State of Depletion: An empirical analysis of groundwater use on State Trust Lands

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Abstract

Resources on public lands are often allocated to private users to both generate revenue for the state and promote economic activity. In these allocations, individuals have limited property rights over their use of such resources. Limited property rights can lead to over-extraction of resources and provide disincentives to conserve resource stocks on public lands. In this paper, making use of a natural experiment, we explore differences in groundwater use between state held State Land Board (SLB) parcels and private parcels in Colorado. The SLB of Colorado leases out land to agricultural producers, with groundwater rights tied to the land leases. Due to limited property rights, individuals on SLB lands may extract more groundwater relative to users on comparable private parcels. As groundwater is a common pool resource where the future availability of groundwater to a producer depends on the extraction behavior of all nearby producers, this presents additional challenges in the estimation of causal effects. We contribute to the literature by demonstrating that SLB wells pump substantially more water compared to wells irrigating private parcels. The results reveal that, on average, SLB wells pump 15 to 32 percent more groundwater compared to wells irrigating nearby private lands.

Introduction

Trust lands make up approximately 156 million surface acres of public land across the United States, as reported by the National Association of State Trust Lands. The State

Land Board (SLB) of Colorado owns and manages 2.8 million acres of trust land in the state, 98 percent of which is leased out for agricultural uses. The revenue from these leases, as in other states, goes towards funding public schools. Leases on trust lands are often married with access to water rights owned by the SLB. The leaseholders on the land have a limited property right, where they have access to the use of water but do not have any transfer rights, and have limited tenure length and limited renewal ability. Due to the limited property rights, leaseholders may be less incentivized to conserve groundwater stocks on these lands compared to private land.

Groundwater resources, such as the Ogallala aquifer, have experienced substantial depletion in the western US (Haacker, Kendall, and Hyndman, 2016). Groundwater resources are a crucial to irrigated agriculture (Lauer et al., 2018) and have substantial impacts on crop choices and agricultural rents (Hornbeck and Keskin, 2014). Given the prevalence of trust lands and the importance of groundwater stocks across the west, it is important to explore whether groundwater use on these lands varies considerably from privately owned land. In this paper, we empirically compare groundwater use on trust lands to water use on private land parcels nearby, allowing us to better understand the extent to which differences in imperfect property rights on public lands may impact common pool resource use.

Historically state trust lands have been dedicated to productive uses, as trust lands have a fiduciary duty to generate revenue for funding public schools and other public beneficiaries. Davis (2008) highlight that the most intense resource extraction among all state managed lands generally occur on trust lands. Given that these lands make up three quarters of all state owned land in the US[1], differences in land use patterns on trust lands can have large consequences for resource depletion and the environment. Despite being germane to resource extraction, there is very little empirical research related to state trust lands. Existing studies on trust lands have largely focused on technical efficiency (Bonds and Hughes, 2007), market returns (Sunderman, Spahr, and Runyan, 2004; Sunderman and Spahr, 2006) and revenue generation (Bonds and Pompe, 2005).

[1]Concentrated mostly in 18 western states

We contribute to this literature by demonstrating the difference in groundwater extraction on state trust lands compared to similar private parcels. In 1875 majority of state trust lands in Colorado were allocated uniformly across space, using the US Public Land Survey System. The resulting allocation acts as a natural experiment, that enables us to look at differences in groundwater use between lands that do not systematically vary in land and environmental characteristics. We combine information on the initial allocation with instrumental variable (IV) and regression discontinuity design (RDD) approaches, to estimate the causal effect of SLB designation on groundwater use. The results suggest that wells irrigating SLB parcels use considerably more groundwater compared to wells irrigating nearby private parcels. The magnitude of the local average treatment effect is around 15 to 32 percent of mean water use in the sample. These results are robust across all models. The results also demonstrate that current levels of saturated thickness is lower for SLB wells, relative to nearby private wells.

Groundwater represents an accumulating resource and its extraction rate is a function of a host of inter-temporal incentives as defined by the associated property rights. Early work exploring the role of property rights and resource usage theorizes that in the absence of complete property rights, resource rents will dissipate due to excessive extraction (Gordon, 1954). In practice, however, limited property rights are common for resources held in public trust, where it is common to lease out land and water to users for a limited tenure. Thus, granting resource users access without perpetually giving up control over the resource. State trust lands provide an opportunity to observe resource usage under limited property rights.

Property rights on state trust lands vary from that of private property in a number of important ways. State trust lands can be bought and sold by the SLB. Although more restrictive than private lands, this provides the SLB a degree of transfer rights over the trust lands. Additionally, leaseholders of trust lands face a limited tenure of 10 years and face an uncertain renewal mechanism. At the end of the lease tenure, the trust land goes up for auction. The current holder of the lease can match the highest bid in the auction to renew for an additional 10 years. This is referred to as the right of first refusal. Existing research on Native American Trust lands, using a natural experimental framework, highlight that limited property rights can lower land utilization (Dippel, Frye, and Leonard, 2020), reduce investment in improving irrigation technology and lower the likelihood of growing high value crops (Ge, Edwards, and Akhundjanov, 2020). We expand this literature by documenting the impact of limited property rights on SLB lands on groundwater extraction, relative to property right arrangements on nearby private lands.

It is important to note, that the estimated differences in water use do not reflect differences in leased lands and owner-operated lands. The tenure type for non-SLB parcels is unobservable in the dataset. Due to the potential presence of privately rented land, the estimates represent a lower bound if interpreted as a difference between leased lands and owner-operated lands. However, we primarily focus on interpreting the results as differences in resource use driven by differences in property right arrangements between private and state trust lands. Property right arrangements on private property, whether owner-operated or rented, may differ from publicly rented property, as owners of private property have additional incentives to conserve the resource stock. On the other hand, due to the presence of a common pool resource, such incentives may not be strong. This outlines the underlying motivation for the empirical analysis. We contribute to the literature by providing evidence on the difference in resource usage between public and private lands in a common pool resource setting.

The research also builds on literature that evaluates whether groundwater users engage in dynamic decision making. Existing research demonstrates that the extraction rate of groundwater users, under the prior appropriation doctrine, correlates with expected prices, expected costs and extraction of neighbors(Oehninger and Lawell, 2021). In this paper, differences in property right arrangements between private and state trust lands are only relevant if groundwater users are influenced by the future availability of groundwater. Thus, if groundwater users were are myopic, we would not see a systematic difference in water use between public leased parcels and private lands. The estimates from this study provide additional evidence suggesting that the behavior of groundwater users is forward looking.

The next section illustrates the theoretical framework for the paper. The following sections describe the historical allocation of SLB lands, description of the data and the empirical strategy used. These sections provide crucial information regarding the natural experiment and describe the process through which causal effects are estimated in this paper. The sections following that discuss the main results, future directions and conclusions of the paper.

Theoretical Framework

In this section, we present a 2-period common pool resource model with 2 producers designed to provide insight into the differences in behavioral incentives on SLB land compared to private land. We are interested in analyzing the difference in water use in period 1 between the two producers, within a setting of differing levels of renewable tenure related to access to a common pool resource. Let ρ represent the assurance level, as defined by the lease contract, which represents the probability that the producer will have access to the resource stock in period 2. Let us assume that each producer maximizes profit subject to a groundwater resource constraint. For simplicity, assume producers only use 1 input, which is groundwater, to produce output and the input has diminishing returns to production. The cost of extracting groundwater per unit is c. This cost reduces by bX_j, where X_j is the saturated thickness in period j. b represents the quantity by which the marginal cost of extraction declines per unit of saturated thickness. $c - bX_j > 0$ such that the marginal cost of extraction remains positive even at high saturated thickness levels.

