The Economic Cost of Groundwater Depletion in the High Plains Aquifer

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

Abstract

Groundwater depletion constrains agricultural production and reduces economic value in regions that rely on groundwater for irrigation. However, estimating the economic value of the stock of groundwater is challenging due to the lack of competitive water markets and bias from feedback effects of irrigation behavior affecting resource conditions. We estimate how changes in groundwater stocks affect the returns to agricultural land in the High Plains Aquifer of the central USA. We avoid bias from feedback effects by exploiting hydrologic variation in pre-development saturated thickness that was determined by natural processes in previous geological eras. Simulation results reveal that the average annual present value of 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. When the initial saturated thickness is less than 70 feet, most of the economic impact (63%) of a decrease in the stock of groundwater occurs through an adjustment in irrigated acreage (extensive margin), while 37% occurs through reduced irrigated rental rates (intensive margin). When saturated thickness is larger, nearly all of the response is at the extensive margin.

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

*Perez-Quesada is a Ph.D. student in the Department of Agricultural Economics at Kansas State University. gperezq@ksu.edu; Hendricks is a professor in the Department of Agricultural Economics at Kansas State University. nph@ksu.edu; Steward is the Walter B. Booth Distinguished Professor in the Department of Civil, Construction and Environmental Engineering at North Dakota State University. david.steward@ndsu.edu

1 Introduction

Groundwater use for irrigation offers a substantial source of water to supplement insufficient growing season rainfall in semi-arid areas around the world. However, the extraction of groundwater for irrigation at rates greater than natural recharge has led to persistent aquifer depletion in many countries (Richey et al., 2015). Stressed aquifer conditions are especially 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). While the change in groundwater stocks is relatively well established, there is much less evidence on the loss in economic value from the change in groundwater stocks.

Accurately estimating the economic value of the stock of groundwater is challenging for two main reasons. First, it is difficult to directly observe the marginal value of groundwater used for irrigation since the market for water is in general thin and has large frictions. Second, the existence of feedbacks across social and environmental dimensions of complex systems makes it difficult to support assumptions about excludability and the 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 stock of groundwater decreases.

One approach to estimate the value of the stock of groundwater is to use revealed preference methods such as the hedonic price model, which obtains an implicit valuation of groundwater irrigation using information from well-functioning markets. As an example, the market value for irrigated and nonirrigated land provides information about the additional value created by groundwater used for irrigation. Hornbeck and Keskin (2014) find that aquifer access resulted in a $25 billion increase in land values, while Sampson et al. (2019) find that agricultural land values are about 53% higher for irrigated parcels than similar nonirrigated parcels in the Kansas portion of the HPA. Yet these studies do not estimate the annual economic cost of a change in the stock of groundwater, which is a measure of key importance to stakeholders who are considering policies to address the depletion of groundwater.

Our paper quantifies the economic value of groundwater stocks using data on cash rental rates for irrigated versus nonirrigated land and the number of irrigated acres. We avoid bias from feedback effects 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 pre-Ogallala surface roughly 5 to 24 million years ago, which led 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.

Two-stage least square (2SLS) models of irrigated acres and irrigated cash rental rates on saturated thickness, controlling for other confounders are estimated. Pre-development saturated thickness is used as an instrument for current saturated thickness. The validity of the exclusion restriction is supported by conducting a falsification test to evaluate if pre-development saturated thickness is correlated with unobserved land productivity as reflected in nonirrigated rental rates. The parameter estimates are then used to simulate the economic impacts of projected aquifer depletion. The simulation results reveal that the average annual present value of 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 three main contributions. First, we estimate the economic value of groundwater stocks, rather than the value of access to groundwater. Measuring the value of the stock is important for estimating the economic value of different scenarios of resource depletion. For example, Hornbeck and Keskin (2014) compare land values in counties over the

HPA aquifer with nearby similar counties to estimate the value of access to water. Edwards and Smith (2018) measure the effect of access to irrigation on land values throughout the entire western United States. Blakeslee et al. (2020) estimate the impact of groundwater access on various economic outcomes in India. One exception is that Sampson et al. (2019) estimate the effect of groundwater stocks on irrigated land values in Kansas. An advantage of our approach to using annual rental rates rather than land values is that annual rental rates do not reflect expectations of future changes in groundwater stocks.

The second contribution is that we use initial resource conditions as an instrument to reduce potential bias from feedback effects. Our approach is similar in spirit to Hornbeck and Keskin (2014) and Blakeslee et al. (2020) in that we exploit plausibly exogenous hydrologic variation. Hornbeck and Keskin (2014) utilize the plausibly exogenous boundary of the High Plains Aquifer. Blakeslee et al. (2020) compare households in India whose first borewell failed to those for whom it is still working within the same village. Blakeslee et al. (2020) argue that the failure of the first borewell is related to hydrologic factors that are exogenous to economic outcomes. However, our approach is different from these studies in that our approach allows us to estimate the value of groundwater stocks and not just access to groundwater. Our approach is also likely relevant to natural resources other than groundwater.

Third, we estimate the economic value of the stock of groundwater across the HPA region using observed irrigated acreage and rental market data. A large literature exists in hydrology that quantifies the extent of 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). There is also a set of economic literature that 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; Manning and Suter, 2019). Fenichel et al. (2016) model the value of natural capital with an application to groundwater stocks in Kansas, where the groundwater valuation model uses expenses from university crop budget and assumes that crop yields are not affected by groundwater stocks. Manning et al. (2020) use willingness to pay for well capacity from a contingent valuation survey to value groundwater stocks in an integrated assessment model. Our approach values groundwater stocks using rental market data and allows groundwater stocks to potentially affect irrigated acres, crop mix, and crop yield.

