The Benefits and Costs of Groundwater Regulation*

Ellen M. Bruno† and Nick Hagerty‡

January 19, 2022

PRELIMINARY DRAFT: Please do not cite or circulate.

Abstract

What are the benefits and costs of a groundwater sustainability mandate to agricultural producers, as measured through hedonic valuation of land values? Following the passage and implementation of a groundwater legislation in California, we compare property values across groundwater agencies that will be subject to greater or lesser pumping restrictions, before and after those policies were first introduced. This difference-in-differences set-up elicits an estimate of the net benefits to landowners. Then, exploiting groundwater's lateral flow and a research design that relies on spatial discontinuities in regulatory stringency, we estimate the gross cost of agricultural groundwater regulation through changes in land values across agency borders. Preliminary results suggest that the costs of regulation are large; each 1 acre-foot per acre of expected future pumping restrictions reduces land values at the border of a GSA in the post-treatment period by 55%. Our analysis sheds light on the cost-effectiveness of groundwater policies designed to achieve sustainability.

*We thank Will Robinson for excellent research assistance.

†Department of Agricultural and Resource Economics, University of California, Berkeley. Email: ebruno@berkeley.edu

‡Department of Agricultural Economics and Economics, Montana State University. Email: nicholas.hagerty@montana.edu

1 Introduction

Many of the world's groundwater aquifers are severely depleted; decades of overextraction have led to declining water tables in many of the most productive agricultural regions of the world (Wada et al., 2010). Despite a broad range of available regulatory solutions – from the formalization of property rights to pumping restrictions and volumetric fees – regulation remains rare (Smith et al., 2017; Bruno and Jessoe, 2021). One challenge is that the optimal extent of groundwater regulation is difficult to determine.

Calls for regulation often seek to achieve sustainability, which in many cases means leaving the future stock of a resource at least as large as it is today. In this scenario, depletion is halted and the resource stock stabilizes well above the open-access steady state. But this definition of sustainability may be too stringent and not privately efficient. In some cases, users may prefer (in present value terms) to draw down the resource over extracting indefinitely at a slower rate. In the groundwater context, high discount rates diminish the importance of higher pumping costs in the future, and when extraction is small relative to the total storage in an aquifer, the gains from management may be negligible (Gisser and Sanchez, 1980; Brill and Burness, 1994). And because regulation has rarely occurred in practice, there have been few opportunities to empirically test whether the benefits of groundwater sustainability outweigh the costs.

In this paper, we shed light on the tradeoffs associated with groundwater regulation in the context of agriculture in California, where legislation recently passed requiring that excessive drawdown of groundwater throughout the state be corrected in the coming years. Specifically, we ask what the welfare effects of a groundwater sustainability mandate are to agricultural producers, as measured through hedonic valuation of land values. Costs arise from reductions in groundwater pumping, both now and in the future. Benefits manifest from higher groundwater levels in the future due to the reduced pumping of other users, and thus lower costs to pump. If sustainability is privately efficient, the benefits of solving the open-access externality are greater than the costs of pumping restrictions. If sustainability is too stringent, the costs are large, and net benefits may be negative. Net benefits are our primary empirical object of interest, while gross benefits and costs can serve as inputs to the further design of optimal regulation.

The ongoing implementation of California's Sustainable Groundwater Management Act of 2014 provides a unique opportunity to estimate the benefits and costs of groundwater regulation. The basins subject to this regulation account for over 90% of the state's groundwater pumping. This fact, combined with the decentralized nature of the policy, which gives local agencies jurisdiction over management in their service areas, provides

substantial variation in regulatory stringency across our empirical setting. Although the implementation horizon is long and restrictions have not yet begun, the law changed farmers' expectations about their future water availability, so they should already be priced into investment decisions and the farmland market (California ASFMRA, 2021). We construct our treatment variable to capture expected changes in future pumping by using hydrologic model output and information contained in management plans submitted by groundwater agencies subject to the regulation. Finally, parcel-level geospatial data on land use and land values allows us to uncover the impacts of the regulation. We evaluate the effect our of treatment variable, a proxy for the expected reductions in pumping under SGMA, on historical sales price information of agricultural parcels in California by exploiting differences in stringency across basins and their boundaries.