The production function is assumed to be $f(d_{ij}) = ad_{ij} - \frac{1}{2}sd_{ij}^2$ for producer i in period j, where d_{ij} is the groundwater use by producer i in period j. The 2-period maximization problem for producer 1 can be written as:

$$\underset{\{d_{11},d_{12}\}}{\text{maximize}} \quad \pi_1 = p(ad_{11} - \frac{1}{2}sd_{11}^2) - (c - bX_{11})d_{11} + \frac{\rho[p(ad_{12} - \frac{1}{2}sd_{12}^2) - (c - bX_{12})d_{12}]}{(1+r)}$$

subject to:

$$X_{12} = X_{11} + \bar{R} - \gamma_1 d_{11} - \gamma_2 d_{21}$$

where p represents price of output, d_{11} represents the water used by producer 1 in period 1, d_{12} is the water used by producer 1 in period 2, d_{21} is water used by producer 2 in period 1, X_{11} represents the initial stock of water available to producer 1 in period 1, X_{12} represents the stock of groundwater available to producer 1 at the beginning of period 2, c represents pumping cost as saturated thickness approaches zero, r represents the discount rate. $\bar{R}$ represents the recharge rate and γ represents the impact of water use on the groundwater stock available to producer 1, with γ_1 being the impact of water use by producer 1 and γ_2 being the impact of water use by producer 2. Both γ_1 and γ_2 reduce groundwater available to producer 1 in period 2. The problem can be simplified to an unconstrained optimization problem by plugging in the resource constraint into the objective function. The first order conditions from the simplified problem can be expressed as:

$$\frac{\partial \pi_1}{\partial d_{11}} = p(a - sd_{11}) - c + bX_{11} - \frac{b\gamma_1 \rho d_{12}}{(1+r)} = 0 \tag{1}$$

$$\frac{\partial \pi_1}{\partial d_{12}} = p(a - sd_{12}) - c + bX_{11} + b\bar{R} - b\gamma_1 d_{11} - b\gamma_2 d_{21} = 0 \tag{2}$$

To examine the difference in water use between producer 1 and 2, we need to derive the Nash equilibrium level of water use by each producer. Assuming symmetry, the best response functions for d_{11} and d_{21} can be expressed as:

$$d_{11} = \frac{[ps(1+r) - b\gamma_1\rho_1][pa - c + bX_{11}] - b^2\gamma_1\rho_1\bar{R}}{(ps)^2(1+r) - (b\gamma_1)^2\rho_1} + \frac{b^2\rho_1\gamma_1\gamma_2 d_{21}}{(ps)^2(1+r) - (b\gamma_1)^2\rho_1} \quad (3)$$

$$d_{21} = \frac{[ps(1+r) - b\theta_1\rho_2][pa - c + bX_{21}] - b^2\theta_1\rho_2\bar{R}}{(ps)^2(1+r) - (b\theta_1)^2\rho_2} + \frac{b^2\rho_2\theta_1\theta_2 d_{11}}{(ps)^2(1+r) - (b\theta_1)^2\rho_2} \quad (4)$$

where X_{21} is the stock of water available to producer 2 in period 1. θ represents the impact of water use on the groundwater stock available to producer 2, with θ_1 being the impact of water use by producer 2 and θ_2 being the impact of water use by producer 1. We assume, following physical groundwater flow properties, that the impact of extraction on groundwater stocks available is highest at the point of extraction and dissipates with distance. Therefore, we assume $\gamma_1 > \gamma_2$ and $\theta_1 > \theta_2$. Due to symmetry, $\theta_1 = \gamma_1$ and $\theta_2 = \gamma_2$. Additionally, ρ_1 and ρ_2 are the assurance levels of producer 1 and 2, respectively. We assume $\rho_1 < \rho_2$, such that producer 1 has a lower level of assurance for accessing the groundwater stock in period 2, as defined by their property right arrangement.

We can summarize equations 3 and 4 as:

$$d_{11} = A_1 + B_1\gamma_2 d_{21} \quad (5)$$

$$d_{21} = A_2 + B_2\theta_2 d_{11} \quad (6)$$

Both terms A and B vary as a function of ρ. The term A represents water demand for producers in the absence of CPR problems. B represents how much producers respond to the water demand of others. Unsurprisingly, $\frac{\partial A}{\partial \rho} < 0$ if we assume $pa > c - b(X_{11} + \bar{R})$. The condition $pa > c - b(X_{11} + \bar{R})$ represents that prices need to be sufficiently large so that pa, which is the intercept of the marginal revenue curve, is greater than $c - b(X_{11} + \bar{R})$, which is the marginal cost in period 2 if there was no extraction in period 1. As tenure security improves, producers have more incentive to conserve the resource stock and so they reduce current extraction.

Interestingly, it can be shown that $\frac{\partial B}{\partial \rho} > 0$. When producers have higher assurance of access to future stocks, they respond to a greater degree to the extraction of others. However, when tenure security is low, the extraction of others weighs less on the resource extraction decisions of producers. If we assume property rights arrangements on private land provide higher assurance than public lands, water use on private lands can still be higher due to increased response to the water demand by other nearby producers.

The existence of CPR effects is an important takeaway that is useful for the empirical specifications. In order to identify the impact of differences in incentives between two producers, it is important that the CPR effects between them are not large. Therefore, we will focus on producers that have relatively low levels of γ_2 (or θ_2) between them. It is also important to mention that there may exist other institutional differences between producers using SLB wells, compared to those using non-SLB wells. For instance, producers on SLB lands may face additional restrictions on using the land and the water right by the SLB. The estimated differences between them will also capture those differences.

Historical background

Historically, state trust lands represent land grants, provided by the US federal government, to the western territories upon receiving statehood by joining the Union (Pounds, 2011). The initial legislation guiding the allocation include the General Land Ordinance of 1785 and the Northwest Ordinance of 1787. To understand the initial allocation of state trust lands, we need to first describe the US Rectangular Public Land Survey System (RPLSS). The RPLSS, initially established by the General Land Ordinance, organizes all land in the US into 36 square mile grids called townships (Webster and Leib, 2011). Each township is composed of 36 one square-mile sections, arranged as shown in Figure 1. Initially under the General Land Ordinance, states held section 16 of every township in trust for the state schools.

6	**5**	**4**	**3**	**2**	**1**
7	**8**	**9**	**10**	**11**	**12**
18	**17**	**16**	**15**	**14**	**13**
19	**20**	**21**	**22**	**23**	**24**
30	**29**	**28**	**27**	**26**	**25**
31	**32**	**33**	**34**	**35**	**36**

Figure 1: A township subdivided into 36 sections as described by the RPLSS

The Northwest Ordinance authorized Congress to pass enabling acts that allowed territories to create a constitution. Once a state constitution was agreed upon by the territory and Congress, the federal government would make an offer to the new state to join the Union. Trust lands were granted to each state as part of joining the Union. One of the big innovations in trust land allocation took place in 1875, when Congress passed the Colorado Enabling Act. Overtime, Congress and the states made gradual changes to how trust lands were allocated and managed. The Colorado Enabling act of 1875 was one of the first enabling acts to explicitly mention the establishment of permanent funds for revenues derived from the trust lands. It also included conditions that set minimum prices on the sale of land and restricted the use of income from the sales.

Upon the statehood of Colorado in 1876, the SLB received sections 16 and 36 of most townships as trust lands (Bedford, 2000) from the federal government. The revenues from the use of these trust lands were to be used to fund public schools in Colorado. The state however did not receive lands in areas where the section was already occupied by Native American territories, homesteaders, reserved for parks, military bases or other federal purposes (Coloarado State Land Board, n.d.). At the time, the federal government allowed states to select "in lieu" lands from elsewhere in the public domain. Thus, the state got to pick additional lands in some counties of Colorado, which were meant to equate to the same acreage as the reserved lands.

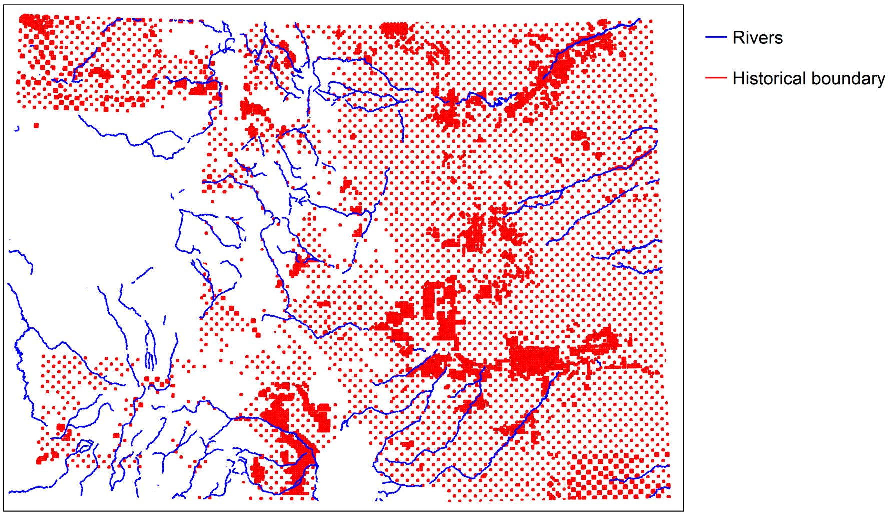


Figure 2: Full historical boundary of SLB lands allocated in 1876

The map in Figure 2 demonstrates the spatial distribution of the 1876 historical boundaries, which are represented by the red borders. As we can see, there are two distinct patterns in which trust lands were allocated. First, we can see many of the lands were allocated uniformly across space in sections 16 and 36. Second, we can see clusters of trust lands in many areas. These clusters partly reflect lands gained "in lieu", where the state had a choice in selecting the location. Some of these clusters appear to be located in riparian areas. Importantly, these allocations were made before the development of groundwater irrigation in Colorado. Therefore, we can expect these allocations to be exogenous to many of the observable and unobservable factors that may drive groundwater use today. However, due to the presence of "in lieu" lands, these historical boundaries may line up with natural features, such as nearness to rivers, that drive water use. This can pose a threat to the identification of causal impact of SLB lands classification on groundwater use. As we are able to fully observe the allocation mechanism, we can reasonably assume that the historical borders that overlap with sections 16 and 36 are exogenous to factors driving groundwater use today. Therefore, we only consider the historical boundaries related to sections 16 and 36 as our reference boundary in the empirical analysis.