2 Background

The High Plains Aquifer (HPA) comprises 118.8 million acres over portions of eight states in the U.S.A: Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (McGuire, 2017). It 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 became evident in many 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). In the period 2000 to 2020, the Central and Southern regions have shown a significant contraction in irrigated area attributable to increasingly scarce groundwater resources (Hrozencik and Aillery, 2021).

The 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 influenced 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 Ogallala geological setting formed roughly 5 to 24 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 pre-Ogallala surface that existed long before human settlement, so it is unrelated to human activity.

It is apparent in figure 1 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.

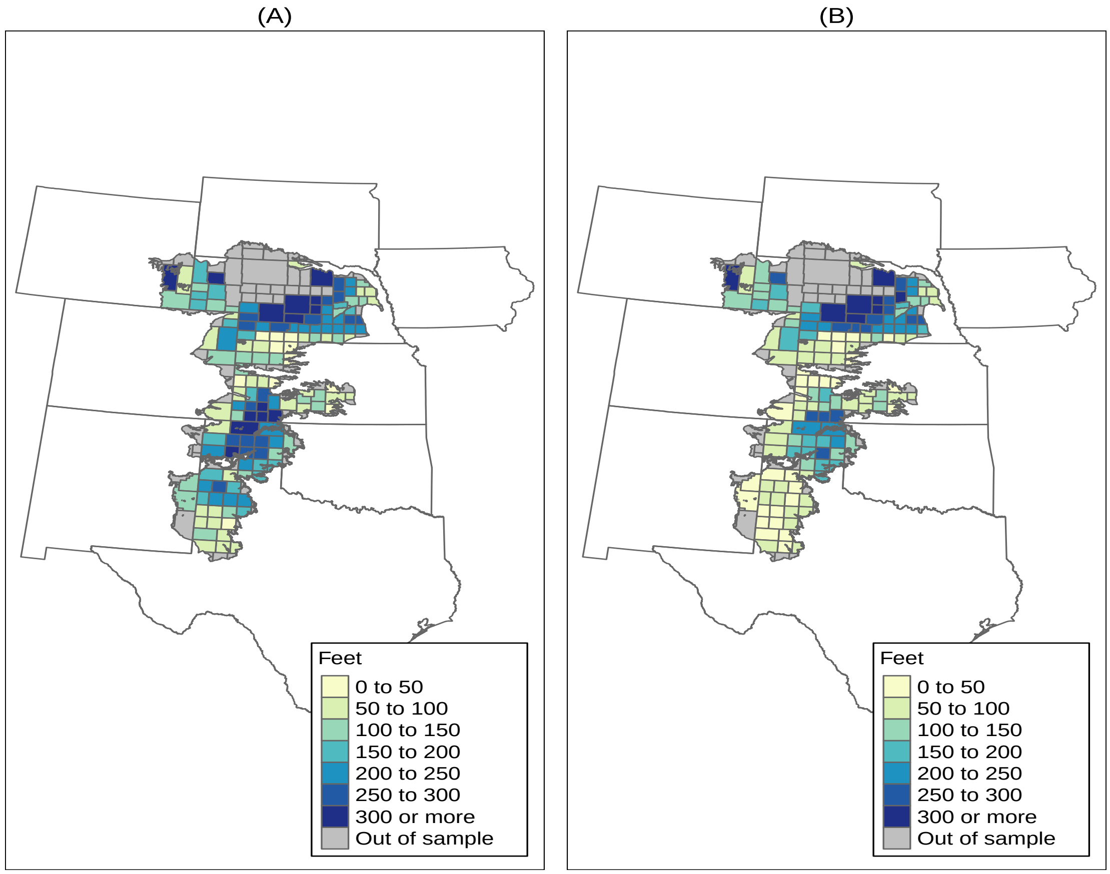

Figure 1: (A) Saturated thickness in 1930 (B) Saturated thickness 2017

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 surficial water into an aquifer and is mainly determined by climate, soil, vegetation, land use, and depth to the water table (Sophocleous, 2005). The surficial rivers incise the Ogallala formation and hydrologicially separate the HPA into three units that are hydrologically disconnected. Much of the nortern area of the aquifer consists of renewable groundwater formations with larger rates of recharge. The Central and Southern parts of the aquifer, however, consist primarily of nonrenewable or fossil groundwater with little recharge (Scanlon et al., 2012).

3 Conceptual Model

We explore the role of variation in groundwater stocks on irrigation decisions using saturated thickness information. Reductions in groundwater availability affect farmers' economic benefits through two main mechanisms: decreasing well yields and increasing pumping costs. The well yield controls the rate of groundwater extraction and is impacted by the saturated thickness and hydraulic conductivity. The cost of pumping increases with groundwater depletion since it requires more energy to pump the water from greater depths. We do not separately estimate these two different mechanisms, but instead we use reduced form models to estimate the overall impact of a change in saturated thickness.

The economic value of the stock of groundwater is reflected in the returns to land and modeled as

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

where B_{it} is the return to land per acre of the county overlying the aquifer for county i in year t, Φ_{it}^{irr} is the proportion of acres in the county that are irrigated, Φ_{it}^{past} is the proportion of acres in the county that are pastureland, and $(1 - \Phi_{it}^{irr} - \Phi_{it}^{past})$ is the proportion of acres in the county that are nonirrigated. Economic variables 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 when saturated thickness decreases, farmers switch to nonirrigated cropland as the next most productive use of land after irrigated cropland. Consequently, the extensive margin response may be underestimated 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. In areas where farms switch to pasture rather than nonirrigated cropland, the rental rate of nonirrigated cropland is likely similar to the rental rate for pasture. Therefore, the assumption that irrigated cropland converts to nonirrigated cropland rather than pasture is a reasonable assumption for our study area.

