volume of water per unit volume of aquifer that can be extracted by pumping. As hydraulic conductivity and specific yield increase, we expect a reduction in pumping costs as water moves more rapidly across porous spaces of the aquifer. Furthermore, hydraulic conductivity is also a measure of the shared nature of an aquifer. As hydraulic conductivity increases, more water can be lost from a given well to the common pool, increasing the incentives to pump more water (Edwards, 2016). Natural recharge is the natural movement of water into an aquifer, not including return flows from irrigation. As we described before, cross sectional differences in the rate of recharge significantly explain variation in current saturated thickness. Hence, natural recharge controls for changes in agricultural outcomes as consequence of different expected rates of aquifer depletion that affect expectations of future aquifer stocks. Finally, to adjust for the effect of different soil characteristics on agricultural production, we control for major soil groups. We also include a national commodity crop productivity index for corn and soybeans to account for the soil's suitability for corn and soybeans.

Our specification also includes state-by-year fixed effects to control for spatial-temporal variation and allow for separate effect for each possible combination of state and year. The state-by-year fixed effects may capture, for example, variation in commodity price shocks and groundwater laws used by the states. For example, Nebraska uses correlative rights, Kansas and Colorado both use prior appropriation rights while in Texas groundwater is governed by the rule of capture. Intuitively, the empirical strategy compares counties within the same state for a given year, with similar climatic, soil, and aquifer characteristics that have a different amount of current saturated thickness caused by variation in pre-development saturated thickness. We also employ robustness tests in which we control for groundwater management districts-by-year fixed effects which show similar results to our preferred estimates.

County fixed effects are problematic in our study to control for unobserved heterogeneity of counties because there is a substantial reduction in the variation of saturated thickness. To investigate the use of county fixed effects, we regress saturated thickness on various sets of fixed effects and then capture the standard deviation of the residuals which reflect the remaining saturated thickness variation (Fisher et al., 2012). The residual standard deviation of saturated thickness is equal to 102.4 when saturated thickness is regressed on an intercept while it drops to 11.3 once we include county fixed effects. We also regress saturated thickness on all covariates and controls used in our main model specification and the residual standard deviation of saturated thickness is equal to 68.3. Therefore, including county fixed effects substantially decreases the residual variation in saturated thickness compared to our preferred specification. Furthermore, we estimate our main model of interest including county fixed effects but the impact of saturated thickness on the outcomes was implausibly large. Another issue with including county fixed effects is that we need to find a new instrument because pre-development saturated thickness has no variation over time[3].

## 4.3 IV Assumptions

To identify $\beta_1$ and $\beta_2$ in the second stage (equation 3), the instruments must be an important factor in accounting for the saturated thickness variation. There is little doubt that the current saturated thickness is correlated with saturated thickness in 1930. As we described in section 2, it is apparent that the geographic patterns of saturated thickness in 2017 resemble the pattern of pre-development saturated thickness in 1930 (figure 1). In general, the greatest contemporaneous saturated thickness occurs in those areas where initial saturated thickness was also the largest. Figure 2 provides a scatter plot of the relationship between pre-development saturated thickness and current saturated thickness. Again, this relationship shows that counties with low pre-development saturated thickness have substantially

[3]The use of county fixed effects do not resolve the endogeneity from feedback effects since a change in irrigated acres affects the change in the stock of groundwater.

less saturated thickness today.

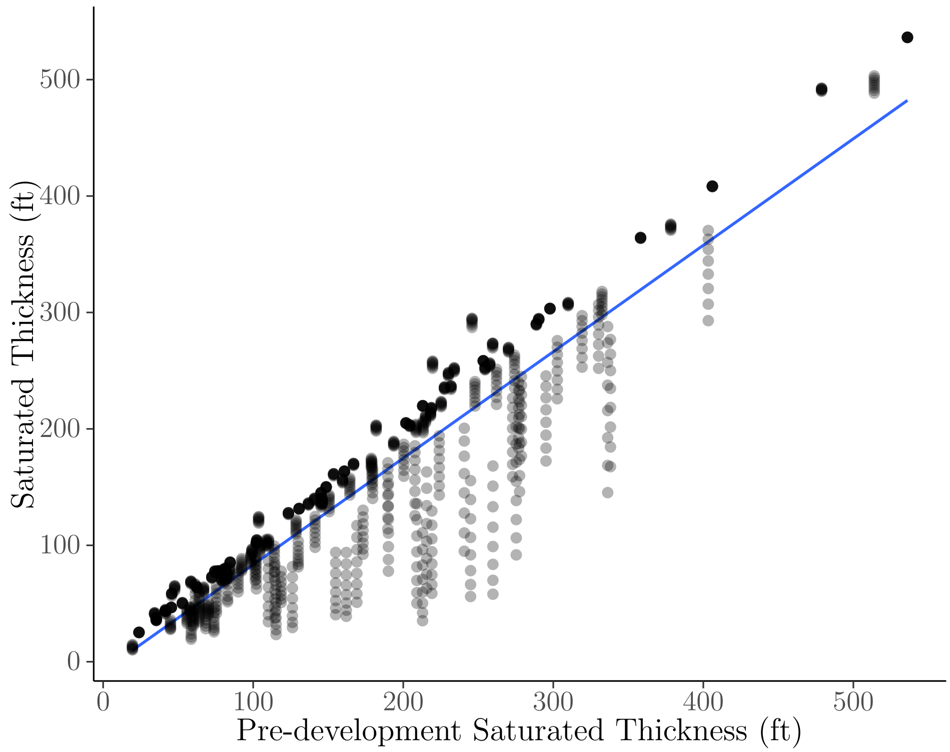


Figure 2: Relationship between pre-development saturated thickness and current saturated thickness

Identification also requires the exclusion restriction to be met. The exclusion restriction implied by our instrumental variable regression is that, conditional on the controls included in the regression, the pre-development saturated thickness has no effect on the percentage of acres irrigated or irrigated cash rents, other than its effect through the current saturated thickness. That is, unobservable effects that impact irrigated acres or irrigated rents are not correlated with variation in pre-development saturated thickness. Our exclusion restriction is plausible since, as explained in section 2, the pre-development saturated thickness was shaped by the structure and features of the eroded pre-Ogallala surface that existed long before human settlement which makes it unrelated to human activity.

