Quantifying the economic costs of High Plains Aquifer depletion

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Abstract

Groundwater depletion is constraining agricultural production and could cause economic distress in regions that strongly rely on groundwater for irrigation. Identifying how varying the stock of natural resource impact economic outputs is challenging due to bias from unobservable heterogeneity and feedback effects—irrigation behavior affects 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 65% of the economic impact of groundwater depletion corresponds to adjustment through reduced irrigated acreage (extensive margin) and 35% 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 $155 million USD from 2017 to 2050, and by $321 million USD from 2017 to 2100. The most severe decrease in returns to land are expected to occur in Colorado, Kansas and Texas.

Keywords: Groundwater, depletion, irrigation, endogeneity.
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; Suarez et al., 2019). The access to groundwater has also increased agricultural land values. Hornbeck and Keskin (2014) estimate that the access to Ogallala aquifer increases the value of 160 acres by \$14,425 in 1950 and by \$38,962 in 1978 (in 2002 US dollars). 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 impact economic outputs is a key challenge that many natural resource settings also face. Two main concerns arise. First, estimates from studies focused on spatial comparisons of long-term environmental conditions are subject to bias from unobservable heterogeneity (Blakeslee et al., 2020). Second, 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.

This paper provides an econometric framework to quantify the economic impacts of groundwater depletion and avoid 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 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 to analyze the effects of saturated thickness on the outcomes of interest. The empirical parameters estimates are used to simulate projected economic impacts of future aquifer depletion.

We find that 65% of the economic impact of groundwater depletion corresponds to adjustment through reduced irrigated acreage (extensive margin) and 35% 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 $155 million USD from 2017 to 2050, and by $321 million USD from 2017 to 2100. The most severe decrease in returns to land are expected to occur in Colorado, Kansas and Texas.

Our paper provides two main contributions. First, the paper contributes to the literature estimating the effect of access to water for irrigation using reduced form methods—"as if random"— to decrease potential bias from unobserved heterogeneity or feedbacks. 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 which are smaller and closer spatial units than counties used by Hornbeck and Keskin (2014). However, these studies do not account for the economic impact of varying groundwater stocks and, as a result, they are not able to estimate the impact of a projected change in aquifer depletion. We provide an econometric framework to quantify the economic impacts of varying resource availability that uses initial resource conditions as an instrument to reduce potential bias from users' behavior.

Second, we estimate projected economic impacts of groundwater depletion 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 economic impact of aquifer depletion but is not validated with observed 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 millions 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 decline 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. 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 and aquifer recharge. Pre-development saturated thickness is the estimated saturated thickness that existed prior to any effects imposed by human activity, and in our study it is represented by a measure of saturated thickness in 1930[1]. Pre-development thickness of the Ogallala formation—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[2]. Therefore, 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 initial saturated thickness was also the largest.