A change in returns to land due to an exogenous change in saturated thickness is is separated into two components:

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

since 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. This intensive margin response captures two main adjustments: a reduction in water intensity for the proportion of the field that is irrigated that could affect crop yield, and a switch from relatively water intensive crops (e.g., corn) towards less water-intensive crops (e.g., wheat). The latter two adjustments will be reflected in farmers paying lower rental rates for irrigated land.

The objective of our empirical model is to estimate the 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 where 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, 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, producers adjust their behavior by either reducing irrigated acres or reducing irrigation intensity.

Data is not directly available on depth to water table—the vertical distance from the land surface to water table—to explicitly control for differences in the cost of pumping. Instead, since saturated thickness and depth to water table are highly directly 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 (Rouhi Rad et al., 2021). Furthermore, 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 also shown how reductions in well yield negatively impact economic outputs (e.g., Peterson and Ding, 2005; Foster et al., 2014, 2015, 2017; Hrozencik et al., 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.

4 Empirical Strategy

The objective of our econometric model is to estimate the impact of 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. Pre-development saturated thickness is used as an instrument to obtain a source of plausibly exogenous variation in saturated thickness.

4.1 Econometric Model

Two-stage least square (2SLS) models are estimated for irrigated acres and irrigated cash rental rates. The nonlinear relationship between saturated thickness on the output of interest is represented 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 is:

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

where K is the location of spline knot, and

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

The variable 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); 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 ε_{it} are idiosyncratic errors.

[2] Even though our dependent variable (percentage of acres irrigated) is constrained to be between 0 and 100, we use a 2SLS model that treats the dependent variable as continuous since all values are in the interior (see table 1).

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 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:

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

and

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

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 there are two endogenous explanatory variables ($[(1-D_{it})ST_{it} + D_{it}K]$ and $(ST_{it} - K)$), and our two instruments are $[(1 - D_{it}^{'})ST1930_{it} + D_{it}^{'}K^{'}]$ and

$D'_{it}(ST1930_{it} - K')$. The variable $ST1930_{it}$ is pre-development saturated thickness and the instruments, $[(1 - D'_{it})ST1930_{it} + D'_{it}K']$ 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 for the instrument is also larger.

For the statistical inference, the 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. We follow Bester et al. (2011), who propose clustering by spatial groups as a simple and flexible method to account for spatial correlation, under the assumption that in 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. Since the irrigated acreage information is based on the harvested acres, we include the contemporaneous cumulative measures for precipitation and reference evapotranspiration demand within the growing season (April 1 - September 30) to isolate contemporaneous weather effects. For example, drought conditions 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. This 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 to a well, and specific yield is the volume of water per unit volume of aquifer that can be extracted by pumping. Where hydraulic conductivity and specific yield have higher values, we expect a reduction in pumping costs as water moves more readily to a well. Furthermore, hydraulic conductivity is also a measure of the shared nature of an aquifer. In regions with larger hydraulic conductivity, more water can be lost from a given well to the common pool, increasing the incentive to pump more water (Edwards, 2016). Natural recharge is the seepage of water into an aquifer, not including return flows from irrigation. It controls for changes in agricultural outcomes as a 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, and 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 a separate effect for each possible combination of state and year. The state-by-year fixed effects absorb the effects of any arbitrary shock, including technological change, variation in commodity price and groundwater laws, which is specific to a state in any given year. For example, Nebraska uses correlative rights, and 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.

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 when county fixed effects are included. We also regress saturated thickness on all covariates and controls used in the main model specification, and the residual standard deviation of saturated thickness is equal to 68.3. These results indicate that there may be insufficient variability in saturated thickness remaining after including county fixed effects compared to preferred specification. Furthermore, we estimate our main model of interest including county fixed effects but the impact of saturated thickness on the outcomes is implausibly large. Another justification for not including county fixed effects is that we need to find a new instrument because pre-development saturated thickness is invariant over time[3].

4.3 IV Assumptions

To identify β_1 and β_2 in the second stage (equation 3), the instruments must account for the saturated thickness variation. There is little doubt that the current saturated thickness is correlated with saturated thickness in 1930. As 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

[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.

current saturated thickness. Again, this relationship shows that counties with low pre-development saturated thickness have substantially less saturated thickness today.

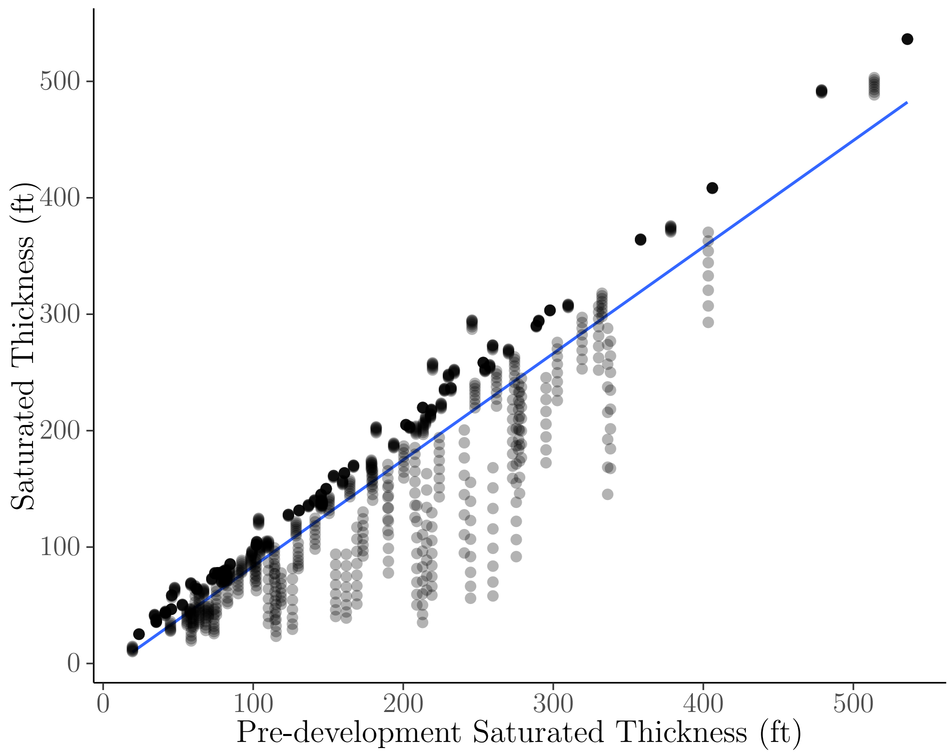

Figure 2: Relationship between pre-development saturated thickness and current saturated thickness