The major concern with this exclusion restriction, however, is that pre-development saturated thickness could be spuriously correlated with productivity of the land today. In this case, the instrumental variables estimates may be assigning the effect of land productivity on outcomes to saturated thickness. This is unlikely to be the case since the ancient structure of the eroded pre-Ogallala surface has no inherent relationship with the agricultural productivity of the current land surface because the geologic process that formed the current land surface was in a different geologic era and a different geologic process. The soil and climate controls included in our models also help reduce concerns that there may happen to be spurious correlations between pre-development saturated thickness and current land productivity that affects irrigated acres and rents. Finally, we include results from a falsification test to evaluate if pre-development saturated thickness is correlated with unobserved land productivity.

# 5 Data and Study Area

Our study area includes 141 counties in seven states overlying the HPA—Colorado, Kansas, Nebraska, New Mexico, Texas and Wyoming. We restrict the analysis to counties with a proportion of their total area over the aquifer greater than 60% to ensure that they depend primarily on groundwater for irrigation. The area of the sand hills in Nebraska overlies the aquifer but has minimal irrigation because the sandy soil makes the region unsuitable for crop farming (USDA-NRCS, 2006; Peterson et al., 2016). Therefore, we exclude from our analysis counties with greater than 55% of their total area in the sand hills. Table 1 shows summary statistics of the variables used in each econometric model. Next, we describe each source of data.

Irrigated area at the county-level are available every five years from the US Census of Agriculture. We calculate the percentage of acres irrigated dividing the irrigated acres by the total land area of the county overlying the aquifer. The empirical analysis of the extensive margin focuses on a balanced panel of 141 counties over the HPA from 1982 to 2017, resulting in a total of 1,128 observations. Annual data on irrigated cash rental rates for cropland at the county-level are obtained from the National Agricultural Statistics Service (NASS). The data are available from 2008 except for 2015 and 2018. We exclude, however, 2008 because the number of reported counties is small. In this case, the empirical analysis of the intensive margin focuses on an unbalanced panel of 141 counties over the HPA from 2009 to 2017, resulting in a total of 1,269 observations.

Daily gridded weather data are obtained from PRISM and aggregated to the county level. We calculate the cumulative measure for precipitation and reference evapotranspiration demand within the growing season (April 1 - September 30) for each year. Reference evapotranspiration is a measure of the evaporative demand independent of crop characteristics and soil factors within a county. It is calculated using the reduced-set Penman-Monteith method following Hendricks (2018). We also construct four long-run climate variables: average precipitation, average reference evapotranspiration, the average number of degree days between 10° and 30°, and the average number of degree days greater than 32°. We calculate the cumulative measure for each of these four variables within the growing season (April 1 - September 30) for each year and then calculate the 30-year average (1987-2017).

Hydrologic characteristics of the HPA are obtained from two different sources. Predevelopment saturated thickness, the average annual saturated thickness and the projected saturated thickness—values of saturated thickness up to 2100—are obtained from Steward and Allen (2016). Hydraulic conductivity, specific yield and natural recharge are obtained from the US Geological Survey. The hydraulic conductivity data set consists of contours and polygons that we aggregate to the county level (USGS, 1998). We use a raster of the average specific yield for the HPA and aggregate it to the county level (USGS, 2012; McGuire et al., 2012). Natural recharge data are also obtained from a raster and aggregated at county level (USGS, 2011; Houston et al., 2013). The average 2000-09 recharge is estimated by

USGS using the Soil-Water Balance (SWB) model which assumes that irrigation systems are 100% efficient and there is no surplus irrigation water for recharge. This means that natural recharge does not include return flows from irrigation (Stanton et al., 2011).

Major soil groups are obtained from Hornbeck and Keskin (2014). For example, some of the soil groups appearing within the HPA are: alluvial, brown, chernozem, and chestnut[4]. The national commodity crop productivity index for corn and soybeans is obtained from the Soil Survey Geographic database (SSURGO). Values range from 0.01 (low productivity) to 0.99 (high productivity).

Figure 3 shows maps of the percentage of acres irrigated and irrigated rental rates in 2017. The spatial distributions of irrigated acres and irrigated rental rates appear to be related to the groundwater availability in the aquifer. In general, irrigated acres are largest in the north-east and decline moving south-west where saturated thickness is low and recharge from precipitation is not enough to balance groundwater demand for irrigation. Similarly, rental rates are largest in the Northern High Plains and decline moving south into the more arid region.

[4]A map can be found in the Hornbeck and Keskin (2014)'s online Appendix: https://assets.aeaweb.org/asset-server/articles-attachments/aej/app/app/0601/2012-0256_app.pdf

Table 1: Summary statistics for variables in the econometric analysis

| | Extensive Margin Sample | | Intensive Margin Sample | |
|---|---|---|---|---|
| Variables | Mean | Std. Dev. | Mean | Std. Dev. |
| Percentage of Acres Irrigated | 18.34 | 15.41 | – | – |
| Cash Irrigated Rent ($/acre) | – | – | 151.64 | 69.58 |
| Saturated Thickness (ft) | 149.69 | 102.50 | 141.29 | 102.76 |
| Growing Season Precipitation (in) | 15.85 | 4.84 | 17.34 | 5.82 |
| Growing Season Evapotranspiration (in) | 34.46 | 2.89 | 34.79 | 3.41 |
| Predevelopment Saturated Thickness (ft) | 172.50 | 103.54 | 172.50 | 103.54 |
| 30-yr Avg. Precipitation (in) | 16.31 | 3.10 | 16.31 | 3.10 |
| 30-yr Avg. Evapotranspiration (in) | 34.56 | 2.60 | 34.56 | 2.60 |
| 30-yr Avg. Growing Degree Days (hundreds) | 18.36 | 2.60 | 18.36 | 2.60 |
| 30-yr Avg. Extreme Degree Days | 32.33 | 17.57 | 32.33 | 17.57 |
| Hydraulic Conductivity (ft/day) | 81.40 | 47.14 | 81.40 | 47.14 |
| Specific Yield (fraction) | 0.16 | 0.02 | 0.16 | 0.02 |
| Natural Recharge (in) | 2.62 | 2.13 | 2.62 | 2.13 |
| Crop Productivity Index (fraction) | 0.30 | 0.14 | 0.30 | 0.14 |
| N | 1,128 | | 1,269 | |