Data

The study area includes the South Platte, Republican and Arkansas river basins located within eastern Colorado[2]. We combine data on agricultural leases and historical boundaries, obtained from the SLB of Colorado, with data on irrigated parcels and water diversion records for the years 2008-2020, obtained from the Colorado Decision Support System (CDSS). The analysis includes SLB leases categorized as agricultural, agricultural and homesite, dry crop, grazing, and irrigation. We then identify irrigated parcels that have more than 80 percent of their land area within currently active SLB land boundaries. These parcels are identified as treatment parcels, which are leased from the SLB. The control parcels include irrigated parcels that have no intersections with any SLB land. The treatment and control designations are assumed to be time invariant in our dataset. SLB leased lands are often re-leased and are rarely converted to private land, which makes this a reasonable assumption for a 12-year sample period. In order to examine within township differences in water use between treatment and control, we restrict our sample to include townships that have at least one treatment and one control parcel. Water rights information tied to the parcels is then used to identify treatment and control wells. Wells irrigating parcels both within and outside of SLB boundaries are removed from the sample. Wells with no water use in a year are removed for that year. This ensures we are comparing water use only across active wells. Additionally, we remove wells that have greater than 1000 ACFT of water use in any year. Wells with such large diversions may either be irrigating a very large number of parcels or they may be diverting water for non-irrigation purposes. In both cases, this makes it likely that those wells are not comparable to the rest of the sample.

NOAA U.S. Climate Gridded datasets are incorporated in the analysis to control for average maximum temperatures and average monthly precipitation during the growing season[3]. Soil type data from the USDA's gSSURGO dataset is utilized to control for the percent sand, silt and clay for each parcel. The soil type variables are assumed to be

[2]Figure 3 was generated by combining spatial data from the CDSS with County shape data from the US Census Bureau.

[3]The growing season in this study includes the months of May, June, July, August and September.

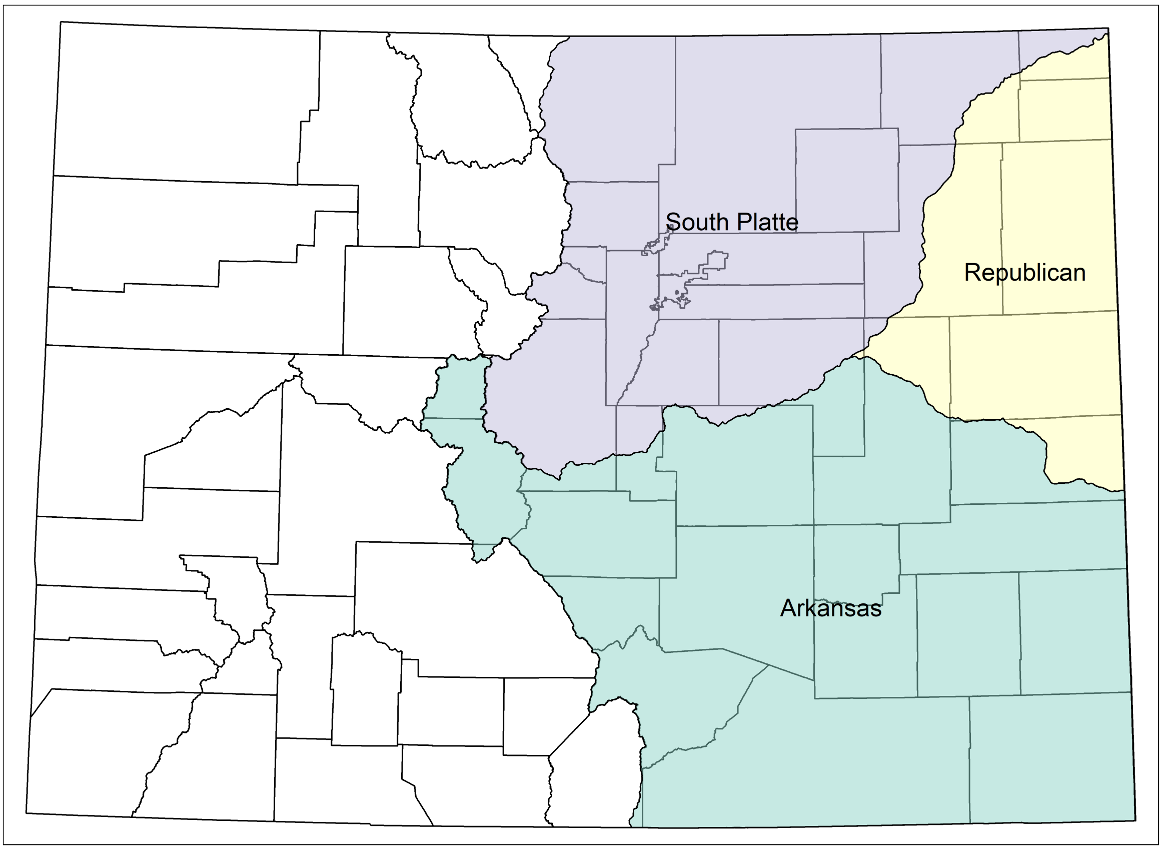


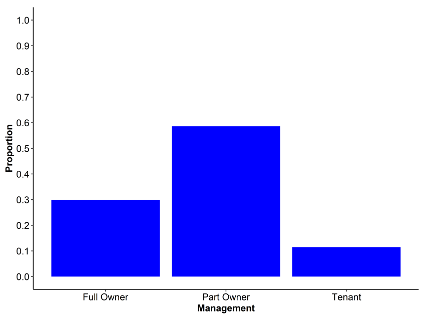
Figure 3: River basins that define the study area

time-invariant. We also make use of annual estimates of saturated thickness as described in Haacker, Kendall, and Hyndman (2016). Additionally, we utilize data from the US Geological Survey (USGS) on well level characteristics such as groundwater appropriation, allowable irrigated acres per well, yield and hydraulic conductivity.

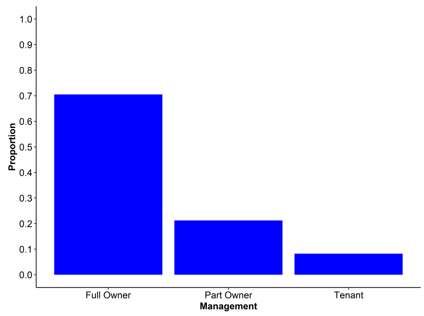
Using spatial data on the irrigated parcels, we estimate distance from the 1876 historical boundary and X and Y coordinates of the centroid of each parcel. All parcel level variables are averaged by well to generate well-level estimates. We also make use of well location obtained from the CDSS in the analysis.

Identification Strategy and Specifications

In the analysis, we compare wells irrigating SLB parcels to wells irrigating nearby private land. In order to identify impacts related to tenure security on SLB lands, ideally we would compare SLB lands to only privately owned or privately leased lands. However, characteristics of the operator are unobservable for control group parcels. Figure 4 represents the proportion of acres farmed and number of farming operations by management type for the counties in the sample based on the 2017 US Census of Agriculture[4]. In the Census, tenure type is categorized as full owner, part owner and tenant. Full owner and tenant categories represent operators that only own land and rent, respectively. Part owners represent operators that both own land and rent land. Looking at the distribution of tenure types, it is likely that some of the wells in the control group are rented. Therefore, it is important to note that the estimated effects only represent a lower bound of actual differences between SLB and owner operated private lands due to differences in tenure security. It is also important to note that the differences in groundwater use may be driven by other institutional factors associated with the SLB. Therefore, we primarily focus on estimating the causal effect of SLB designation on groundwater use, regardless of the channel of the impact.



(a) Proportion of acres operated



(b) Proportion of farming operations

Figure 4: Proportion of acres and operations by management type

In order to estimate the impact of SLB leases on water use, we would require an exogenous assignment of SLB lands that is independent of environmental, farmer specific, farm specific or other factors that may influence water use. In practice the existing allocation of SLB lands are a function of decisions made by the SLB. Overtime, the SLB have bought and sold lands with the objective of benefiting the trust. This makes it unlikely that the current distribution of SLB lands is independent of other factors that may influence groundwater demand. Fortunately, part of the initial allocation of SLB lands in 1876,

[4]The figure was constructed from using 2017 Agricultural Census data. It can be retreived from: https://quickstats.nass.usda.gov/

related to sections 16 and 36, were made uniformly across space in Colorado. Whereas, part of the historical boundary, related to the "in lieu" lands, are subject to selection bias due to the state being able to choose the location of those lands. The historical boundary used in the analysis excludes boundaries related to the "in lieu" lands. Apart from being uniformly located across space, the historical boundary was allocated before the development of the Ogallala aquifer, which lies beneath majority of the wells used in this study[5]. These factors make it likely that the boundaries are independent of individual or environmental factors that may dictate the present water demand. This initial allocation acts as a natural experiment that we use to estimate the causal impact of SLB lands classification on groundwater use.