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 Ogallala geological formations that existed long before human settlement, and so it is unrelated to human activity.

This exclusion restriction implies that pre-development saturated thickness is not spuriously correlated with productivity of the land today. In this case, the instrumental variable estimates may be assigning the effect of land productivity on outcomes to the effect of saturated thickness. This is unlikely to be the case since the ancient structure of the buried Ogallala geological formations has no inherent relationship with the agricultural productivity of the current land surface. Instead, the soil and climate controls are included in our models to address potential spurious correlations between pre-development saturated thickness and current land productivity, which affects irrigated acres and rents. Results from a falsification test are presented later to evaluate whether pre-development saturated thickness is correlated with unobserved land productivity.

5 Data and Study Area

Our study area includes 141 counties in six 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 the availability of 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 areas at the county-level are available every five years from the US Census of Agriculture. We calculate the percentage of acres irrigated by 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). These data are available from 2008 except for 2015 and 2018, and 2008 is excluded 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.

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	

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. Pre-development 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. This 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. Thus, 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, soil groups appearing within the HPA include: 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). This variable ranges from 0.01 (low productivity) to 0.99 (high productivity). The maps in Figure 3 show 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 lower and recharge from precipitation is less than groundwater demand for irrigation.

[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

Similarly, rental rates are largest in the Northern High Plains and decline moving south into the more arid region.

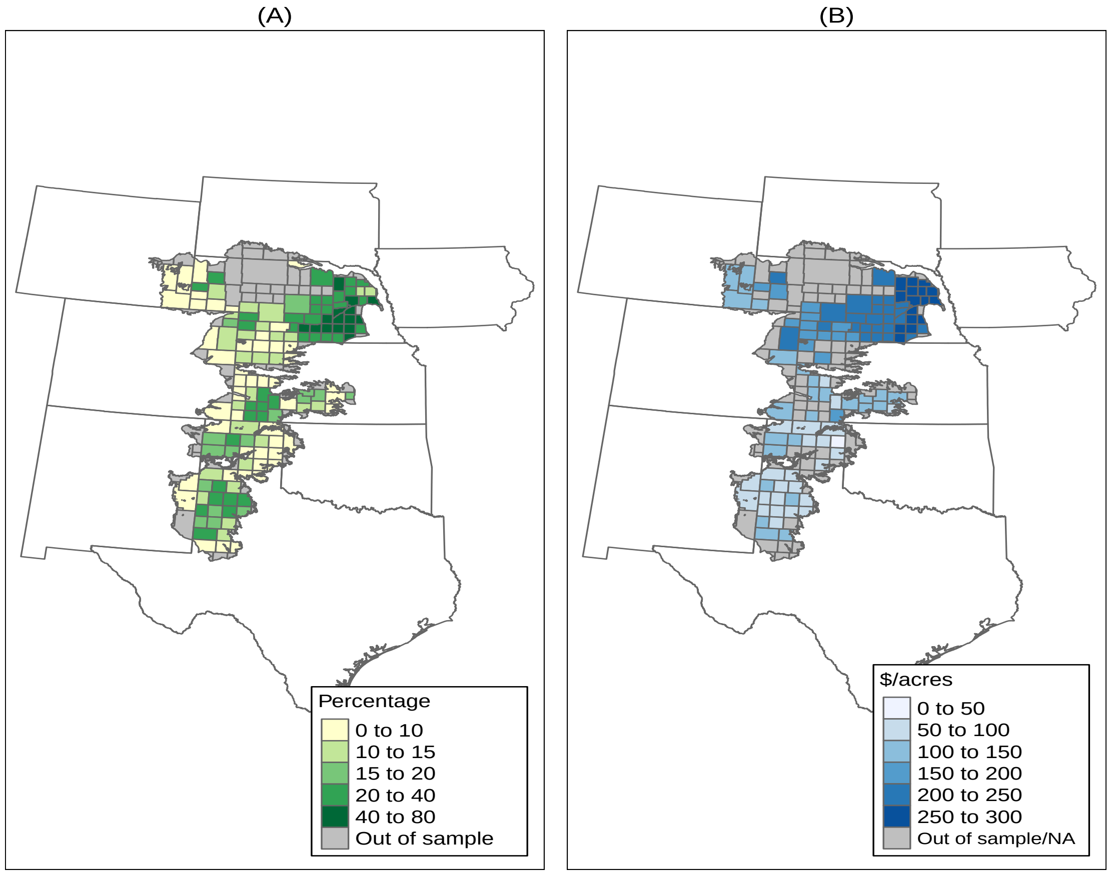

Figure 3: (A) Percentage of acres irrigated in 2017 (B) Irrigated rental rates in 2017

6 Results and discussion

6.1 2SLS Regressions Results

Estimates are presented next using the econometric models described in the previous section, which regress each of the outcomes of interest—percentage of acres irrigated or irrigated rental rates—on saturated thickness. These parameter estimates provide the information required to simulate the impact of the 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, OLS estimates show a positive and significant relationship between irrigated acres and saturated thickness. However, this result cannot be interpreted 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, weak instruments are not a concern (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 approximately 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 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.