We proceed in three steps. First, we estimate the net effects of the policy overall with a difference-in-difference design. We compare land values across groundwater management agencies that will be subject to greater or lesser pumping restrictions, before and after those policies were first announced. We estimate the average effect of greater pumping restrictions in a stacked fixed effects regression, which controls for time-invariant parcel-level characteristics as well as annual shocks common to each GSA and its comparison group. Then, we estimate the gross cost of the policy by using spatial discontinuities in regulation stringency at the borders of management agencies. Since groundwater moves laterally in response to pressure changes, a cross-sectional comparison of the value of agricultural parcels across the boundaries of groundwater agencies will capture only the costs of the policy, and no benefits from improved groundwater levels (Ayres et al., 2021). The sum of these two effects reveals the gross benefits of the policy.

Preliminary estimates suggest the costs of groundwater regulation are large. Using the stacked regression discontinuity design, we find that each 1 acre-foot per acre of expected future pumping restrictions reduces land values at the border of a GSA in 2020 by 0.8 log units – about 55%, or $4,300 for a typical acre. Border discontinuities are generally not significant for the years 2007-2018, before GSA plans were announced. In aggregate, this estimate implies that the statewide costs of SGMA are $1.1 billion. Estimates of (net and gross) benefits are in progress and will be available in the next version of this manuscript.

This paper weighs in on whether regulation of a dynamic, common-pool resource is privately optimal. Our results provide an empirical complement to the largely structural and dynamic groundwater literature that seeks to determine if optimal control improves welfare relative to open access use (Gisser and Sanchez, 1980; Brill and Burness, 1994). More recent studies have challenged the long-standing notion that gains from optimal groundwater management may be minimal (Brozović et al., 2010; Pfeiffer and Lin, 2012;

Edwards, 2016; Merrill and Guilfoos, 2017). We contribute empirical support to this debate.[1]

Our paper also contributes to an empirical literature that considers the impacts of water supplies on agricultural land values in order to measure the value of water or access to irrigation (Faux and Perry, 1999; Buck et al., 2014; Hornbeck and Keskin, 2014; Sampson et al., 2019), as well as various studies on the effects of irrigation policies (e.g., well drilling moratoria or adjudication) on land values (Ifft et al., 2018; Ayres et al., 2021). In contrast to these studies, we exploit rich and plausibly exogenous variation in expected future changes in groundwater pumping to capture its effects in welfare terms. A primary contribution of this paper stems from our ability to credibly estimate gross benefits and gross costs and see how these accrue separately over time.

2 Background

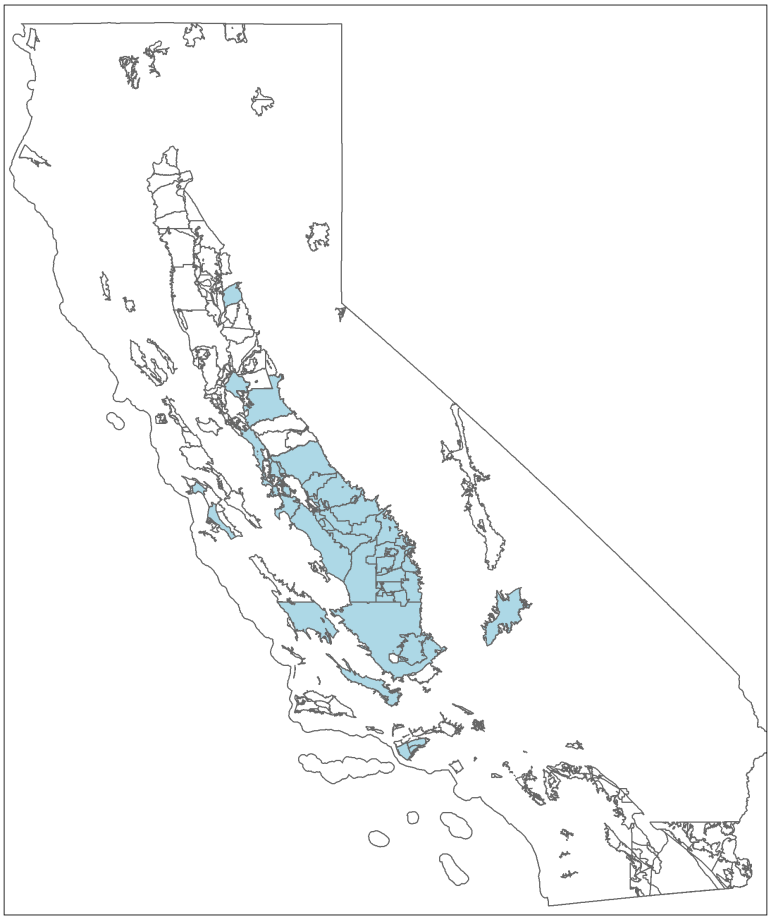
The passing of California's Sustainable Groundwater Management Act (SGMA) in 2014 provides an ideal opportunity to study the implementation of a sustainability policy. Groundwater reserves in California's Central Valley have been declining over the last several decades, raising fears about the long-term availability of the resource. It serves as a critical buffer during periods of surface water scarcity, with average use increasing from 40 to 80% of the water supply during drought years.