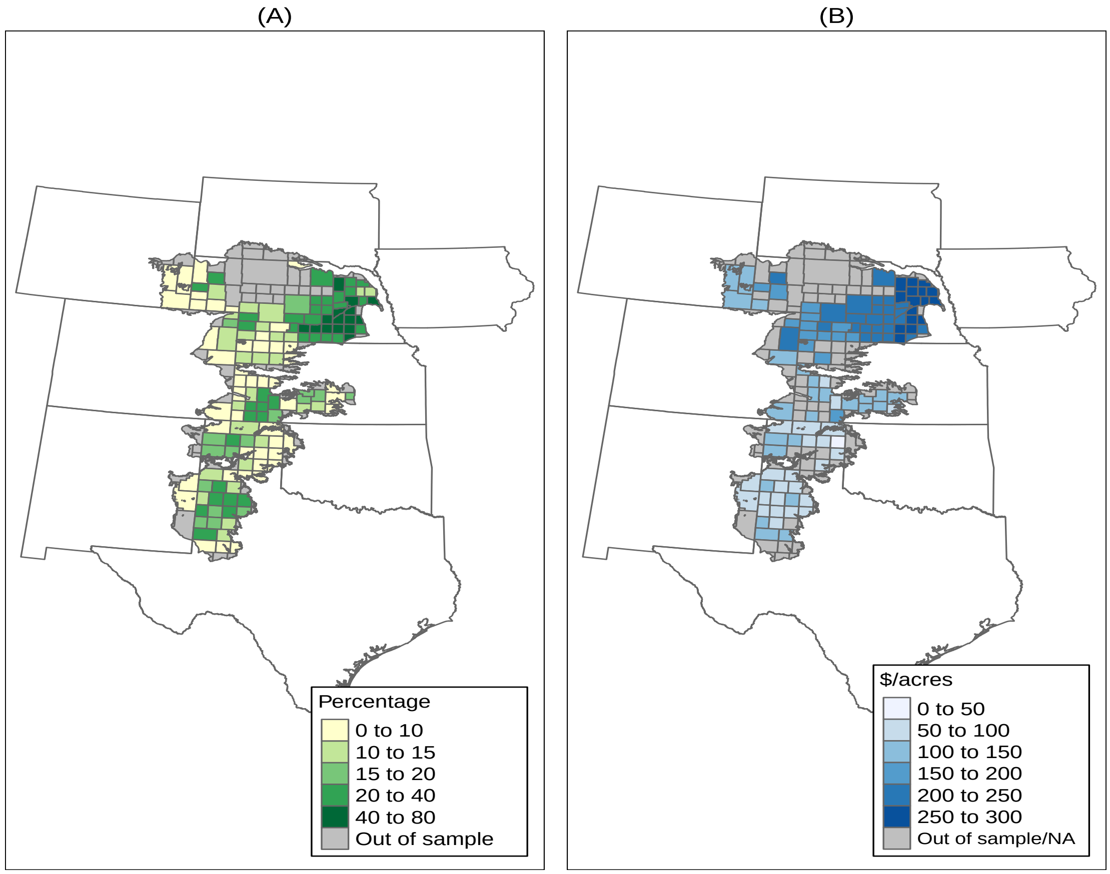


Figure 3: (A) Percentage of acres irrigated in 2017 (B) Irrigated rental rates in 2017

# 6 Results and discussion

## 6.1 2SLS Regressions Results

In this section, we present the estimates from the econometric models described in the previous section which regress each of the outcomes of interest—percentage of acres irrigated and irrigated rental rates—on saturated thickness. These parameter estimates provide the information required to simulate how farmers respond to projected saturated thickness in the future. Our focal variables throughout the analysis are the saturated thickness linear splines.

The main results of the regression of percentage of acres irrigated are shown in table 2. In column 1, we present OLS estimates which show a positive and significant relationship between irrigated acres and saturated thickness. However, we cannot interpret this result as causal because the estimates are subject to bias due to feedback effects. Since larger irrigated acres reduce saturated thickness through the hydrologic feedback, we expect the coefficients on saturated thickness to be biased downward. The corresponding 2SLS estimates are shown in column 2. The coefficients on the saturated thickness linear splines are significant at the 5% level and larger than the OLS estimates. We also report the Wu-Hausman test statistic, which examines the null hypothesis that the spline saturated thickness variables are exogenous. The test statistic (11.10) is significant at the 1% level indicating that the downward bias of OLS from the feedback effect is statistically significant. Furthermore, the value of F-statistics testing the null hypothesis that the instruments are equal to zero in the first stage regressions are greater than 10 (65.70 and 106.61). Therefore, we are not concerned about weak instruments (Staiger and Stock, 1997).

The coefficient on the first saturated thickness linear spline indicates that when the level of saturated thickness is less than 70 ft, a 1 ft decrease in saturated thickness results in a 0.211 percentage point decrease in the area of the county that is irrigated (column 2 of table 2). This reflects about a 2.1% decrease in irrigated acres since 10.24% of a county is irrigated on average when saturated thickness is less than 70 ft. By contrast, when the level of saturated thickness is greater than 70 ft, a 1 ft decrease in saturated thickness results in a 0.044 percentage point decrease in the area of the county that is irrigated. This result reflects about a 0.22% decrease in irrigated acres since 21.04% of a county is irrigated on average if saturated thickness is greater than 70 ft. As expected, the effect of a decrease in saturated thickness is larger if the initial saturated thickness is already small.