The magnitude of the average effect of a decrease in saturated thickness in terms of irrigated acres is illustrated 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. Our results indicate that this 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. In this case, our results show that the 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. 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.

The main results of the regression of irrigated cash rents are summarized in Table 3. We expect that if groundwater is constrained, farmers either switch to less profitable crops or 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 but is still a concern. Intuitively, it could be that more productive land with higher water use 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 rental rate (\$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 illustrate 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—when growing season precipitation is larger, then a farmer may pump less water so irrigation costs decrease and rent increases. 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 are used to define new values of the dependent variable following Cameron et al. (2008) and Roodman et al. (2019).

For ease of interpretation, we discuss 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. This effect represents a 0.9% decrease in the average returns per acre of cropland. Most of

[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).

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

The economic impact of projected decreases in saturated thickness is estimated next 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, while holding other variables constant. We use the projected values of saturated thickness in 2050 and 2100 from Steward and Allen (2016) 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 the annual present value of 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. In addition, irrigated acres are expected to decrease by 20.5%, 13.5% and 23.2% by 2050. By contrast, saturated thickness is projected to decrease on average only by 5 ft in Nebraska which implies an average reduction in the annual present value of 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.

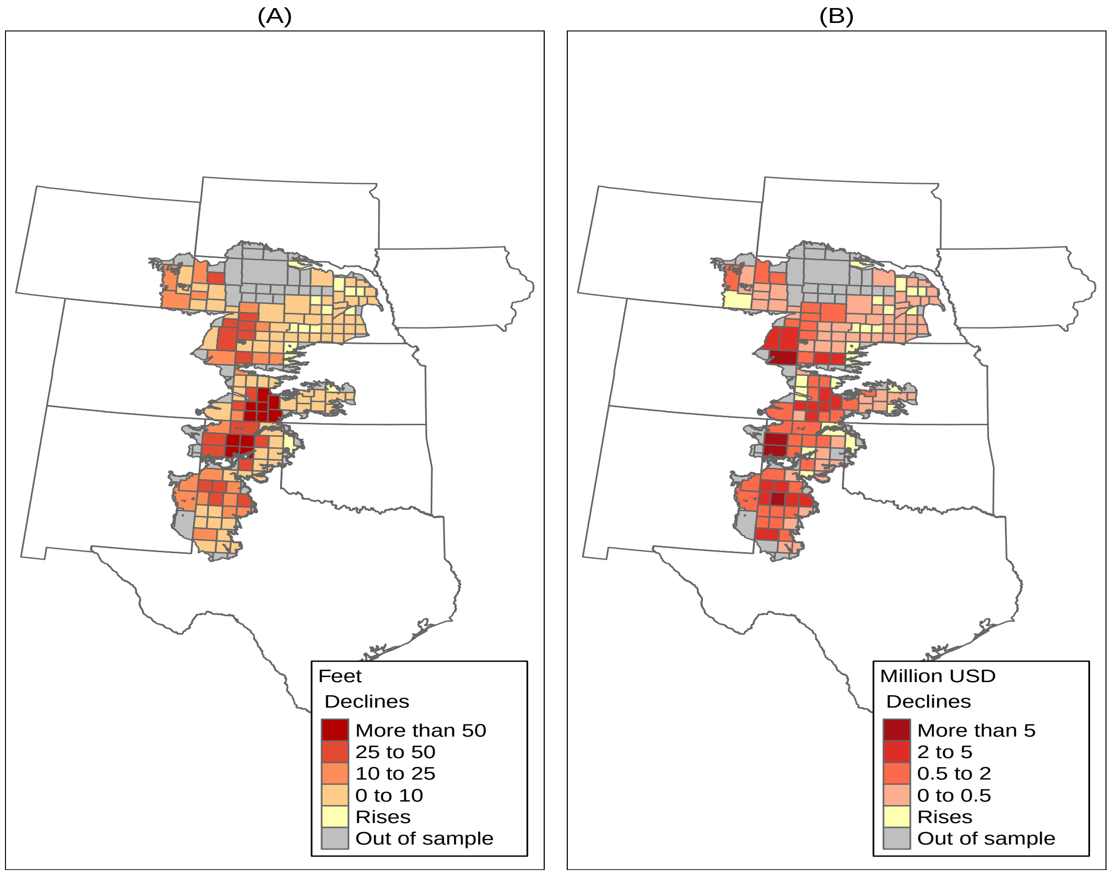

Figure 4: (A) Change in saturated thickness 2020 to 2050 (B) Annual change in returns to land