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

[2] http://northplainsgcd.org/about-us/ogallala-aquifer/

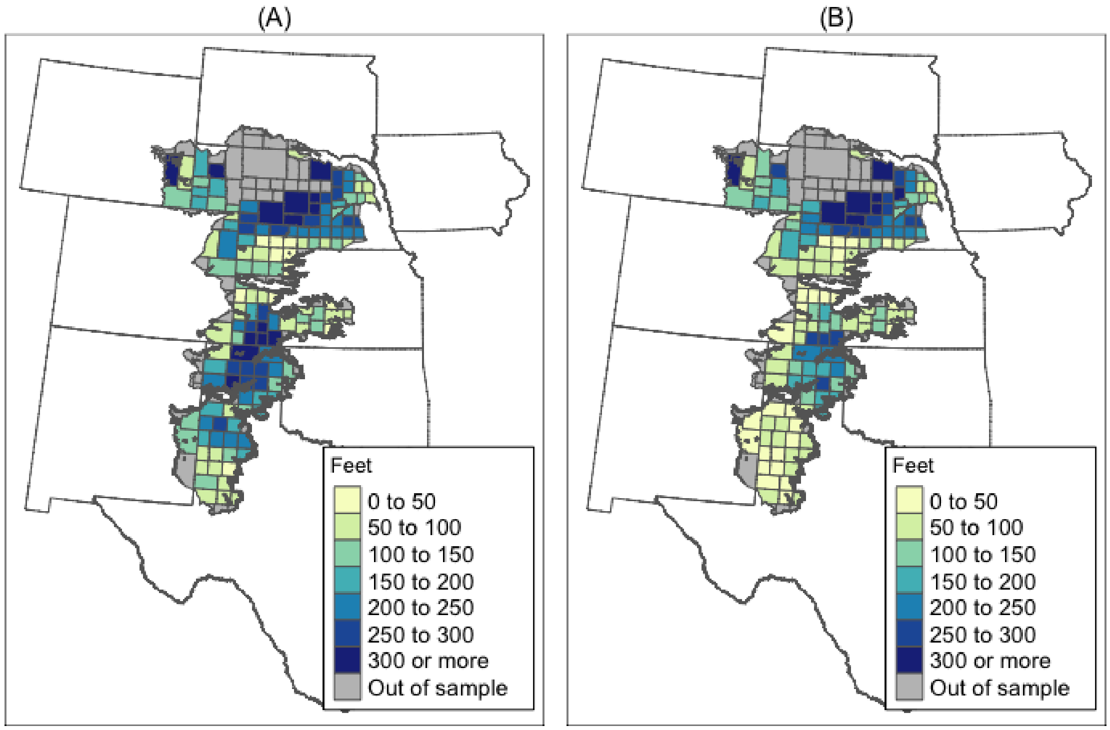

Figure 1: (A) Saturated thickness in 1930 (B) Saturated thickness 2017

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 water table (Sophocleous, 2005). In general, natural recharge to the HPA from precipitation is low in part because much of the rain falls during the growing season when it is used by vegetation. However, natural recharge is higher in the northern portion of the HPA than in the southern. The HPA is commonly divided into three subregions 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—measured by saturated thickness, 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. Hence,

$$B_{it}(ST_{it}) = A_{it}^{irr}(ST_{it})R_{it}^{irr}(ST_{it}) + (1 - A_{it}^{irr}(ST_{it}))R_{it}^{dry} \tag{1}$$

where B_{it} is the return to land for county i at time t per acre of the county overlying the aquifer, A_{it}^{irr} is the proportion of acres in the county that are irrigated, $(1 - A_{it}^{irr})$ is the proportion of acres in the county that are dryland, R_{it}^{irr} is the irrigated cash rental rate, R_{it}^{dry} is the dryland cash rental rate, and ST_{it} is the saturated thickness. A change in returns to land due to an exogenous change in saturated thickness is expressed as:

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

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 rain-fed and irrigated crops. The intensive margin response accounts for 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 intensive margin is represented by irrigated cash rental rates. We expect that if groundwater is constrained, farmers may irrigate less per acre and this could affect crop yields and net returns or they may switch to crops that require less water leading to lower net returns.

The objective of our empirical model is to estimate nonlinear functions in saturated thickness of $A^{irr}_{it}(ST_{it}, X_{it}, \delta_g, \gamma_{rt})$ and $R^{irr}_{it}(ST_{it},, X_{it}, \delta_g, \gamma_{rt})$ 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 to reduce the negative biophysical and economic impacts of intraseasonal groundwater supply constraints. Intuitively, that is when saturated thickness is above a certain level, then well yield is not a binding constraint and different levels of saturated thickness may have no impact on producer behavior. But then for lower saturated thickness where well yields become constraining, then producers will adjust their behavior by either reducing acres irrigated or reducing depth applied of water. Furthermore, when the saturated thickness drops below 30 ft, the aquifer cannot supply adequate water for irrigation and irrigated crop production is assumed to be impractical due to low well yield (Deines et al., 2020).

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 plausible source of exogenous variation in saturated thickness. Using the instrument, allows us to exploit hydrological variation in pre-development saturated thickness that is uncorrelated with contemporaneous irrigation behavior.

4.1 Econometric Model

To mitigate bias induced by the feedback effects between saturated thickness and irrigation behavior, we estimate two-stage least square (2SLS) models of irrigated acres and irrigated cash rental rates on saturated thickness. Pre-development saturated thickness is used as an instrument for current saturated thickness. We model the nonlinear predictive 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 each knot (Harrell, 2001).