We make use of both instrumental variable (IV) methods and regression discontinuity design (RDD) methods to identify the causal impact of SLB classification on groundwater use. Both methods use exogenous variation in SLB designation generated by the historical boundary. The IV models make use of more data to estimate local average treatment effects, whereas the RDD models use observations close to the boundary to estimate a discontinuity. The RDD models also require sufficient spatial granularity of the data to identify effects. However, the RDD models can also be used to test whether environmental factors vary across the boundary. Therefore, there are benefits to looking at treatment effects generated by both models.

Before describing identification under the two models, we must first introduce concepts related to the bandwidth and well exclusion distance. In figure 5, the historical SLB boundary is depicted by the red square. The orange dot represents a treatment well, whereas the blue dots represent control wells. In the sharp RDD, treatment wells are strictly inside the boundary and the control wells will remain outside the boundary. This may not be the case for the IV model. The (outer) buffer around the historical boundary represents a 1 mile distance from the historical SLB boundary. We refer to this as the bandwidth. Wells nearer to the historical boundary are likely to be similar to each other in terms of observable and unobservable characteristics that may influence water use.

[5]Around 83 percent of all wells and 84 percent of treatment wells in this study lie above the Ogallala aquifer.

Therefore, limiting the sample to a certain bandwidth enables us to estimate differences in water use across comparable wells. As the historical SLB parcels represent 1 mile by 1 mile sections, we include all observations inside the boundary at bandwidths of 0.5 miles or higher. At bandwidths lower than that, we may exclude some of the treatment wells. As groundwater is a common pool resource, wells located near each other may impact each other's water use. To reduce the impact of potential spillovers, we exclude all non-SLB wells that lie within 1 mile of a SLB well[6]. We refer to this as the well exclusion distance, as shown by the circle around the treatment well in figure 5.

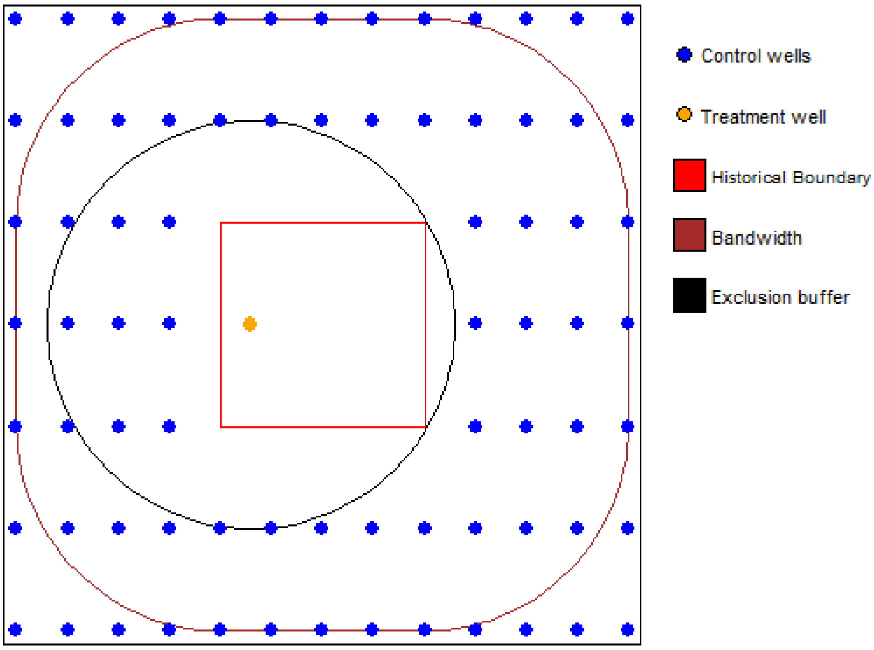


Figure 5: Bandwidth and Well exclusion distance

Not all of the historical SLB parcels contain wells that irrigate SLB parcels. In order to avoid including sections with no treatment wells, we only include the historical SLB parcels that contain at least one SLB well. We refer to this as the treatment boundary. Similarly for all the placebo analysis, we include only sections of the historical boundary that contain at least one non-SLB well. This part of the historical boundary represents historical SLB parcels that may have been sold off. We drop any SLB wells in specifications that do not have any non-SLB wells within the specified bandwidth to be compared

[6]For the placebo analysis, we remove all control wells within 1 mile of a placebo treatment well.

to[7]. The panels in figure 6 show the treatment historical SLB boundaries. The treatment sections are represented by the red squares.

(a) (b) (c)

Figure 6: Treatment historical boundary

Instrumental Variable Method

The IV models require an observable instrument which adequately predicts the assignment of SLB designation but does not directly impact groundwater use through any other channel. As the majority of SLB lands are located inside the historical boundary, wells located inside the boundary are more likely to be SLB wells compared to wells outside the boundary. The historical border was established prior to the development of the Ogallala aquifer and was uniformly allocated across space. Therefore, we assume that the relative location of a well to the boundary does not impact groundwater use directly. We use information on whether a well is located inside the historical SLB boundary or outside as the instrument in the IV model. Using a two stage least squares approach, we then estimate the impact of SLB designation on annual groundwater use.

Table 1 presents differences in means between SLB and non-SLB wells using wells within a 2 mile bandwidth[8]. The table shows that SLB wells use more water than non-

[7]This only leads to dropping 2 wells in some specifications.

[8]This is the largest bandwidth in that we use. The data here also excludes control wells that lie

SLB wells. The table also reveals that, on average, the SLB and non-SLB wells in the sample look very similar based on observables. Additionally, the table reveals that the number of non-SLB wells in the sample is substantially higher than the SLB wells.

Table 1 Test of mean differences between SLB and Non-SLB parcels

Variable	Non-SLB	SLB	Difference (SLB - Non-SLB)	p-value
Time-varying				
Annual groundwater use (ACFT)	195.117	212.283	17.167**	0.016
Precipitation (inches)	59.918	59.602	−0.316	0.752
Max Temperature (°C)	28.818	28.898	0.080	0.317
Time-invariant				
Additional well	0.192	0.205	0.013	0.854
Percent clay	20.270	20.260	−0.011	0.995
Percent sand	49.180	48.108	−1.073	0.813
Percent silt	30.264	32.018	1.754	0.567
Surface water access	0.146	0.154	0.008	0.903
Number of wells	369	39	−330	—
Depth to water	152.258	155.525	3.267	0.751
Groundwater rights appropriated (ACFT)	428.084	420.633	−7.451	0.748
Hydraulic conductivity major	14.780	14.667	−0.114	0.661
Hydraulic conductivity minor	19.780	19.667	−0.114	0.661
Irrigated acres appropriated	176.205	178.200	1.995	0.894
Specific Yield Major	56.503	51.667	−4.837	0.105
Specific Yield Minor	113.007	103.333	−9.673	0.105
Well Capacity	813.650	810.242	−3.409	0.960

Significance levels are defined as *p<0.1; **p<0.05; ***p<0.01.

As levels of the observable variables may have been impacted by the SLB treatment itself, it would be useful to look at mean differences among pre-treatment variables across the boundary. However, as wells largely either remain SLB wells or non-SLB wells, there is not a clear pre-treatment period. Instead, we explore differences across private parcels across the historical boundary as a placebo test. The majority of the historical SLB boundaries either contain non-SLB wells or SLB wells, with less than 3 sections containing both. The differences among non-SLB wells across the historical boundary should reflect differences driven by environmental differences across the historical boundary that are independent of the SLB treatment.

within 1 mile of a SLB well, as described earlier and only includes observations with lower than 1000 ACFT of annual water use.

Table 2 Test of mean differences between non-SLB wells across the boundary

Variable	Outside	Inside	Difference (Inside - Outside)	p-value
Time-varying				
Annual groundwater use (ACFT)	175.309	171.011	−4.299	0.267
Precipitation (inches)	57.753	57.187	−0.565	0.245
Max Temperature (°C)	28.831	28.841	0.009	0.796
Time-invariant				
Additional well	0.280	0.333	0.054	0.167
Percent Clay	18.480	19.886	1.405*	0.097
Percent Sand	52.730	49.417	−3.313	0.134
Percent Silt	28.795	30.764	1.969	0.205
Surface water access	0.272	0.303	0.031	0.411
Number of wells	379	231	−148	—
Depth to water	149.368	149.034	−0.334	0.954
Groundwater rights appropriated	435.146	426.227	−8.919	0.600
Hydraulic conductivity major	14.247	14.244	−0.003	0.992
Hydraulic conductivity minor	19.247	19.244	−0.003	0.992
Irrigated acres appropriated	175.822	181.328	5.506	0.481
Specific yield major	51.142	50.210	−0.931	0.599
Specific yield minor	102.283	100.420	−1.863	0.599
Well capacity	808.939	777.646	−31.293	0.423

Significance levels are defined as *p<0.1; **p<0.05; ***p<0.01.