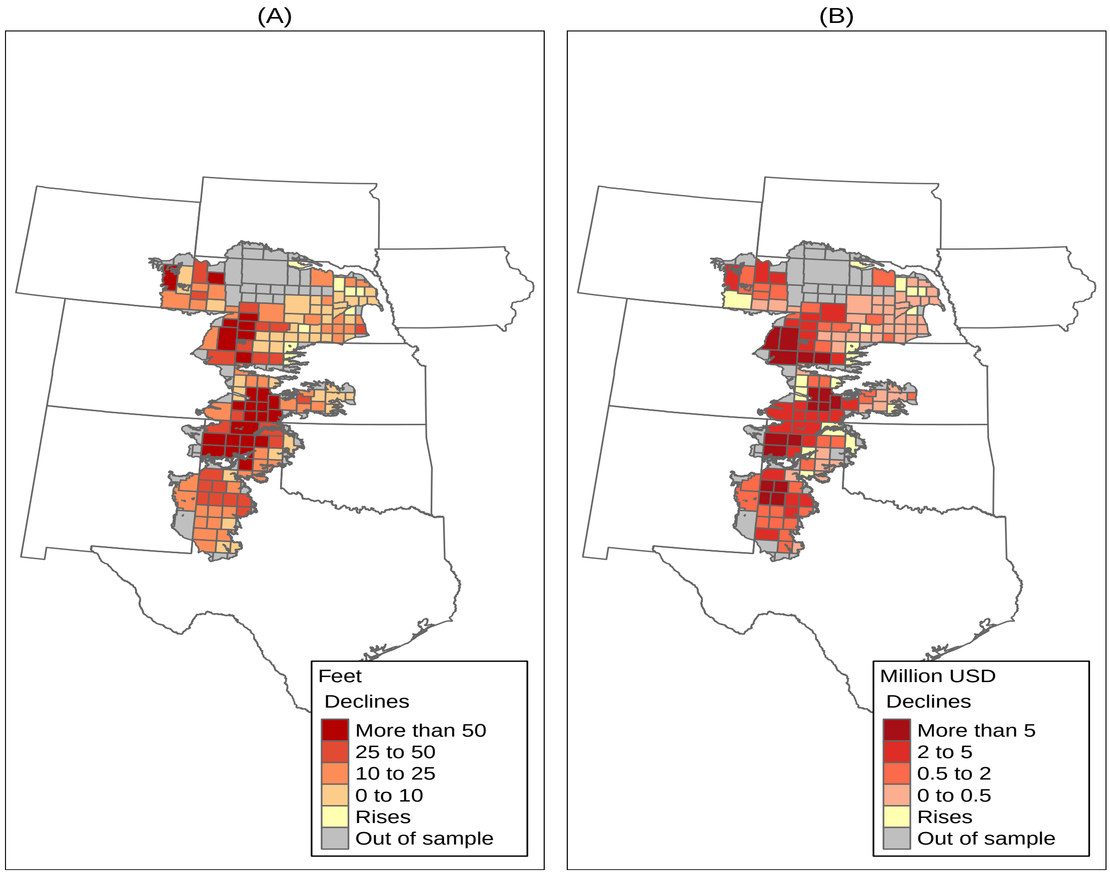

Figure 5: (A) Change in saturated thickness 2020 to 2100 (B) Annual change in returns to land

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

Across the entire High Plains Aquifer region, the average annual present value of returns to land are projected to decrease by $120.6 million 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 present value of 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 for the period 2030-2100 compared to returns in 2020. Kansas and Texas show the strongest downward trend in returns to land. Even though the changes in returns to land are smaller in magnitude in Colorado and Nebraska, these states also show a decreasing trend. Note that these findings extrapolate existing economic conditions and policies into the future in order to isolate the impact of projected declines in groundwater resources alone.

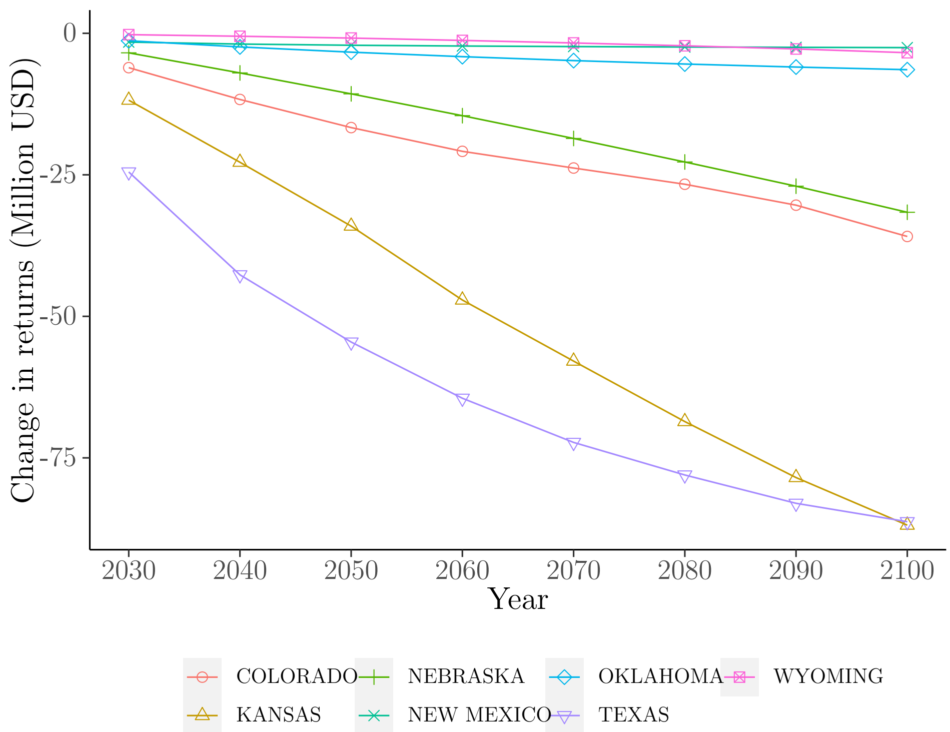

Figure 6: Annual change in returns to land compared to 2020

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.

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 Checks

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 heterogeneous across groundwater management districts (Schoengold and Brozovic, 2018).

In our preferred specification, we control for state-by-year fixed effects. However, 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 many policy changes were only implemented in the HPA recently (see Schoengold and Brozovic (2018) for a detailed discussion). For instance, Kansas established the first Local Enhanced Management Area (LEMA), Sheridan 6, in 2013 which covers a local township sized portion of the GMD to reduce water allocations. Other groundwater management plans in Kansas have not substantially reduced water use during our sample period (Perez-Quesada and Hendricks, 2021).

Table 6, Panels B and C, report the results of regressions for different locations of the spline knots. We increase (decrease) by 10 ft both the saturated thickness spline knot (K)

and the 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. 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.