The second-stage equation estimates a regression nonlinear in the endogenous variables—linear spline functions of saturated thickness:

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

where K is the location of the change point and

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

Y_{it} reflects agricultural outcomes either the percentage of acres irrigated of the total county area over the aquifer—note we scale proportion of acres irrigated to hundreds—or the irrigated rental rate (R_{it}^{irr}) in county i at time t [3]; ST_{it} is the average saturated thickness; $[(1 - D_{it})ST_{it} + D_{it}K]$ and $D_{it}(ST_{it} - K)$ are linear spline functions of saturated thickness; X_{it} is a vector of several controls (e.g., climatic variables, aquifer characteristics, and soil suitability for corn and soybeans); δ_g is the fraction of county area in each soil group; γ_{rt} are state-by-year fixed effects for state r and year t; and errors (ε_{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. The coefficients of interest throughout the paper are β_1 and β_2. The estimated β_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 β_2 is the effect of saturated thickness on agricultural outcomes when the level of saturated thickness is equal or greater than K.

Based on exploratory analysis of our data and previous studies described above, we allow for one knot location. Then, we define a set of plausible knots locations based on where a change point is more likely to occur in our data. To choose the optimal location of the knot we use k-fold cross-validation (k=10 in our study). This approach randomly divides the set of observations into 10-folds of approximately equal size. We estimate our regression model using data from k-1 folds and estimate the mean squared error for the prediction on the held-out fold or validation set. Then we repeat this process k times—each time a different fold is treated as validation set, and average the prediction error across the k-folds. The optimal knot location is $K = 70$.

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.

[3] 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 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 location of the change point 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, however, the standard 2SLS estimator using as instruments ($[(1-D_{it}^{'})ST1930_{it}+D_{it}^{'}K^{'}]$, $D_{it}^{'}(ST1930_{it}-K^{'})$, $X_{it}, \delta_g^2, \gamma_{rt}^2$). $ST1930_{it}$ 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.

4.2 Controlling for Potential Confounders

We explicitly include several variables to account for cross sectional heterogeneity between counties in our model (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 but does not include return flows from irrigation. As we described before, variation in the rate of depletion is significantly explained by cross sectional differences in the rate of recharge. Hence, natural recharge controls for changes in agricultural outcomes as consequence of different expected depletion rates. 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 (e.g., commodity price shocks, water conservation policies). 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 cannot be used in our study to control for unobserved heterogeneity of counties because there is a substantial reduction in the within-county 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 102.5 when saturated thickness is regressed on an intercept while it drops to 12.4 once we include county fixed effects. Furthermore, we estimate our main model of interest including county fixed effects but the impact of saturated thickness on the outcomes was implausible large. Another issue with including county fixed effects is that we need to find a new instrument because pre-development saturated thickness has not variation over time.

For the statistical inference, standard errors are clustered at the agricultural district level by state 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 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.

4.3 IV Assumptions

To identify β_1 and β_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 more depletion today.