For ease of interpretation, we show the average effect of a decrease in saturated thickness in terms of irrigated acres using two examples: Wichita County in Kansas and Dallam

County in Texas. Saturated thickness in Wichita County has declined from 46 ft in 1982 to 26 ft in 2017 (decrease of 20 ft). Our results indicate that a decrease of 20 ft in saturated thickness decreased acres irrigated from 65,696 to 46,288 (30% reduction). By comparison, saturated thickness in Dallam has declined from 153 ft in 1982 to 77 ft in 2017 (decrease of 76 ft). In this case, our results show that a decrease of 76 ft in saturated thickness decreased acres irrigated from 186,135 to 153,919 (17% reduction).

Table 2: OLS and 2SLS Regression of Percentage of Acres Irrigated

| | OLS (1) | 2SLS (2) |
|---|---|---|
| $[(1-D_{it})ST_{it} + D_{it}K]$ | 0.133** | 0.211** |
| | (0.057) | (0.098) |
| $D_{it}(ST_{it} - K)$ | 0.035*** | 0.044*** |
| | (0.011) | (0.014) |
| Growing Season Precipitation | -0.174* | -0.152 |
| | (0.100) | (0.096) |
| Growing Season Evapotranspiration | -1.192** | -1.220*** |
| | (0.446) | (0.468) |
| 30-yr Avg. Precipitation | -2.566*** | -2.372*** |
| | (0.744) | (0.786) |
| 30-yr Avg. Evapotranspiration | 2.790*** | 3.135*** |
| | (0.690) | (0.703) |
| 30-yr Avg. Growing Degree Days | 5.083*** | 5.539*** |
| | (0.880) | (0.707) |
| 30-yr Avg. Extreme Degree Days | -0.782*** | -0.823*** |
| | (0.093) | (0.098) |
| Hydraulic Conductivity | 0.005 | 0.016 |
| | (0.025) | (0.024) |
| Specific Yield | 63.199 | 52.986 |
| | (44.801) | (44.954) |
| Natural Recharge | 5.076*** | 4.912*** |
| | (0.993) | (1.010) |
| Crop Productivity Index | -13.639 | -12.415 |
| | (13.941) | (14.175) |
| Soil groups | Yes | Yes |
| State-by-year FE | Yes | Yes |
| *F-statistics for IVs in first stage* | | 65.70 |
| | | 106.61 |
| Wu-Hausman test | | 11.10*** |
| N | 1112 | 1112 |

Standard errors clustered by agricultural district are reported in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Other covariates in the regression of percentage irrigated acres are also significant. The long-term precipitation and evapotranspiration are both significant and show the expected signs. Since precipitation and evapotranspiration are measures of natural water supply and water demand, irrigation is more valuable—and thus irrigated acres are larger—when precipitation is low and evapotranspiration is large. Natural recharge is associated with increases in the percentage of acres irrigated. That is, if a county has greater recharge then farmers might expect less future depletion which could lead them to invest in irrigation infrastructure, increasing irrigated acres. The crop productivity index is insignificant. However, we also capture the variation in climatic factors and soil productivity affecting crop productivity by including the climatic variables and soil groups.

Table 3 summarizes the main results of the regression of irrigated cash rents. We expect that if groundwater is constrained, farmers may irrigate less per acre and this could affect crop yields and net returns on land remaining in irrigation. The feedback between irrigated rents and saturated thickness is less obvious than when considering irrigated acres. Intuitively, it could be that more productive land that uses more water has higher cash rental rates, but the use of more water on this land decreases current saturated thickness. The OLS estimated coefficients on the saturated thickness linear splines are lower than the corresponding 2SLS coefficients, and the Wu-Hausman test statistic (3.64) is significant at the 5% level indicating that the bias of OLS is statistically significant. Table 3 also presents the values of the F-statistics (33.03 and 60.08) for the first stage model which provides support regarding the strength of our instruments.

The 2SLS coefficients on the saturated thickness linear splines show the expected sign but only the coefficient for the first segment is significant at the 5% level (column 2 of table 3). Therefore, when the level of saturated thickness is less than 70 ft, a 1 ft decrease in saturated thickness results in a \$0.72/acre decrease in irrigated cash rent. This effect represents 0.71% of the average irrigated cash rents (\$102/acre) in a county with saturated thickness less than 70 ft. By contrast, saturated thickness does not significantly impact irrigated cash rents for levels greater than 70 ft. We also use Wichita and Dallam counties as examples to understand the impact of saturated thickness on irrigated rents. Results indicate that a decrease of 20 ft in saturated thickness since 1982 in Wichita County decreased irrigated rental rates from \$102/acre to \$87/acre (14% reduction). By contrast, results show that a decrease of 76 ft in saturated thickness in Dallam County decreased irrigated rental rates from \$101/acre to \$100.2/acre but this impact is not statistically different from zero.