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.

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

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 formed during 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 substantial decrease in returns to land are expected to occur in the Central and Southern portions of the aquifer. There, the annual present value of 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 present value of 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 provide 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 due to aquifer depletion. These results inform groundwater managers about the projected magnitude of reductions in returns under the existing policy framework and potential gain from implementing policies that could preserve the stock of groundwater.

References

Bester, C. A., T. G. Conley, and C. B. Hansen (2011). Inference with dependent data using cluster covariance estimators. *Journal of Econometrics 165*, 137–151.

Blakeslee, D., R. Fishman, and V. Srinivasan (2020). Way down in the hole: Adaptation to long-term water loss in rural India. *American Economic Review 110*(1), 200–224.

Cameron, A. C., J. B. Gelbach, and D. L. Miller (2008). Bootstrap-based improvements for inference with clustered errors. *The Review of Economics and Statistics 90*(3), 414–427.

Deines, J. M., M. E. Schipanski, B. Golden, S. C. Zipper, S. Nozari, C. Rottler, B. Guerrero, and V. Shard (2020). Transitions from irrigated to dryland agriculture in the Ogallala Aquifer: Land use suitability and regional economic impacts. *Agricultural Water Management 233*, 1–10.

Ding, Y. and J. M. Peterson (2012). Comparing the Cost-Effectiveness of Water Conservation Policies in a Depleting Aquifer: A dynamic Analysis of Kansas High Plains. *Journal of Agricultural and Applied Economics 44*(2), 223–234.

Edwards, E. C. (2016). What lies beneath? Aquifer heterogeneity and the economics groundwater management. *Journal of the Association of Environmental and Resource Economists 3*(2), 453–491.

Edwards, E. C. and S. M. Smith (2018). The role of irrigation in the development of agriculture in the United States. *The Journal of Economic History 78*(5), 1103–1141.

Fenichel, E. P., J. K. Abbott, J. Bayham, W. Boone, E. M. Haacker, and L. Pfeiffer (2016). Measuring the value of groundwater and other forms of natural capital. *Proceedings of the National Academy of Sciences 113*, 2382–2387.

Ferraro, P. J., J. N. Sanchirico, and M. D. Smith (2019). Causal inference in coupled human and natural systems. *Proceedings of the National Academy of Sciences 116*(12), 5311–5318.

Fisher, A. C., W. M. Hanemann, M. J. Roberts, and W. Schlenker (2012). The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather: comment. *American Economic Review 102*(7), 3749–3760.

Foster, T., N. Brozovi, and A. P. Butler (2017). Effects of Initial Aquifer Conditions on Economic Benefits from Groundwater Conservation. *Water Resources Research 53*(1), 744–762.

Foster, T., N. Brozovic, and A. Butler (2015). Analysis of the impacts of well yield and groundwater depth on irrigated agriculture. *Journal of Hydrology 523*, 86–96.

Foster, T., N. Brozović, and A. P. Butler (2014). Modeling Irrigation Behavior in Groundwater Systems. *Water Resources Research 50*(8), 6370–6389.

Haacker, E. M., A. D. Kendall, and D. W. Hyndman (2016). Water level declines in the High Plains Aquifer: predevelopment to resource senescence. *Groundwater 54*(2), 231–242.

Harrell, F. E. (2001). *Regression modeling strategies: with applications to linear models, logistic regression, and survival analysis* (Second ed.). New York: Springer.

Hendricks, N. and J. Peterson (2012). Fixed Effects Estimation of the Intensive and Extensive Margins of Irrigation Water Demand. *Journal of Agricultural and Resource*.

Hendricks, N. P. (2018). Potential benefits from innovations to reduce heat and water stress in agriculture. *Journal of the Association of Environmental and Resource Economists 5*(3), 545–576.

Hornbeck, R. and P. Keskin (2014). The Historically Evolving Impact of the Ogallala Aquifer: Agricultural Adaptation to Groundwater and Drought. *American Economic Journal: Applied Economics 6*(1), 190–219.

Houston, N. A., S. L. Gonzales-Bradford, A. T. Flynn, S. L. Qi, S. M. Peterson, J. S. Stanton, D. W. Ryter, T. L. Sohl, and G. B. Senay (2013). Geodatabase compilation of hydrologic, remote sensing, and water-budget-component data for the high plains aquifer, 2011. U.S. Geological Survey Scientific Data Series 777, United States Geological Survey.

Hrozencik, R. A. and M. Aillery (2021). Trends in U.S. irrigated agriculture: Increasing resilience under water supply scarcity. Eib-229, U.S. Department of Agriculture, Economic Research Service.

Hrozencik, R. A., D. T. Manning, J. F. Suter, C. Goemans, and R. T. Bailey (2017). The heterogeneous impacts of groundwater management policies in the Republican River Basin of Colorado. *Water Resources Research 53*, 10757–10778.

Manning, D. T., M. R. Rad, J. Suter, C. Goemans, Z. Xiang, and R. Bailey (2020). Non-market valuation in integrated assessment modeling: The benefits of water right retirement. *Journal of Environmental Economics and Management 103*.

Manning, D. T. and J. F. Suter (2019). Production Externalities and the Gains from Management in a Spatially-Explicit Aquifer. *Journal of Agricultural and Resource Economics 44*(1), 194–211.

McGuire, V., M. Johnson, R. Schieffer, J. Stanton, S. Sebree, and I. Verstraeten (2003). Water in storage and approaches to groundwater management, High Plains Aquifer, 2000. Circular 1243, U.S. Geological Survey.

McGuire, V. L. (2017). Water-level and recoverable water in storage changes, high plains aquifer, predevelopment to 2015 and 2013-15. Geological Survey Scientific Investigations Report 2017-5040, United States Geological Survey.