Table 2 presents the differences between non-SLB wells inside and outside the boundary. The placebo sample includes all wells that lie within 1 mile of historical boundary. The mean estimates suggest that groundwater use is not systematically different across the boundary. It is important to mention that, when including all wells within 2 miles, groundwater use inside the boundary is larger. However, when limiting the sample to 1 mile of the boundary, the differences no longer persists. The table reflects that, within the 1 mile buffer, there are no systematic differences in observable water use, weather, soil composition, hydrology and water rights across the historical boundary.

We estimate separate IV models on restricted samples that include wells located within 1 and 2 miles of the historical SLB boundaries. The well exclusion distance is set to 1 mile for all models. We generate estimates using a two stage least squares (2SLS) approach. The second stage of the IV is specified as:

$$Y_{it} = \beta_s S\hat{L}B_i + \mathbf{\Theta X_{it}} + \delta_t + \alpha_c + \epsilon_{it} \tag{7}$$

and the first stage is specified as:

$$SLB_{it} = \beta_{hb} B_i + \mathbf{\Gamma X_{it}} + d_t + a_c + v_{it} \tag{8}$$

where Y_{it} is groundwater use by well i in year t, SLB_i is a dummy variable for whether the well is irrigating SLB parcels and B_i is a dummy for wells located within the historical SLB boundary. The first and second stage include the same set of control variables (X_{it}) which include average latitude and longitude of parcels being irrigated by well i, average maximum temperature, average precipitation, percent sand and silt, distance to nearest river and saturated thickness in 1935. a_c and α_c represent township fixed effects, d_t and δ_t represent time fixed effects, and v_{it} and ϵ_{it} represent the error term in the first and second stage, respectively.

Regression Discontinuity Design

The identification strategy for the spatial regression discontinuity design (RDD) is similar to Ge, Edwards, and Akhundjanov (2020). We assume a continuity-based framework for identification of local average treatment effects. The central identifying assumption under this framework is that all potential variables impacting water use, except SLB land classification, should vary continuously at the historical border. Thus, any discontinuous change in water use across the historical boundary would be attributable to the SLB classification (treatment). Figure 7 represents the relationship between the probability of finding current SLB irrigated parcels and the distance from the historical boundary. The distances outside the boundary are represented by positive numbers and the distances within are represented by negative numbers. As shown by the figure, there is a sharp decline in the probability of finding a SLB parcel as we move outside the historical boundary. This provides us with an exogenous source of variation in treatment assignment right near the historical borders, which enables us to identify the causal impact of SLB status on annual groundwater use.

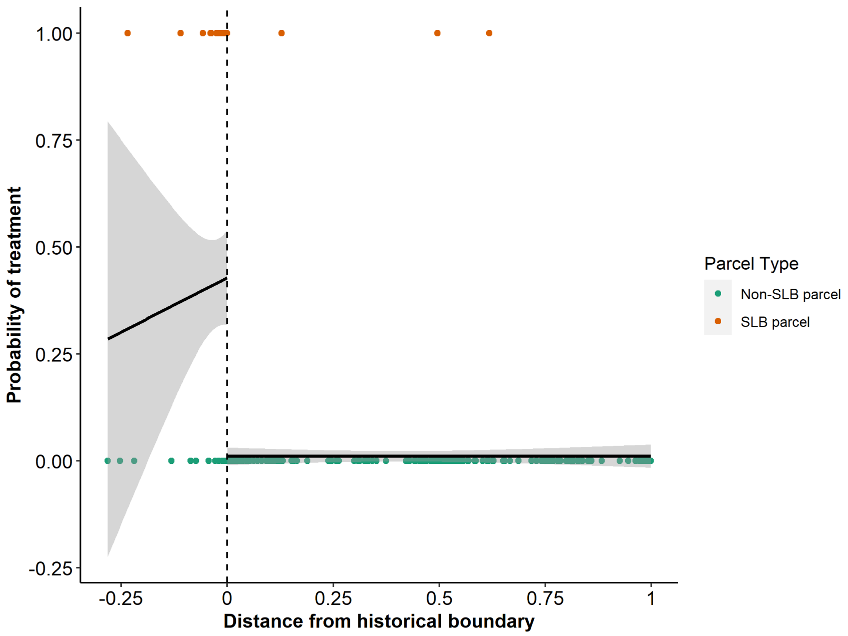


Figure 7: Probability of treatment and distance from historical boundary

Following Wuepper, Wimmer, and Sauer (2020), we test the continuity assumption for other variables by examining the presence of discontinuities along the historical boundary for a set of observable variables, that may impact water use, using a sharp RDD[9]. Table 3 represents the treatment coefficients from sharp RDDs with different dependent variables

[9]We are unable to test this for unobservable factors that may impact water use. Thus, we only present tests based on observable data available to us.

to demonstrate whether there are any other discontinuities generated by the historical boundary, other than the treatment. In the presence of other discontinuities, it is difficult to attribute a discontinuous jump in water use to solely the SLB classification. The table shows there are almost no significant discontinuities in water access, water rights, weather and soil type variables along the historical boundary.

Table 3 Testing for continuity of variables across multiple bandwidths

	Distance within			
Dependent Variable	1 mile	0.75 miles	0.5 miles	0.25 miles
Water access:				
Distance to nearest river	0.027	−0.041	−0.046	0.186
	(0.353)	(0.364)	(0.393)	(0.395)
Saturated thickness in 1935	−1.703	−1.272	−0.455	−0.709
	(1.183)	(1.200)	(1.172)	(1.170)
Water rights:				
Surface water rights	0.004	−0.007	−0.015	−0.015
	(0.014)	(0.015)	(0.014)	(0.013)
Other groundwater rights	0.150*	0.109	0.114	0.111
	(0.079)	(0.078)	(0.079)	(0.077)
Weather:				
Average maximum temperature	−0.006	−0.006	−0.010	−0.021*
	(0.010)	(0.010)	(0.011)	(0.012)
Average monthly precipitation	−0.112	−0.128	−0.043	0.160
	(0.176)	(0.167)	(0.184)	(0.207)
Soil type:				
Percent clay	−1.119	−0.933	−1.092	0.229
	(1.510)	(1.643)	(1.742)	(1.720)
Percent sand	1.474	1.579	0.898	−0.243
	(3.716)	(4.128)	(4.232)	(4.249)
Percent silt	−0.142	−0.673	0.085	0.320
	(2.296)	(2.602)	(2.582)	(2.610)
Observations	2,793	2,346	1,519	987
Polynomial	Quadratic	Quadratic	Quadratic	Quadratic
Fixed effects	Township & Year	Township & Year	Township & Year	Township & Year

Notes: Standard errors are clustered at the well level and are provided in parenthesis. *p<0.1; **p<0.05; ***p<0.01

We estimate both parametric and non-parametric models for the RDD. Following Wuepper, Wimmer, and Sauer (2020), the running variable in the analysis is geographic location as defined by average longitude and latitude, $L_i = (L_{ix}, L_{iy})$, of the centroid of parcels being irrigated by well i. We define treatment ($T_i = 1$) as a dummy for when the longitude and latitude of well location coincide with any points at or inside the historical boundary. The empirical model for the sharp RDD is specified as:

$$Y_{it} = \beta_s T_i + f(geolocation_i) + \mathbf{\Theta K_{it}} + \delta_t + \alpha_c + \epsilon_{it} \tag{9}$$

where $f(geolocation_i)$ is defined as:

$$f(geolocation_i) = L_{ix} + L_{iy} + L_{ix} \times L_{iy} + L_{ix}^2 + L_{iy}^2 + L_{ix}^2 \times L_{iy} + L_{iy}^2 \times L_{ix} \tag{10}$$

We select a quadratic polynomial of the running variable as recommended by Gelman and Imbens (2019). Y_{it} represents groundwater use by well i in year t, L_{ix} and L_{iy} represents the average longitude and latitude of parcels being irrigated by well i. The control variables, $\mathbf{K_{it}}$, include average maximum temperature, average precipitation, percent sand and silt, distance to nearest river and saturated thickness in 1935. α_c represent township fixed effects, δ_t represent time fixed effects, and ϵ_{it} represent the error term. We present results for the parametric RDD models at bandwidths of 0.5 and 0.25 miles. For the non-parametric model, we use distance to historical boundary as the running variable. The optimal bandwidth of the non-parametric model is selected according to Calonico, Cattaneo, and Titiunik (2015).