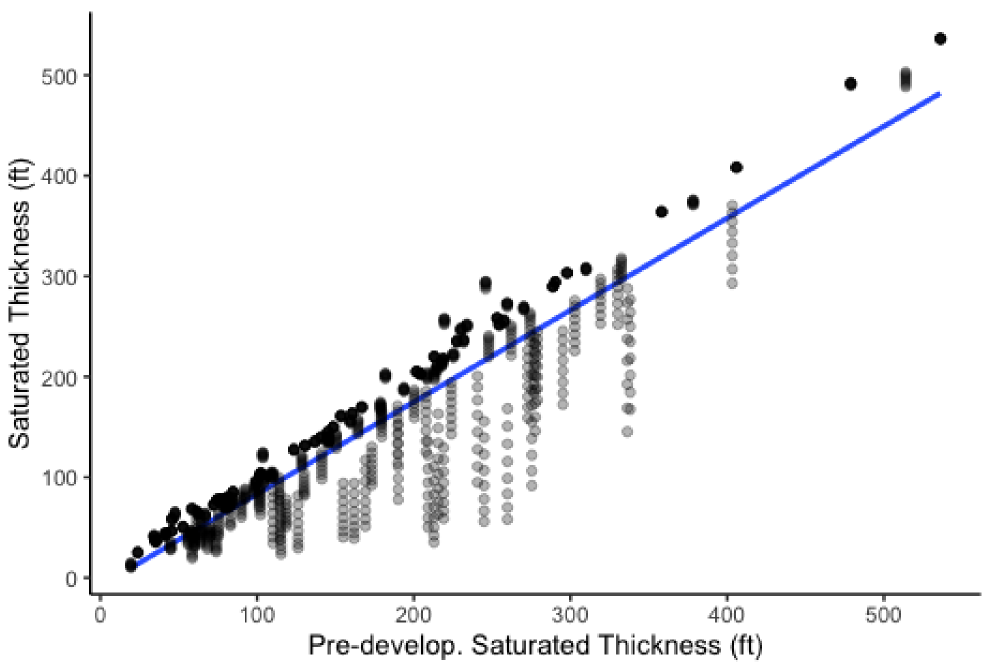

Figure 2: First-stage relationship between pre-development saturated thickness and current saturated thickness

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. We believe that 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 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. We believe that 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. Furthermore, the soil and climate controls included in our models help us to reduce concerns that there may happen to be some random correlations between pre-development saturated thickness and current land productivity that affects irrigated acres and rents.

5 Data and Study Area

Our study area includes 141 counties in seven states—Colorado, Kansas, Nebraska, New Mexico, Texas and Wyoming, overlying the HPA. 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 is characterized by large saturated thickness of 600 ft or more and large natural recharge but irrigation in this area is minimal since the sandy soil makes the region unsuitable for crop farming (USDA-NRCS, 2006; Peterson et al., 2016). Therefore, we also exclude from our analysis counties with a proportion of their total area over the sand hills greater or equal to 55%.

As we explained above, the main objective of our econometric models is to estimate the effect of a change in saturated thickness on the percentage of acres irrigated and irrigated cash rents. Hence, the data used for our estimation are drawn from multiple sources. 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 county-level is 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 a 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. 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).

Hydrology 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 in 2050 and 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[4]. We use a raster of the average specific yield for the HPA and we aggregate it to the county level[5] (McGuire et al., 2012). Natural recharge data is also obtained from a raster and aggregated at county level[6] (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). Some of the soil groups appearing within the HPA are: alluvial, brown, chernozem, and chestnut[7]. 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 a map of the percentage of acres irrigated and irrigated rental rates in 2017. The spatial distributions of irrigated acres and irrigated rental rates are obviously highly related to the groundwater availability in the aquifer. In general, irrigated acres

[4] https://water.usgs.gov/GIS/metadata/usgswrd/XML/ofr98-548.xml

[5] https://water.usgs.gov/GIS/metadata/usgswrd/XML/sir12-5177_hp_sp_yield.xml

[6] https://www.usgs.gov/mission-areas/water-resources/science/high-plains-aquifer?qt-science_center_objects=0#qt-science_center_objects

[7] 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

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.

Table 1: Summary statistics for variables in the econometric analysis

	Mean	Std. Dev.	Min	Max
Variables used in the regression of irrigated acres				
Percentage of Acres Irrigated	18.34	15.41	0.27	76.43
Saturated Thickness (ft)	149.69	102.50	10.15	536.44
Growing Season Precipitation (in)	15.85	4.84	4.61	28.82
Growing Season Evapotranspiration (in)	34.46	2.89	28.09	41.36
Variables used in the regression of irrigated rents				
Cash Irrigated Rent ($/acres)	151.64	69.58	30.00	363.00
Saturated Thickness (ft)	141.29	102.76	10.15	536.21
Growing Season Precipitation (in)	17.34	5.82	1.56	38.25
Growing Season Evapotranspiration (in)	34.79	3.41	28.27	44.14
Variables used in both regressions				
Predevelopment Saturated Thickness (ft)	172.50	103.54	19.53	536.04
30-yr Avg. Precipitation (in)	16.31	3.10	9.88	23.28
30-yr Avg. Evapotranspiration (in)	34.56	2.60	29.91	39.37
30-yr Avg. Growing Degree Days (hundreds)	18.36	2.60	11.53	25.15
30-yr Avg. Extreme Degree Days	32.33	17.57	2.34	81.65
Hydraulic Conductivity (ft/day)	81.40	47.14	12.50	229.77
Specific Yield (fraction)	0.16	0.02	0.06	0.20
Natural Recharge (in)	2.62	2.13	0.12	7.94
Crop Productivity Index (fraction)	0.30	0.14	0.04	0.63