Table 3: OLS and 2SLS Regression of Irrigated Rental Rates

| | OLS | 2SLS |
|---|---|---|
| | (1) | (2) |
| $[(1 - D_{it})ST_{it} + D_{it}K]$ | 0.510** | 0.723** |
| | (0.228) | (0.294) |
| $D_{it}(ST_{it} - K)$ | 0.002 | 0.010 |
| | (0.030) | (0.029) |
| Growing Season Precipitation | 0.773* | 0.815** |
| | (0.389) | (0.357) |
| Growing Season Evapotranspiration | 0.758 | 0.784 |
| | (1.491) | (1.336) |
| 30-yr Avg. Precipitation | -6.497** | -6.210*** |
| | (2.476) | (2.321) |
| 30-yr Avg. Evapotranspiration | -10.525*** | -9.777*** |
| | (3.524) | (3.409) |
| 30-yr Avg. Growing Degree Days | 4.299 | 5.551 |
| | (3.844) | (3.912) |
| 30-yr Avg. Extreme Degree Days | -0.474 | -0.585 |
| | (0.491) | (0.467) |
| Hydraulic Conductivity | -0.003 | 0.019 |
| | (0.038) | (0.038) |
| Specific Yield | -28.002 | -46.783 |
| | (148.839) | (149.472) |
| Natural Recharge | 3.550** | 3.309** |
| | (1.448) | (1.338) |
| Crop Productivity Index | 129.681** | 130.946*** |
| | (48.428) | (46.301) |
| Soil groups | Yes | Yes |
| State-by-year FE | Yes | Yes |
| *F-statistics for IVs in first stage* | | 33.03 |
| | | 69.08 |
| Wu-Hausman test (p-value) | | 3.64** |
| N | 819 | 819 |

Standard errors clustered by agricultural district are reported in parentheses.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Our results also highlight the role of other covariates in determining irrigated cash rents and the coefficient estimates generally follow intuition. We find that growing season precipitation positively affects irrigated rents, indicating that when growing season precipitation is larger then a farmer may pump less water so irrigation costs should decrease and rent should increase. Results also show that a larger crop productivity index is associated with increases in irrigated rents. This result also aligns with intuition given that more productive land for high-value crops may result in higher yield and higher rents.

We use the parameters estimates and equation 2 to estimate the average economic impact of a 1 ft decrease in saturated thickness on returns to land along the extensive and intensive margins (Table 4). To estimate uncertainty due to regression estimation, we use the wild cluster bootstrap (WCB) with 1,000 replications which preserves the regressors but resamples the residuals which can be then used to define new values of the dependent variable following Cameron et al. (2008) and Roodman et al. (2019).

For ease of interpretation, we describe the average economic impact of a 10 ft decrease in saturated thickness. Our results indicate that a 10 ft decrease in saturated thickness decreased the average returns to land by \$2.27/acre of land overlying the aquifer with initial saturated thickness less than 70 ft. This effect represents a 7.9% decrease in the average returns per acre of cropland[5]. Additionally, 63% of the economic impact corresponds to adjustment through reduced irrigated acreage (extensive margin) (\$1.43/acre) while 37% occurs through reduced irrigated rental rates (intensive margin) (\$0.84/acre).

By contrast, when saturated thickness is greater than 70 ft, a 10 ft decrease in saturated thickness decreased the average returns to land by \$0.46/acre of land overlying the aquifer.

[5]We estimate the change in returns to land per acre of cropland overlying the aquifer as $\frac{\partial \hat{B}_{it}}{\partial ST_{it}} \times \frac{A^{tot.aq}}{A^{cropl.aq}}$, where $A^{tot.aq}$ is total area of the county overlying the aquifer, and $A^{cropl.aq}$ is total cropland area overlying the aquifer. Alternatively, this calculation can be interpreted as the marginal effect per acre of total land divided by the total land that is cropland. To put this marginal effect in relative terms, we divide by the weighted average cropland rental rate (area of cropland irrigated times irrigated rent plus the area of cropland nonirrigated times nonirrigated rent).

This effect represents a 0.9% decrease in the average returns per acre of cropland. Most of the economic impact occurs at the extensive margin ($0.43/acre) while adjustments at the intensive margin do not have a statistically significant impact on returns to land.

Table 4: Marginal Economic Impact of a Decrease in Saturated Thickness

| Margin of Adjustment | Marginal Effect |
|---|---|
| *Saturated thickness less than 70 ft* | |
| Extensive | -0.143*** |
| | (0.052) |
| Intensive | -0.084** |
| | (0.034) |
| Total | -0.227*** |
| | (0.051) |
| *Saturated thickness greater to 70 ft* | |
| Extensive | -0.043*** |
| | (0.012) |
| Intensive | -0.002 |
| | (0.007) |
| Total | -0.046*** |
| | (0.015) |

Bootstrap standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

## 6.2 Projections of Future Economic Returns

In this section, we estimate the economic impact of projected decrease in saturated thickness across the HPA. Parameter estimates are used to simulate how projected changes in saturated thickness impact irrigated acres and irrigated rental rates for each county in our sample holding constant other variables. We use the projected values of saturated thickness in 2050 and 2100 to calculate a change from current values in 2020.

As figures 4 and 5 show, saturated thickness is projected to decrease more rapidly in the central and southern portions of the HPA. The simulation results show that, on average, the two future saturated thickness scenarios result in more severe reductions in annual returns to land in the Central and Southern portions of the HPA. Saturated thickness is projected to decrease on average by 21 ft, 21 ft and 20 ft in Texas, Kansas and Colorado respectively, from 2020 to 2050. Simulation results show that annual returns to land decrease on average by $53.5, $34.1 and $15.7 million in Texas, Kansas and Colorado, respectively. These effects represent about 11.6%, 5.3% and 7.7% of the current predicted returns to cropland, respectively. In addition, irrigated acres are expected to decrease by 20.5%, 13.5% and 23.2% by 2050, respectively. By contrast, saturated thickness is projected to decrease on average only by 5 ft in Nebraska which implies an average reduction in annual returns to land of $10.9 million which represents about 0.42% of the current predicted returns to land. This decrease in saturated thickness would reduce irrigated acres by 1% in 2050.