Results

Annual groundwater use per well

Table 4 presents estimates of the average treatment effect of SLB designation on groundwater use for both IV models and RDD models. The bandwidth for specifications 1 and 2 are constructed based on proximity of the well location to the historical boundary. Wells near the boundary are likely to be more similar and therefore can serve as better comparisons. Therefore, we present results for wells within 2 miles and 1 mile for the IV models[10]. The bandwidth for specifications 3, 4 and 5 are constructed using the average

[10]We test the sensitivity of the estimates to differences in bandwidth, which is provided in the Appendix. The results are qualitatively similar for a range of bandwidths.

distance between parcels irrigated by a well and the historical boundary.

The results reveal that wells irrigating SLB parcels use substantially more water compared to non-SLB wells. We see that the sign of the treatment effect is robust across all specifications. SLB wells use between 30 to 64 acre feet more water compared to non-SLB wells. Given the average water use in the sample is 196 acre feet, estimates of the LATE ranges between 15 to 32 percent of mean water use. The full regression tables can be found in the Appendix.

Table 4 Regression results: Differences in groundwater use between SLB and non-SLB wells

	Dependent variable:				
	Groundwater use per well				
	Instrumental Variable		Regression Discontinuity		
			Parametric		Non-parametric
	(1)	(2)	(3)	(4)	(5)
Treatment effect	29.716*	37.604**	36.340**	64.827***	57.277***
	(16.487)	(18.465)	(16.553)	(17.286)	(5.578)
Bandwidth (miles)	2	1	0.5	0.25	0.184
Observations	3,369	984	1,084	687	631
Treatment observations	307	296	307	307	305
Fixed Effects	Township & Year	Township & Year	Township & Year	Township & Year	Township & Year
Clustered SEs	Well level	Well level	Well level	Well level	Well level

Notes: Significance levels are described by *(p<0.1), **(p<0.05), ***(p<0.01).
F-stats from the first stage of both IV models imply strong instruments (F>400).
Controls for IV includes: latitude, longitude, percent sand and silt, max temperature, average precipitation, distance to nearest river and saturated thickness in 1935. Controls for RDD are similar but they also include a fully flexible set of geographical location variables.
The estimate for the parametric model represents biased corrected estimates as described in Calonico, Cattaneo, and Titiunik (2015) with the optimal bandwidth selected according to Calonico, Cattaneo, and Titiunik (2014). The number of observations in the non-parametric model reflect the effective number of observations.

In the remaining parts of the results section we explore a few additional results. The SLB wells may have a higher level of water rights appropriated, which may contribute to the difference in water use between SLB and non-SLB parcels. To explore this, we estimate the difference in groundwater use as a percentage of the water right appropriated between SLB and non-SLB parcels. We then explore the extent to which differences in groundwater use between SLB and non-SLB parcels are driven by differences in the intensive (water use per acre) and extensive margin (acres irrigated). Finally, we explore the impact of SLB designation on groundwater stocks, by looking at differences in saturated thickness between SLB and non-SLB parcels.

Groundwater use as percentage of groundwater appropriated

The coefficient estimates presented in table 5 reflect differences in groundwater use as a percentage of annual groundwater appropriated between SLB and non-SLB wells. Estimates from the non-parametric model in table 5 provide some indication of SLB wells using a larger proportion of groundwater appropriated by their water right. However, the statistical significance is not robust across specifications. Looking at the remaining specifications, there seems to be limited evidence to suggest systematic differences groundwater use as a percentage of groundwater appropriated between SLB and non-SLB wells. It is important to note, that the sample size decreases when we incorporate the water rights data. The lack of statistical significance maybe due to a drop in statistical power.

Table 5 Regression results: Impact of SLB designation on proportion of groundwater use

	Dependent variable: Water use as a proportion of groundwater appropriated				
	Instrumental Variable		Regression Discontinuity		
			Parametric		Non-parametric
	(1)	(2)	(3)	(4)	(5)
Treatment effect	0.094	0.115	0.017	0.063	0.10^{***}
	(0.077)	(0.078)	(0.030)	(0.039)	(0.026)
Bandwidth (miles)	2	1	0.5	0.25	0.205
Observations	2,834	837	938	578	536
Treatment observations	249	240	262	262	253
Fixed Effects	Township & Year	Township & Year	Township & Year	Township & Year	Township & Year
Clustered SEs	Well level	Well level	Well level	Well level	Well level

Notes: Significance levels are described by *(p<0.1), **(p<0.05), ***(p<0.01).
F-stats from the first stage of both IV models imply strong instruments (F>400).
Controls for IV includes: latitude, longitude, percent sand and silt, max temperature, average precipitation, distance to nearest river and saturated thickness in 1935. Controls for RDD are similar but they also include a fully flexible set of geographical location variables.
The estimate for the parametric model represents biased corrected estimates as described in Calonico, Cattaneo, and Titiunik (2015) with the optimal bandwidth selected according to Calonico, Cattaneo, and Titiunik (2014). The number of observations in the non-parametric model reflect the effective number of observations.

Intensive and extensive margin effects

In order to understand the margin along which SLB classification impacts groundwater use, we inspect the impact of SLB designation on water use per acre, representing the intensive margin, and number of irrigated acres, representing the extensive margin. We combine the existing data set with yearly irrigated acres data, obtained from the CDSS, to get irrigated acres and water use per irrigated acre for each well in the sample. Irrigated acres data is only available for a few years, which reduces the sample size to almost half. We then proceed to estimate the regression models using water user per acre (intensive margin) and acres irrigated (extensive margin) as dependent variables.

The coefficient estimates in table 6 reflect the average difference in groundwater use per acre between SLB and non-SLB parcels. This reflects differences in water use that may be driven by factors that impact the intensity of water use on each acre. The estimates from the non-parametric model in table 6 suggest that SLB wells use more water per acre, relative to non-SLB wells. However, the statistical significance of the estimates are not robust across models. The IV and remaining parametric RDD specifications provide little evidence of any systematic difference in water use per acre between SLB and non-SLB wells.

Table 6 Regression results: Impact on the intensive margin

	Dependent variable: Groundwater use per acre				
	Instrumental Variable		Regression Discontinuity		
			Parametric		Non-parametric
	(1)	(2)	(3)	(4)	(5)
Treatment effect	0.783	1.368	0.819	0.045	1.255***
	(0.901)	(0.835)	(0.636)	(0.752)	(0.478)
Bandwidth (miles)	2	1	0.5	0.25	0.048
Observations	1,444	407	479	296	186
Treatment observations	135	129	135	135	114
Fixed Effects	Township & Year	Township & Year	Township & Year	Township & Year	Township & Year
Clustered SEs	Well level	Well level	Well level	Well level	Well level

Notes: Significance levels are described by *(p<0.1), **(p<0.05), ***(p<0.01).
F-stats from the first stage of both IV models imply strong instruments (F>140).
Controls for IV includes: latitude, longitude, percent sand and silt, max temperature, average precipitation, distance to nearest river and saturated thickness in 1935. Controls for RDD are similar but they also include a fully flexible set of geographical location variables.
The estimate for the parametric model represents biased corrected estimates as described in Calonico, Cattaneo, and Titiunik (2015) with the optimal bandwidth selected according to Calonico, Cattaneo, and Titiunik (2014). The number of observations in the non-parametric model reflect the effective number of observations.
Full regression tables can be found in the Appendix.

The estimates presented in table 7 represent the difference in the number of acres irrigated between SLB and non-SLB parcels. The statistical significance is not robust across models. We do not find sufficient evidence to suggest that the number of acres irrigated systematically varies between SLB and non-SLB parcels.

The results suggest that higher water use by SLB parcels, relative to non-SLB parcels, is not systematically driven solely by the intensive or extensive margin differences. It is likely that the differences are driven by a combination of both margins. The sample size for these estimates is reduced due to incorporating data on acres irrigated. Therefore, these results may also be driven by a lack of statistical power. However, it is important to mention that even when using this sample, we are able to identify statistically significant differences in groundwater use between SLB and non-SLB parcels. The regression estimates exploring differences in groundwater use using the reduced sample are provided in the Appendix.

Table 7 Regression results: Impact on the extensive margin

	Dependent variable: Acres irrigated per well				
	Instrumental Variable		Regression Discontinuity		
			Parametric		Non-parametric
	(1)	(2)	(3)	(4)	(5)
Treatment effect	3.988	2.944	−2.506	28.440	18.421***
	(11.934)	(18.188)	(15.272)	(18.911)	(5.620)
Bandwidth (miles)	2	1	0.5	0.25	0.123
Observations	1,444	407	479	296	245
Treatment observations	135	129	135	135	130
Fixed Effects	Township & Year	Township & Year	Township & Year	Township & Year	Township & Year
Clustered SEs	Well level	Well level	Well level	Well level	Well level

Notes: Significance levels are described by *(p<0.1), **(p<0.05), ***(p<0.01).
F-stats from the first stage of both IV models imply strong instruments (F>140).
Controls for IV includes: latitude, longitude, percent sand and silt, max temperature, average precipitation, distance to nearest river and saturated thickness in 1935. Controls for RDD are similar but they also include a fully flexible set of geographical location variables.
The estimate for the parametric model represents biased corrected estimates as described in Calonico, Cattaneo, and Titiunik (2015) with the optimal bandwidth selected according to Calonico, Cattaneo, and Titiunik (2014). The number of observations in the non-parametric model reflect the effective number of observations.
Full regression tables can be found in the Appendix.