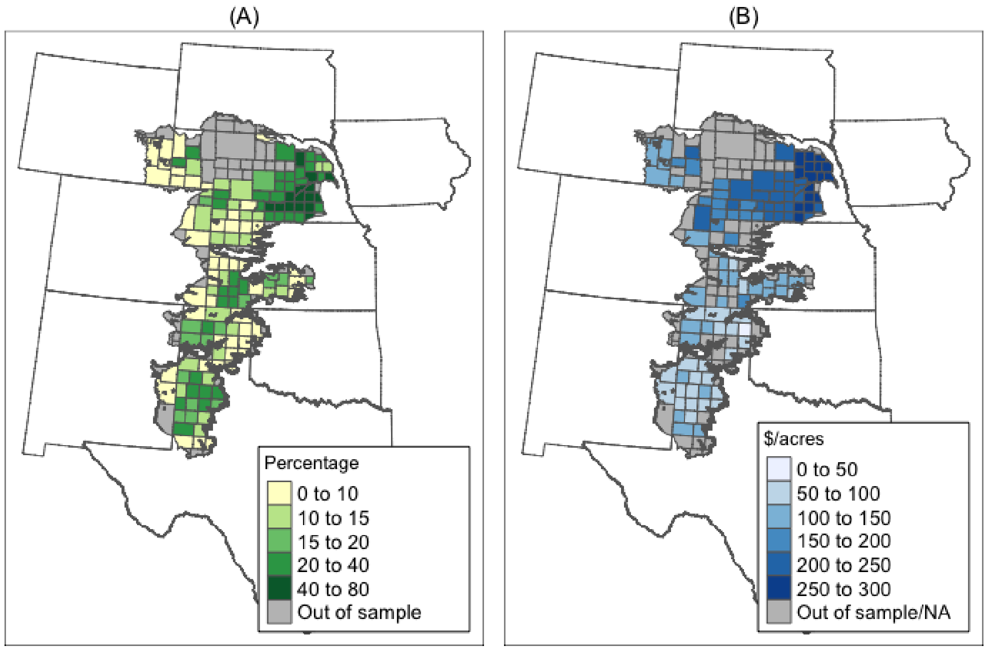

Figure 3: (A) Percentage of acres irrigated in 2017 (B) Irrigated rental rates in 2017

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 outcome 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 changes in depletion. 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 we the coefficients on saturated thickness to be downward biased. The corresponding 2SLS estimates are shown in column 2. The coefficients on the saturated thickness linear splines are significant at 5% level and larger than the OLS estimates. We also report the Hausman test statistic, which examine the null hypothesis that the spline saturated thickness variables are exogenous. The test statistic (11.10) is significant at 1% level suggesting that the 2SLS model is preferred to OLS. 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 foot decrease in saturated thickness results in a 0.211 percentage point decrease in the area of the county that is irrigated. 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 equal or greater than 70 ft, a 1 foot 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 equal or greater than 70 ft.

For ease of interpretation, we show the effect of depletion in terms of actual irrigated acres using the information of two examples: Wichita County in Kansas and Dallam County in Texas. Saturated thickness in Wichita 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).

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 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 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-statistic for IVs in first stage		65.70
		106.61
Hausman test		11.10***
N	1112	1112

Standard errors clustered at ag. district in parentheses

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

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 OLS estimated coefficients on the saturated thickness linear splines are lower than the corresponding 2SLS coefficients. Even though, the feedback between irrigated rents and saturated thickness is less obvious than when considering irrigated acres, we still observe downward biased OLS estimates. Moreover, the 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 value of the F-statistic (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 (table 3). Therefore, when the level of saturated thickness is less than 70 ft, a 1 foot 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 equal or greater to 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 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.

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 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.

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

	OLS (1)	2SLS (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-statistic for IVs in first stage		33.03
		69.08
Hausman test (p-value)		3.64^{**}
N	819	819

Standard errors clustered at ag. district in parentheses

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

Finally, we use the parameters estimates and plug them into equation 2 to estimate the average economic impact of a 10 ft decrease in saturated thickness along the extensive and intensive margins. Our results indicate that a 10 ft decrease in saturated thickness decreased the total average returns to land by \$2.13/acre of the county overlying the aquifer with saturated thickness less than 70 ft. Hence, 65% of the economic impact corresponds to adjustment through reduced irrigated acreage (extensive margin) (\$1.39/acre) while 35% occurs through reduced irrigated rental rates (intensive margin) (\$0.74/acre). By contrast, when saturated thickness is greater or equal to 70 ft, a 10 ft decrease in saturated tickness decreased the average returns to land by \$0.45/acre of the county overlying the aquifer. 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.