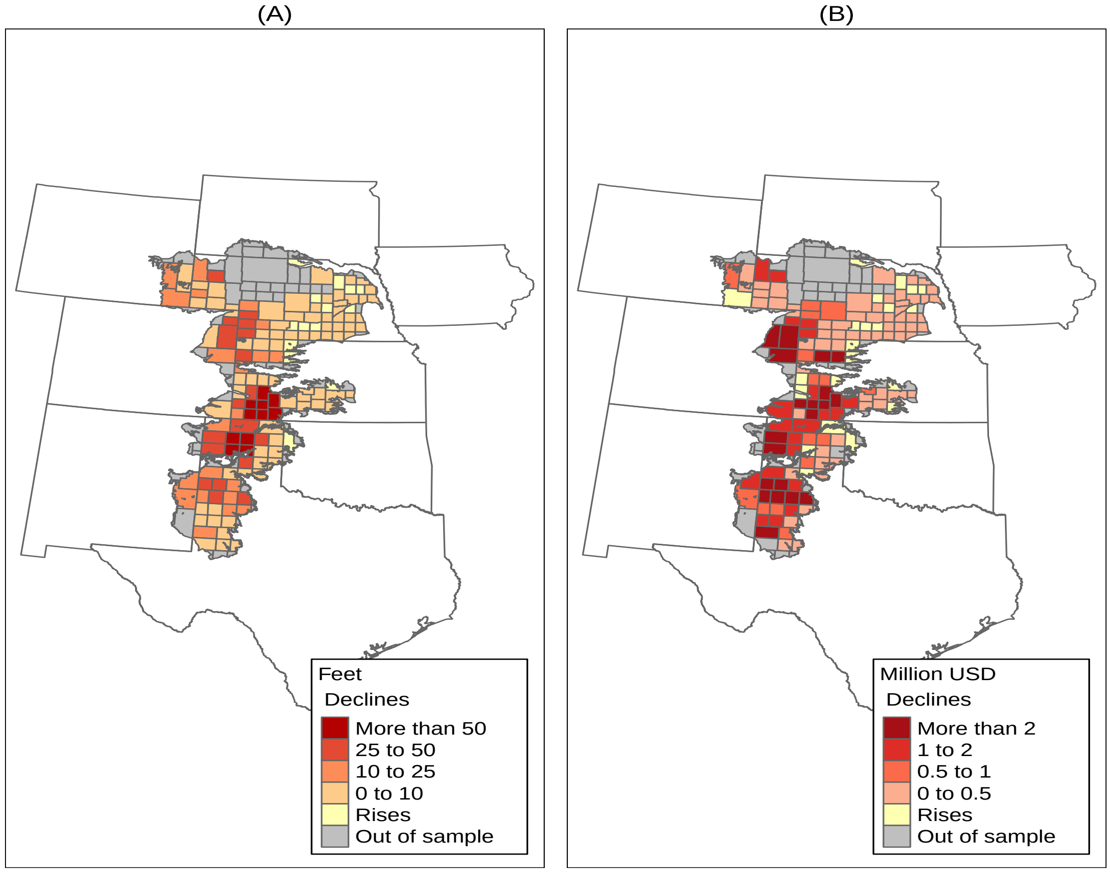


Figure 4: (A) Change in saturated thickness 2020 to 2050 (B) Annual change in returns to land

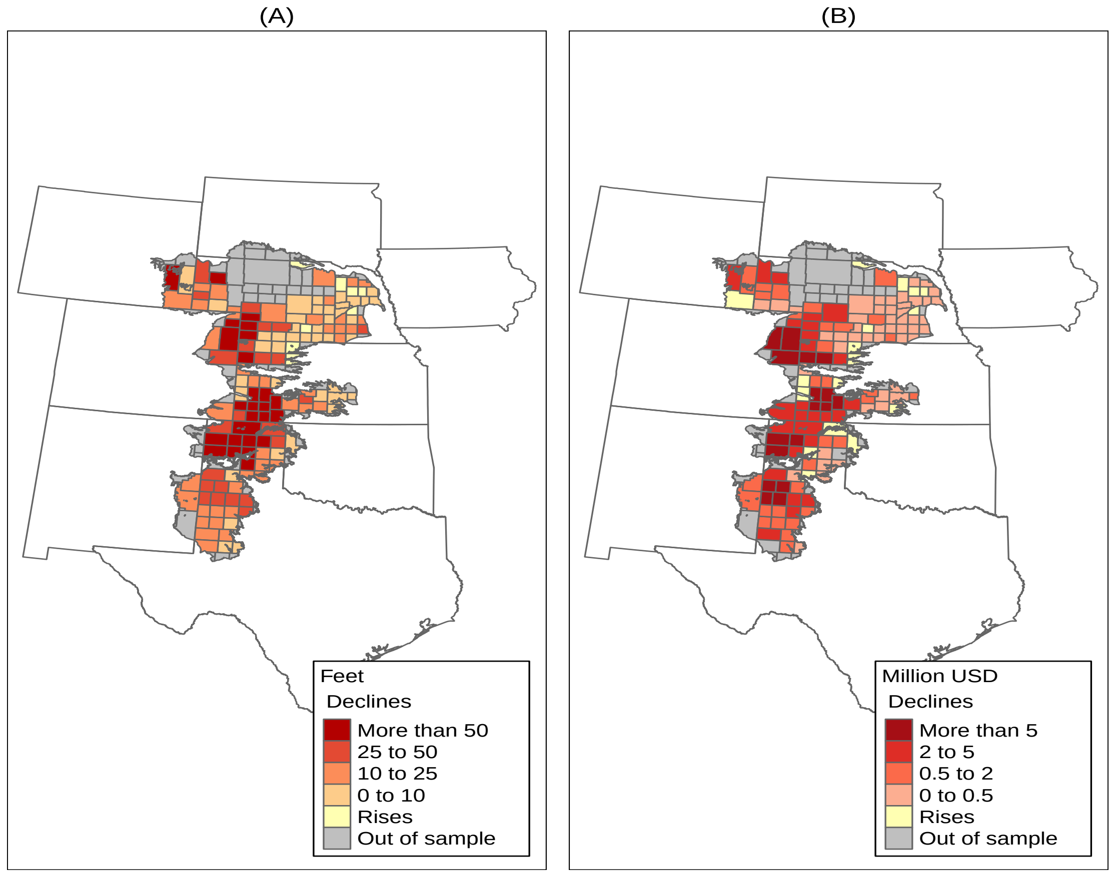


Figure 5: (A) Change in saturated thickness 2020 to 2100 (B) Annual change in returns to land