Passing during the peak of the state's last major drought, California's SGMA provides a statewide framework for local agencies to manage groundwater and bring their basins into balance. It requires groundwater sustainability agencies (GSAs) in overdrafted basins throughout California to reach and maintain long-term stable groundwater levels. Local agencies are given the authority and flexibility to manage the resource however they see fit, as long as their approach is documented in a "Groundwater Sustainability Plan" (GSP) outlined and approved by the state. The timeline to do so is determined by a state-designated level of priority. All GSPs for high- and medium-priority basins must be adopted by January 31, 2022. GSAs managing groundwater in high- and medium-priority basins subject to critical conditions of overdraft must adopt a GSP two years earlier, by January 31, 2020.[2]

[1] Our results also support a related literature that seeks to answer questions related to policy instrument choice. A rapidly growing body of empirical work evaluates the potential for and impacts of different mechanisms to overcome market failures in water use, from command-and-control (Drysdale and Hendricks, 2018) to pricing (Smith et al., 2017; Burlig et al., 2019; Bruno and Jessoe, 2021) and markets (Bruno and Sexton, 2020; Hagerty, 2021).

[2] Once they adopt, the plan goes into effect.

Figure 1: Map of Groundwater Sustainability Agencies in our Sample



Note: The figure highlights the groundwater agencies that remain in our sample: medium- and high-priority basins (as designated by the state), excluding regions exclusively covering cities.

SGMA created substantial variation in regulatory stringency, since basins with more overdraft must adopt greater pumping restrictions in order to achieve sustainability. There were 111 GSAs determined to be of high and medium priority under SGMA, together accounting for over 90% of the groundwater pumping in the state. Oftentimes, multiple GSAs joined together to collaboratively develop one GSP and were thus treated as the same unit in our analysis. GSAs exclusively covering cities were removed from our sample. The 31 highlighted regions in Figure 1 form the basis of our analysis.

2.1 Sustainability as Defined by the Law

Understanding how sustainability is defined and implemented under the law is important for interpreting what it means for farmer's expectations about their future water availability. Sustainability under SGMA is formally defined by the use and management of groundwater in a manner that can be maintained without causing "undesirable results" in regards to six key indicators. The six indicators include (1) chronic lowering of groundwater levels (depletion of supply), (2) reduction of groundwater storage, (3) seawater intrusion, (4) degraded water quality, (5) land subsidence, and (6) depletion of interconnected surface water. Avoidance of these six features to a "significant and unreasonable" degree constitutes a sustainable outcome. Plans are reviewed by the state for comprehensiveness and sufficiency. Inadequate plans are returned for revisions. Failure to comply will result in the state coming in as the backstop and taking over control.

While these six key indicators were determined by the state and are required to be monitored by all GSAs, the precise levels which trigger an "undesirable result" are quantified and set forth by the individual GSA. Each agency's groundwater sustainability plan must detail how they are measuring the indicators and what triggers an undesirable result. In defining what triggers an undesirable result, each GSP must establish minimum thresholds for each applicable sustainability indicator.[3] Minimum thresholds define when the effects become significant and unreasonable, producing an undesirable result, and therefore not achieving sustainability. The minimum thresholds are generally set at, or above, groundwater conditions observed in the basin since 2015.[4] Using a network of monitoring wells, each agency sets thresholds likes these that must be justified reasonably with the best available information and science, else the state can reject it.

2.2 Defining our Treatment Variable

Our goal is to characterize farmers' expectations regarding future groundwater availability due to the passing of SGMA. Our ideal treatment variable would capture the degree to which farmers in an agency's jurisdiction are required to reduce their groundwater pumping in order to achieve the basin's sustainability goals. We construct three different treatment variables that attempt to capture this, each using slightly different information

[3]For example, an agency may set the minimum threshold for chronic lowering of groundwater levels to be one foot above the groundwater levels observed in 2015 and an undesirable result occurs when 15% or more of the wells in the monitoring network exceeds this minimum threshold.