Impact on Saturated thickness

Persistent differences in groundwater extraction between SLB and non-SLB parcels can lead to differences in saturated thickness overtime. In order to explore the impact of extraction by SLB wells, we incorporate hydrological data modeled in Haacker, Kendall, and Hyndman (2016). The data provides estimated saturated thickness levels at 250 by 250 m (0.16 by 0.16 mile) grids. Due to the data resolution, it is difficult to explore discontinuities in saturated thickness, especially when the border of the grids do not align with section boundaries. As a result, saturated thickness across the border seem to be continuous by construction.

Figure 8 shows a snippet of the study area. The black squares represent treatment townships and the red squares represent sections of the historical border. As we can see, although saturated thickness varies inside and outside the border, it varies smoothly across the border. The lack of spatial granularity makes it difficult to identify effects using RDD methods, which specifically are focused towards estimating discontinuities

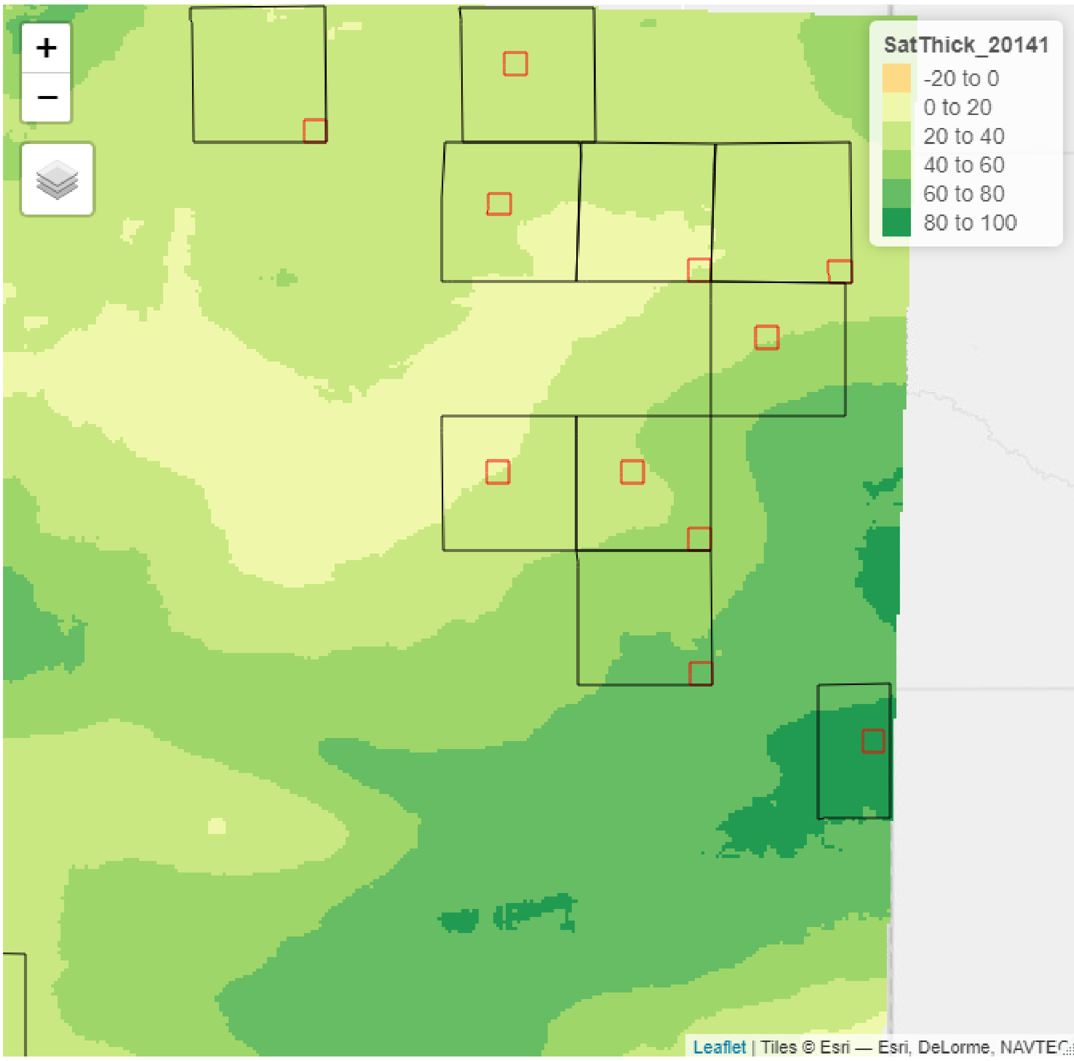


Figure 8: Saturated thickness

local to the border. Therefore, we only use IV methods at large bandwidths to identify differences in saturated thickness between SLB and non-SLB wells.

Table 8 Regression results: Differences in saturated thickness

	Dependent variable:	
	Saturated thickness	
	IV	
	(1)	(2)
Treatment effect	-1.136^{***}	-0.654^{**}
	(0.326)	(0.309)
Bandwidth (miles)	2	1
Observations	2,194	644
Treatment observations	201	195
Fixed Effects	Township & Year	Township & Year
Clustered SEs	Well level	Well level
R^2	0.993	0.996
Adjusted R^2	0.993	0.996

Notes: Significance levels are described by:
*(p<0.1), **(p<0.05), ***(p<0.01).
F-stats from the first stage of both IV models
imply strong instruments (F>400).
Controls for IV includes: latitude, longitude,
percent sand and silt, max, temperature,
average precipitation, distance to nearest river and saturated
thickness in 1935.

The results from table 8 reveal that current saturated thickness under SLB wells are lower than that of non-SLB wells. A lower saturated thickness can correlate to a higher pumping costs. It is interesting to see that, despite lower levels of saturated thickness, SLB wells pump more groundwater annually compared to non-SLB wells. It is also important to note that we control for initial saturated thickness in 1935. Therefore, the estimated differences in the above specifications are not driven by the initial endowment of groundwater stocks.

Robustness testing

Placebo testing

It is important to explore whether the differences in groundwater use are driven by environmental factors. There are non-SLB wells that irrigate non-SLB parcels inside the historical boundary. This allows us to also estimate differences in water use across the boundary using RDD methods. These differences in groundwater use should represent the impact of non-institutional or non-behavioral factors that are not uniquely associated with SLB leaseholders but may correlate with the nature of the boundary itself.

We define non-SLB wells inside the historical SLB boundary as the placebo treatment and non-SLB wells outside as the control. Similar to other specifications, we remove any control wells that fall within 1 mile of a placebo treatment well. Finally, we remove all SLB wells from the sample for the placebo analysis.

Table 9 Regression results: Placebo testing

	Dependent variable:			
	Annual groundwater use per well			
	(1)	(2)	(3)	(4)
Placebo testing	−2.016	−2.016	−5.082	−54.178*
	(9.143)	(9.143)	(14.143)	(28.072)
Bandwidth (miles)	2	1	0.5	0.25
Observations	5,067	5,067	2,445	2,015
Fixed effects	Township & Year	Township & Year	Township & Year	Township & Year
Clustering	Well level	Well level	Well level	Well level

Notes: Significance levels are described by *(p<0.1), **(p<0.05), ***(p<0.01). Controls include: percent sand and silt, max temperature, average precipitation, distance to nearest river and saturated thickness in 1935 and a flexible set of geographical location variables.

Table 9 represent the results of the placebo tests. The estimates do not suggest that there are any systematic differences in environmental factors across the boundary. As we approach the boundary, the estimated coefficient gets lower but the standard error also increases. The result suggests that the differences in groundwater use between SLB and non-SLB wells are not likely to be driven by environmental factors.

Testing the robustness of SUTVA assumption

In the base specification we exclude control group wells that fall within 1 mile of any treatment group wells, to ensure the control group is not impacted by the treatment. In this section we test whether a 1 mile distance between wells are sufficient to ensure there that the results are not largely driven by spillover effects. We explore this by systematically excluding control wells that fall within 1 mile to 1.25, 1.5, 1.75 and 2 miles of the treatment. For the IV model, we are unable to make these exclusions for models with a bandwidth of 1 mile, as we end up dropping too many observations. Therefore, we only test the well exclusion criteria for the IV model with a 2 mile bandwidth.