Saturated thickness is projected to decrease on average by 38 ft, 40 ft and 47 ft in Texas, Kansas and Colorado, respectively, from 2020 to 2100. In this case, annual returns to land are expected to decrease on average by \$84.3, \$86.3 and \$35.0 million in Texas, Kansas and Colorado, respectively. These effects represent about 18.3%, 13.4% and 17.2% of the current predicted returns to cropland, respectively. In this case, irrigated acres are expected to decrease by 35.8%, 32.7% and 47.3% by 2050, respectively. In Nebraska, saturated thickness is projected to decrease on average only by 15 ft in Nebraska which implies an average reduction in annual returns to land of \$32.2 million which represents about 1.3% of the current predicted returns to land. Irrigated acres are expected to decrease by 3%.

The average annual returns to land are projected to decrease by \$120.6 million in the entire High Plains region as a result of a projected average decrease in saturated thickness of 14 ft from 2020 to 2050. This effect represents about 3.0% of the current predicted returns to cropland and irrigated acres are expected to decrease by 8.4% by 2050. Similarly, saturated thickness is projected to decrease on average by 29 ft from 2020 to 2100 in the HPA which decreases average annual returns to land by \$250.5 million, representing about 6.3% of the current predicted returns to cropland. Irrigated acres are expected to decrease by 17.0% by 2100.

Finally, figure 6 shows the trend of projected annual change in returns to land by state regarding returns in 2020 for the period 2030-2100. Kansas and Texas show the strongest downward trend in returns to land during the period considered. Even though the changes in returns to land decrease in a smaller magnitude in Colorado and Nebraska, they also show a decreasing trend in returns to land.

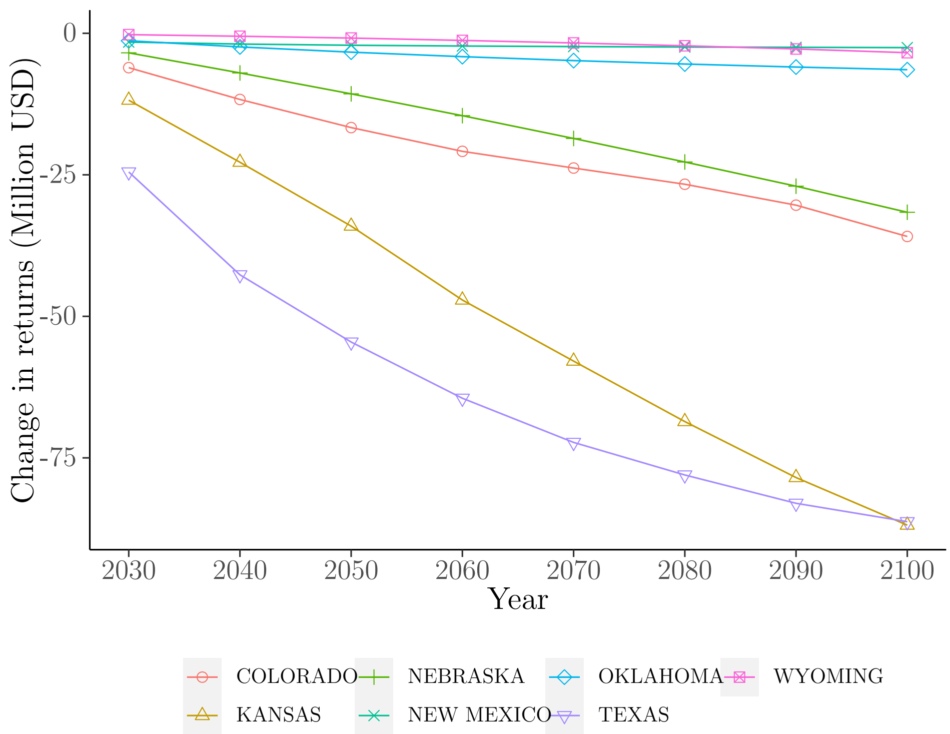


Figure 6: Annual change in returns to land from 2020

### 6.3 Falsification Test

The purpose of the falsification test is to evaluate the validity of the exclusion restriction. We estimate a reduced form regression using an alternative outcome that should not be affected by pre-development saturated thickness but would be affected by potential confounders. We select nonirrigated cash rental rates as an alternative outcome. The nonirrigated cash rental rates likely reflect the productive ability of the climate and soils and it would violate the exclusion restriction if unobserved productivity is correlated with predevelopment saturated thickness. The results in table 5 support the exclusion restriction since pre-development saturated thickness has a statistically insignificant relationship with nonirrigated rents indicating that pre-development saturated thickness is not correlated with unobserved land productivity.

Table 5: OLS Regression of Nonirrigated Rental Rates

| | OLS |
|---|---|
| $[(1 - D'_{it})ST1930_{it} + D'_{it}K']$ | 0.152 |
| | (0.151) |
| $D'_{it}(ST1930_{it} - K')$ | -0.018 |
| | (0.035) |
| Growing Season Precipitation | 0.404 |
| | (0.276) |
| Growing Season Evapotranspiration | -0.818 |
| | (2.331) |
| 30-yr Avg. Precipitation | -1.254 |
| | (2.246) |
| 30-yr Avg. Evapotranspiration | -9.886** |
| | (4.341) |
| 30-yr Avg. Growing Degree Days | 3.297 |
| | (4.124) |
| 30-yr Avg. Extreme Degree Days | -0.298 |
| | (0.516) |
| Hydraulic Conductivity | 0.096* |
| | (0.049) |
| Specific Yield | -335.762** |
| | (130.868) |
| Natural Recharge | 5.377** |
| | (2.535) |
| Crop Productivity Index | 171.924*** |
| | (52.942) |
| Soil groups | Yes |
| State-by-year FE | Yes |
| $R^2$ | 0.87 |
| N | 935 |

Standard errors clustered by agricultural district are reported in parentheses.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

## 6.4 Robustness

In this section, we examine whether estimates from our main model specification are sensitive to the inclusion of different fixed effects and to alternative splines' knot locations.