McGuire, V. L., K. D. Lund, and B. K. Densmore (2012). Saturated thickness and water in storage in the high plains aquifer, 2009, and water level change and changes in water in storage in the high plains aquifer, 1980 to 1995, 1995 to 2000, 2000 to 2005, and 2005 to 2009. U.S. Geological Survey Scientific Investigations Report 2012-5177, United States Geological Survey.

Mieno, T. and N. Brozović (2017). Price Elasticity of Groundwater Demand: Attenuation and Amplification Bias due to Incomplete Information. *American Journal of Agricultural Economics 87*(2), 401–426.

NPGCD (2021). Ogallala aquifer. http://northplainsgcd.org/about-us/ogallala-aquifer/. [Online; accessed 10-October-2021].

Perez-Quesada, G. and N. P. Hendricks (2021). Lessons from local governance and collective action efforts to manage irrigation withdrawals in Kansas. *Agricultural Water Management 247*(106736).

Peterson, J. M. and Y. Ding (2005). Economic Adjustments to Groundwater Depletion in the High Plains: Do Water-Saving Irrigation System Save Water? *American Journal of Agricultural Economics 87*(147-159).

Peterson, S. M., A. T. Flynn, and J. P. Traylor (2016). Groundwater-flow model of the Northern High Plains Aquifer in Colorado, Kansas, Nebraska, South Dakota, and Wyoming. Scientific Investigations Report 2016-5153, U.S. Geological Survey.

Pfeiffer, L. and C. Y. C. Lin (2014). The effects of energy prices on agricultural groundwater extraction from the High Plains Aquifer. *American Journal of Agricultural Economics 95*(5), 1349–1362.

Richey, A. S., B. F. Thomas, M.-H. Lo, J. T. Reager, J. S. Famiglietti, K. Voss, S. Swenson, and M. Rodell (2015). Quantifying renewable groundwater stress with GRACE. *Water Resources Research 51*(5217-5238).

Roodman, D., M. Ø. Nielsen, J. G. MacKinnon, and M. D. Webb (2019). Fast and wild: Bootstrap inference in stata using boottest. *The Stata Journal 19*(1), 4–60.

Rouhi-Rad, M., N. Brozovic, T. Foster, and T. Mieno (2020). Effects of instantaneous groundwater availability on irrigated agriculture and implications for aquifer management. *Resource and Energy Economics 59*(101129).

Rouhi Rad, M., D. T. Manning, J. F. Suter, and C. Goemans (2021). Policy leakage or policy benefit? Spatial spillovers from conservation policies in common property resources. *Journal of the Association of Environmental and Resource Economists 8*(5), 923–953.

Sampson, G. S., N. P. Hendricks, and M. R. Taylor (2019). Land market valuation of groundwater. *Resource and Energy Economics 58*.

Scanlon, B. R., C. C. Faunt, L. Longuevergne, R. C. Reedy, W. M. Alley, V. L. McGuire, and P. B. McMahon (2012). Groundwater Depletion and Sustainability of Irrigation in the US High Plains and Central Valley. *Proceedings of the National Academy of Sciences of the United States of America 109*(24), 9320–9325.

Scheierling, S. M., J. B. Loomis, and R. A. Young (2006). Irrigation water demand: A mete-analysis of price elasticities. *Water Resources Research 42*(W01411).

Schlenker, W., W. M. Hanemann, and A. C. Fisher (2006). The impact of global warming on U.S. agriculture: an econometric analysis of optimal growing conditions. *The Review of Economics and Statistics 88*(1), 113–125.

Schoengold, K. and N. Brozovic (2018). The future of groundwater management in the high plains: evolving institutions, aquifers and regulations. *Western Economics Forum 16*(1).

Schoengold, K., D. L. Sunding, and G. Moreno (2006). Price elasticity reconsidered: Panel estimation of an agricultural water demand function. *Water Resources Research 42*(W09411).

Sophocleous, M. (2005). Groundwater recharge and sustainability in the High Plains aquifer in Kansas, USA. *Hydrogeology Journal 13*, 351–365.

Staiger, D. and J. H. Stock (1997). Instrumental variables regression with weak instruments. *Econometrica 65*(3), 557–586.

Stanton, J., S. Qi, D. Ryter, S. Falk, N. Houston, S. Peterson, S. Westenbroek, and S. Christenson (2011). Selected approaches to estimate water-budget components of the High Plains, 1940 through 1949 and 2000 through 2009: U.S. Scientific Investigations Report 5183, United States Geological Survey.

Steward, D. R. and A. J. Allen (2016). Peak Groundwater Depletion in the High Plains Aquifer, Projections from 1930 to 2110. *Agricultural Water Management 170*, 36–48.

Steward, D. R., P. J. Bruss, X. Yang, S. A. Staggenborg, S. M. Welch, and M. D. Apley (2013). Tapping Unsustainable Groundwater Stores for Agricultural Production in the High Plains Aquifer of Kansas, Projections to 2110. *Proceedings of the National Academy of Sciences 110*(37), E3477–E3486.

USDA-NRCS (2006). Land resource regions and major land resource areas of the United States, the Caribbean, and the Pacific Basin. U.S. Department of Agriculture Handbook 296, U.S. Department of Agriculture, Natural Resources Conservation Service.

USGS (1998). Digital map of hydraulic conductivity for the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. https://water.usgs.gov/GIS/metadata/usgswrd/XML/ofr98-548.xml.

USGS (2011). High Plains aquifer. https://www.usgs.gov/mission-areas/water-resources/science/high-plains-aquifer?qt-science_center_objects=0#qt-science_center_objects.

USGS (2012). Specific yield, High Plains aquifer. https://water.usgs.gov/GIS/metadata/usgswrd/XML/sir12-5177_hp_sp_yield.xml.