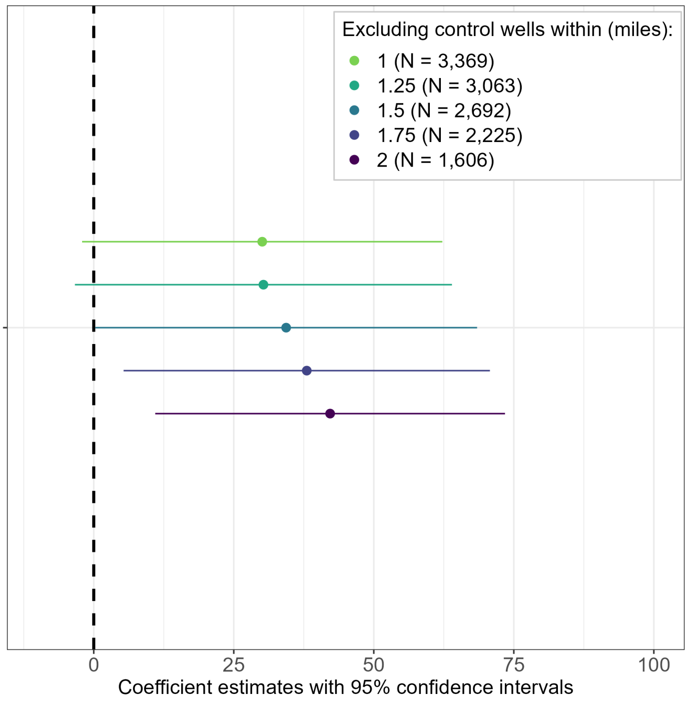


Figure 9: SUTVA testing for IV model (BW = 2 miles)

Figure 9 illustrates the treatment effects for IV models with a fixed bandwidth of 2 miles and at varying well exclusion distances. It is interesting to see that as we exclude more control wells nearby the treatment wells, the precision improves. Increasing exclusion distance beyond 1.25 miles enables us to identify effects at a 5 percent significance level. However, there is very large overlap between the confidence intervals, which indicates that the estimates are not statistically different from each other.

We also explore the impact of these exclusions for the sharp RDD. Figure 10 illustrates the treatment effects by different exclusion distances while fixing the bandwidth to 0.5 miles. The results reveal large overlapping confidence intervals for the estimates with different exclusion distances. This implies that the estimates are not statistically different from each other.

This suggests that the treatment effect estimates, with an exclusion distance of 1 mile, are not substantially impacted by the spillover effects.

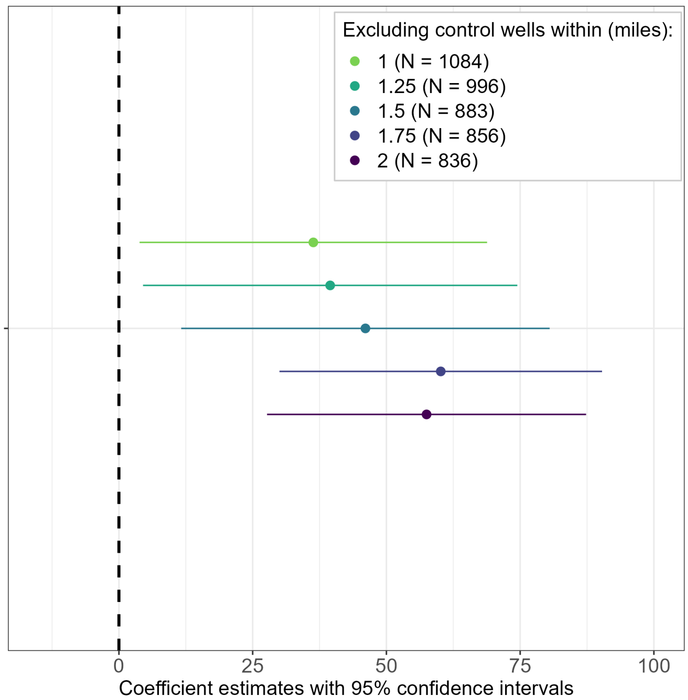


Figure 10: SUTVA testing for RDD model (BW = 0.5)

Conclusion

The results of this study highlight the substantially higher impact of SLB wells on groundwater use and stocks, relative to comparable non-SLB wells. These differences imply that existing agricultural use of state trust land may impact long term sustainability of sensitive groundwater resources, such as the Ogallala aquifer. On the other hand, agricultural leases bring in large funding for public schools in Colorado. These results bring attention to the need for sustainable management practices and policies regarding the use of state trust lands. Existing research on state trust lands are largely focused on exploring revenue generation. However, in order to understand the inter-temporal trade-offs faced by states, research focused on evaluating long run economic cost of excess extraction of resource stocks is necessary. Given the scarcity of groundwater resources, achieving sustainable groundwater use on trust lands is crucial. Trust Lands provide us with a setting where revenues from natural capital extraction are invested in human capital generation. Thus, understanding the extent to which natural capital is being diminished is critical for evaluating the sustainability of trust land management.

It is important to mention that trust lands have a range of uses in Colorado beyond grazing and agriculture. State trust lands are also used for recreational use, renewable energy generation and conservation. Research on the costs and benefits of transitioning to different land uses can be an important area of exploration that can inform sustainable management of state trust lands. Trust lands can also be enrolled in conservation programs. If the benefits of enrolling trust lands is higher than that of private land, providing a higher price for trust land parcels may increase SLB revenues as well as improve conservation in the region.

This research, although highlighting important impacts of state trust lands, is not without limitations. First, due to not having information on farmer specific characteristics, we are unable to fully evaluate the effectiveness of our identification strategy. If farmers that prefer to only operate on private lands have systematically different water demands, compared to farmers on SLB lands, then this would pose a threat to identification. As groundwater use is likely to be driven largely by profitability, we do not expect it to systematically vary by preferences for SLB participation. Second, use of state trust lands vary substantially across states. Therefore, these results may have limited ability to inform trust land management outside of Colorado. Finally, although we demonstrate a difference in groundwater use between SLB and non-SLB wells, the mechanism through which the differences arise is not empirically demonstrated in this paper. The differences could be due to incentives, institutional policies or a range of other reasons. Given the large impact on groundwater, future research uncovering these mechanisms can have major implications for sustainable water use on state trust lands.

References

Bedford, C.E. 2000. "The New Colorado State Land Board." *Denv. UL Rev.* 78:347.

Bonds, M.H., and D.R. Hughes. 2007. "On the productivity of public forests: A stochastic frontier analysis of Mississippi school trust timber production." *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie* 55:171–183.

Bonds, M.H., and J.J. Pompe. 2005. "Improving institutional incentives for public land management: an econometric analysis of school trust land leases." *Journal of Institutional Economics* 1:193–215.

Calonico, S., M.D. Cattaneo, and R. Titiunik. 2015. "Rdrobust: an R package for robust nonparametric inference in regression-discontinuity designs." *R J.* 7:38.

—. 2014. "Robust nonparametric confidence intervals for regression-discontinuity designs." *Econometrica* 82:2295–2326.

Coloarado State Land Board. n.d. "Our agency's history."

Davis, S.M. 2008. "Preservation, resource extraction, and recreation on public lands: A view from the states." *Natural Resources Journal*, pp. 303–352.

Dippel, C., D. Frye, and B. Leonard. 2020. "Property Rights without Transfer Rights: A Study of Indian Land Allotment." Working paper, National Bureau of Economic Research.

Ge, M., E.C. Edwards, and S.B. Akhundjanov. 2020. "Irrigation investment on an american indian reservation." *American Journal of Agricultural Economics* 102:1083–1104.

Gelman, A., and G. Imbens. 2019. "Why high-order polynomials should not be used in regression discontinuity designs." *Journal of Business & Economic Statistics* 37:447–456.

Gordon, H.S. 1954. "The economic theory of a common-property resource: the fishery." In *Classic papers in natural resource economics*. Springer, pp. 178–203.

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

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* 6:190–219.

Lauer, S., M. Sanderson, D. Manning, J. Suter, R. Hrozencik, B. Guerrero, and B. Golden. 2018. "Values and groundwater management in the Ogallala Aquifer region." *Journal of Soil and Water Conservation* 73:593–600.

Oehninger, E.B., and C.Y.C.L. Lawell. 2021. "Property rights and groundwater management in the High Plains Aquifer." *Resource and Energy Economics* 63:101147.

Pounds, E. 2011. "State Trust Lands: Static Management and Shifting Value Perspectives." *Envtl. L.* 41:1333.

Sunderman, M., R. Spahr, and S. Runyan. 2004. "A Relationship of Trust: Are State "School Trust Lands" Being Prudently Managed for the Beneficiary?" *Journal of Real Estate Research* 26:345–370.

Sunderman, M.A., and R.W. Spahr. 2006. "Management policy and estimated returns on School Trust Lands." *The Journal of Real Estate Finance and Economics* 33:345–362.

Webster, G.R., and J. Leib. 2011. "Living on the Grid: the US Rectangular Public Land Survey System and the Engineering of the American Landscape." In *Engineering Earth*. Springer, pp. 2123–2138.

Wuepper, D., S. Wimmer, and J. Sauer. 2020. “Is small family farming more environmentally sustainable? Evidence from a spatial regression discontinuity design in Germany.” *Land Use Policy* 90:104360.