6.2 The Economic Impact of Projected Aquifer Depletion

In this section, we estimate the economic impact of projected aquifer depletion across the HPA. Empirical parameters 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 2017.

The simulation results reveal that average annual returns to land decrease by \$155 million USD in the entire High Plains region as a result of a projected average decrease in saturated thickness of 16 ft from 2017 to 2050. This effect represents about 3% of the current predicted returns to land. Similarly, saturated thickness is projected to decrease on average by 31 ft from 2017 to 2100 in the HPA which decreases average annual returns to land by \$321 million USD, representing about 6% of the current predicted returns to land.

As figures 4 and 5 show, depletion is projected to occur 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. For instance, saturated thickness is projected to decrease on average by 22 ft, 23 ft and 24 ft in Colorado, Kansas and Texas, respectively, from 2017 to 2050. Simulation results show that annual returns to land decrease on average by \$19.2, \$41.9 and \$73.7 million USD in Colorado, Kansas and Texas, respectively. These effects represent about 6%, 5% and 11% of the current predicted returns to land, respectively. By contrast, saturated thickness is projected to decrease on average only by 6 ft in Nebraska which implies an average reduction in annual returns to land of \$11.7 million USD which represents about 0.32% of the current predicted returns to land. Furthermore, saturated thickness is projected to decrease on average by 49 ft, 42 ft and 41 ft in Colorado, Kansas and Texas, respectively, from 2017 to 2100. In this case, the simulated results show that annual returns to land decrease on average by \$41.9, \$107 and \$123 million USD in Colorado, Kansas and Texas, respectively. These effects represent about 14%, 13% and 18% of the current predicted returns to land, respectively. In Nebraska, saturated thickness is projected to decrease on average only by 16 ft in Nebraska which implies an average reduction in annual returns to land of \$32.8 million USD which represents about 0.89% of the current predicted returns to land.