Policies regarding groundwater use not only vary by state but also within states. Local governance institutions that collectively manage the aquifer have been developed as a potential solution to promote water conservation. Colorado, Kansas, Nebraska and Texas use some type of local management district to regulate groundwater use. In Colorado, there are eight Designated Groundwater Basins with 13 groundwater management districts within these basins. Kansas has 5 Groundwater Management Districts with the authority to implement corrective measures for water conservation for a particular region. Nebraska has 23 Natural Resources Districts governed by a publicly-elected board of directors. There are 16 groundwater management areas in Texas and all groundwater conservation districts are part of at least one groundwater management area. In general, groundwater management districts (GMDs) are local districts with additional administrative authority to act on the behalf of local water users. However, the design and implementation of corrective measures for water conservation are very heterogeneous across groundwater management districts (Schoengold and Brozovic, 2018).

In our preferred specification, we control for state-by-year fixed effects. However, one might still be concerned that differences between how each groundwater management district choose to design policy might affect the outcomes of interest. Table 6, Panel A, reports the results of regressions that include groundwater management districts (GMDs) by year fixed effects. The pattern of the results is unchanged, perhaps because relatively little policy changes were implemented in the HPA until recently (see Schoengold and Brozovic (2018) for a detailed information). For instance, Kansas established the first Local Enhanced Management Area (LEMA), Sheridan 6, in 2013 which covers only a small portion of the GMD to reduce water allocations. Despite Sheridan 6, other groundwater management plans in Kansas have not substantially reduced water use (Perez-Quesada and Hendricks, 2021).

Table 6: Regression results based on GMDs-by-year fixed effects and alternative spline knot

| | Percentage of Irrigated Acres | Irrigated Rental Rates |
|---|---|---|
| | 2SLS | 2SLS |
| *Panel A: Results with GMDs-by-year FE* | | |
| $[(1-D_{it})ST_{it}+D_{it}K]$ | 0.211*** | 0.610*** |
| | (0.073) | (0.150) |
| $D_{it}(ST_{it}-K)$ | 0.044*** | -0.031 |
| | (0.015) | (0.026) |
| GMDs-by-year FE | Yes | Yes |
| F-statistic for IVs in first stage | 43.38 | 46.39 |
| | 73.13 | 49.19 |
| Wu-Hausman test | 20.31*** | 1.83 |
| *Panel B: Results with $K=60$ and $K^{'}=80$* | | |
| $[(1-D_{it})ST_{it}+D_{it}K]$ | 0.241* | 1.064** |
| | (0.124) | (0.448) |
| $D_{it}(ST_{it}-K)$ | 0.046*** | 0.011 |
| | (0.015) | (0.030) |
| GMDs-by-year FE | Yes | Yes |
| F-statistic for IVs in first stage | 46.90 | 36.84 |
| | 97.88 | 62.36 |
| Wu-Hausman test | 11.32*** | 5.69** |
| *Panel C: Results with $K=80$ and $K^{'}=100$* | | |
| $[(1-D_{it})ST_{it}+D_{it}K]$ | 0.191** | 0.543** |
| | (0.086) | (0.225) |
| $D_{it}(ST_{it}-K)$ | 0.041*** | 0.008 |
| | (0.014) | (0.030) |
| GMDs-by-year FE | Yes | Yes |
| F-statistic for IVs in first stage | 59.96 | 24.31 |
| | 108.22 | 72.07 |
| Wu-Hausman test | 10.91*** | 2.30 |

Standard errors clustered by agricultural district are reported in parentheses.

* $p<0.10$, ** $p<0.05$, *** $p<0.01$

Table 6, Panels B and C, also reports the results of regressions for a different location of the spline knot. We increase (decrease) by 10 ft both saturated thickness spline knot ($K$) and predevelopment saturated thickness spline knot ($K'$). The similarity of the estimates of the percentage of irrigated acres and irrigated rental rates regressions to those obtained with the previous knots suggests that our results are robust to changes in the optimal knot. It makes sense that the coefficient of the saturated thickness linear spline is larger (smaller) than before when the new threshold is smaller (larger) which may impose a larger (smaller) restriction on well yield.

# 7 Conclusions

In this paper, we estimate how changes in groundwater stocks affect the returns to agricultural land in the High Plains Aquifer of the central US. We address feedback effects by exploiting hydrologic variation in pre-development saturated thickness that was determined by natural processes in a previous geological era. Ignoring the feedback effect results in significant downward bias.

We find that 63% of the economic impact of a decrease in the stock of groundwater corresponds to adjustment through reduced irrigated acreage (extensive margin) and 37% occurs through reduced irrigated rental rates (intensive margin) when saturated thickness is less than 70 feet and nearly all of the response is at the extensive margin when saturated thickness is larger. The simulation results show that the economic impact of the projected decrease in saturated thickness varies significantly across regions of the HPA. The most severe decrease in returns to land are expected to occur in the Central and Southern portions of the aquifer. Annual returns to land are expected to decrease on average by \$53.5, \$34.1 and \$15.7 million by 2050 and by \$84.3, \$86.3 and \$35.0 million by 2100 in Texas, Kansas and Colorado, respectively. Furthermore, the average annual returns to land are expected to decrease in the High Plains region by \$120.6 million by 2050 and by \$250.5 million by 2100.

The results of this study are useful information for the management of groundwater. We estimate the economic impact of varying groundwater stocks and, as a result, we are able to predict the impact of a projected change in aquifer depletion. These results could be used to inform water management policies by understanding the magnitude of reductions in returns and the location where the reductions will be largest under the existing policy framework.

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