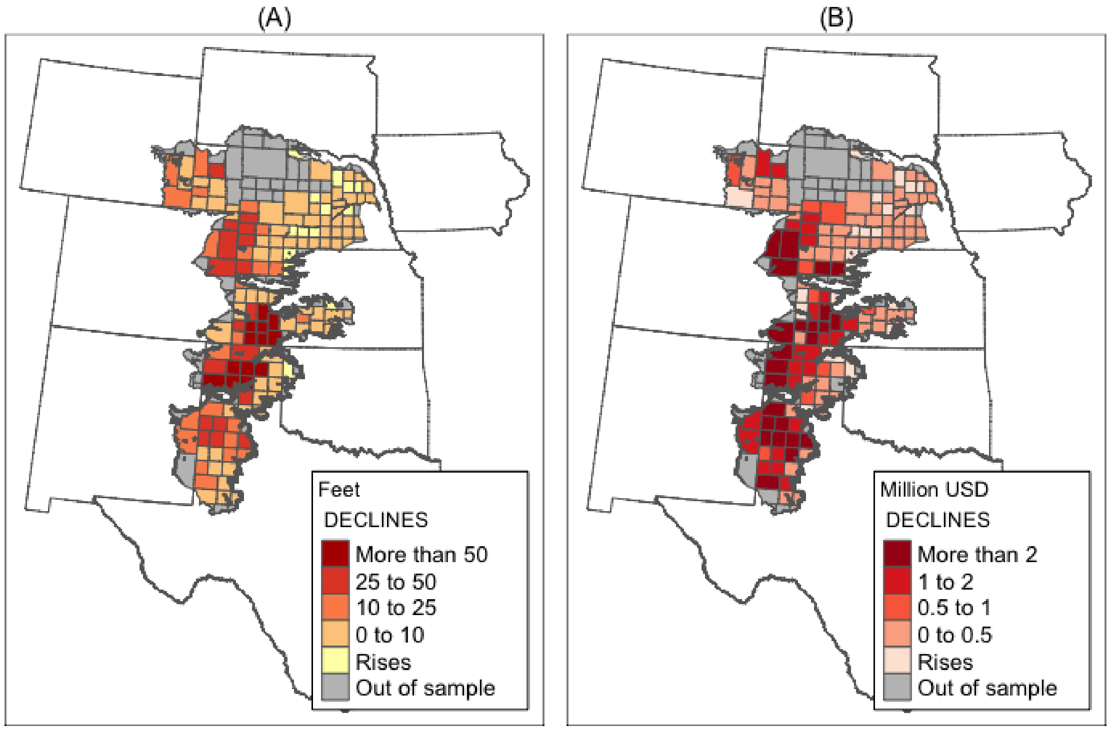

Figure 4: (A) Change in saturated thickness 2017 to 2050 (B) Annual change in returns to land

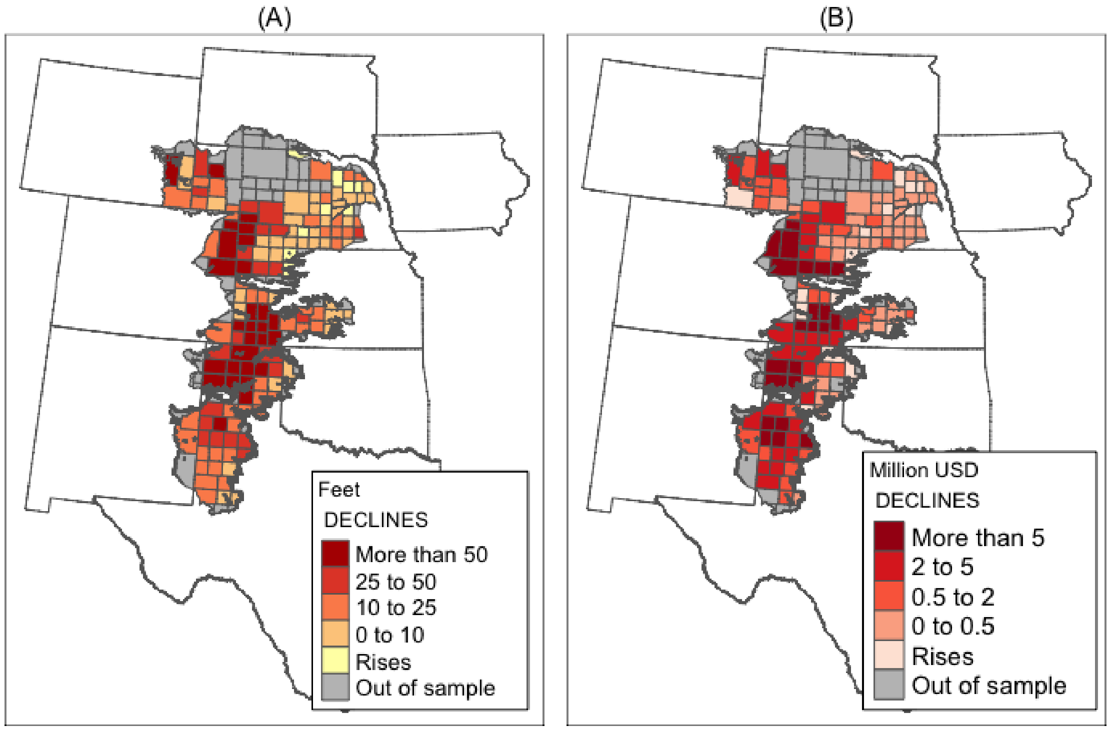

Figure 5: (A) Change in saturated thickness 2017 to 2100 (B) Annual change in returns to land

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 the change in pre-development saturated thickness but would be affected by potential confounders correlated with our instruments. 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 that we do not observe and it would violate the exclusion restriction if unobserved productivity is correlated with predevelopment saturated thickness. The results in table 4 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 4: 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 at ag. district in parentheses

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

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 65% of the economic impact of groundwater depletion corresponds to adjustment through reduced irrigated acreage (extensive margin) and 35% 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 \$155 million USD from 2017 to 2050, and by \$321 million USD from 2017 to 2100. 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 \$19.2, \$41.9 and \$73.7 million USD in Colorado, Kansas and Texas, respectively, from 2017 to 2050 while from 2017 to 2100, economic returns to land decrease on average by \$41.9, \$107 and \$123 million USD in Colorado, Kansas and Texas, respectively.

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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