[4]Plans also contain measurable objectives defined by the GSA, which largely aim to improve groundwater conditions over time. Measurable objectives are more like goals that the agency would like to meet, but, to our knowledge, failing to do so has no consequence.

available to us.

Our first treatment measure comes from output from a hydrologic model of surface and groundwater in California's Central Valley. The model estimates a yearly volumetric change in groundwater storage. Using this measure for our treatment relies on the assumption that negative changes in storage must be corrected in order for the basin to achieve sustainability. We then take the total volume and divide it by the acreage of undeveloped area in the GSA to get a per-acre measure of estimated cut-back for agriculture. Our second measure of expected future pumping comes directly from management plans submitted by GSAs which report estimates of average annual volumes of groundwater overdraft.[5] In a similar fashion to the first treatment variable, we divide these annual GSA-level volumes of overdraft by the acreage in the GSA that is undeveloped to arrive at a per-acre estimate of expected agricultural pumping reduction. Finally, for our third treatment variable, we compare direct estimates of current and future pumping as outlined in each GSP. Pulling from each GSP's water budgets for current and future sustainable conditions, we take the difference between current and future pumping and again divide this by undeveloped acreage.

Our choice to focus on groundwater storage or overdraft to derive our treatment variable is for three reasons. First, it is one of the six sustainability indicators and one that is relevant for all basins subject to SGMA. Contrast this to seawater intrusion or the depletion of interconnected surface water, which are only relevant for basins that are hydrologically connected to the ocean or surface water bodies, respectively. Second, it is a well-understood metric for which there exist several publicly available models that predict basin-level changes in storage.[6] This allows us to calculate our treatment variable in an objective and consistent way across all basins. Some of the other indicators, such as groundwater quality, are more complex to measure, do not have an obvious focal point, and may be measured differently by different GSAs. Finally, the reduction of groundwater storage drives many of the other sustainability indicators, such as land subsidence, degraded water quality, and the depletion of interconnected surface water.

2.3 Timing of Treatment

One complication in our setting is the timing of treatment. We would like to consider a treatment period that corresponds to the time in which farmers changed their expec-

[5] Each plan contains several water budgets that are based on different subsets of historical data. The plans state their preferred water budget and corresponding preferred overdraft estimate, which we use.

[6] Storage and overdraft are conceptually very similar, however one incorporates lateral flow. Overdraft tells us the difference between pumping (out) and recharge (in), net of lateral flows.

tations about the future availability of water under SGMA. However, we lack complete information on how and when farmers update their expectations. SGMA was passed into law in September of 2014, initiating a timeline for agencies to form and develop groundwater management plans. The deadline for agencies to form was June 30, 2017. The formal establishment of these GSAs and their boundaries determined which jurisdiction a given parcel of farmland falls within. Given this timeline, we consider treatment to have occurred from 2014-2017. In our analysis, we therefore consider 2013 to be the last pre-treatment year and 2018 to be the first post-treatment year.

While a fully informed landowner may understand the consequences of SGMA passing in 2014, one concern is that other landowners may not have been aware of the changing regulatory landscape and its consequences. This concern is mitigated by the fact that community outreach and engagement were codified into the law. In fact, GSAs were required to record their public outreach efforts. With effective stakeholder engagement on behalf of the GSAs, including the dissemination of resources regarding SGMA implementation and several public comment hearings at the local level, it is likely that landowners successfully updated their expectations about changes to future pumping during this four year period.

3 Data

The primary data for this analysis consist of annual basin-level groundwater overdraft volume estimates, spatial land use information, and parcel-level sales transaction history of agricultural land in California subject to SGMA. Secondary data were collected from GSPs. Descriptive statistics on parcel-level property characteristics are reported in Table 1.

Our primary outcome variable is the sales price of agricultural land. We purchased from ParcelQuest a dataset on the transaction history and parcel boundaries of all properties in California that fall within GSAs and outside of urban areas. ParcelQuest collects and curates publicly available data on property sales from each California county assessor's offices. Data include transaction prices for the most recent three sales of every parcel dating back to 1960, 2021 assessed values, lot size, the geolocation of each parcel, and other property characteristics. Figure 2 shows the average price per acre, adjusted for inflation, from 1960 to 2021.

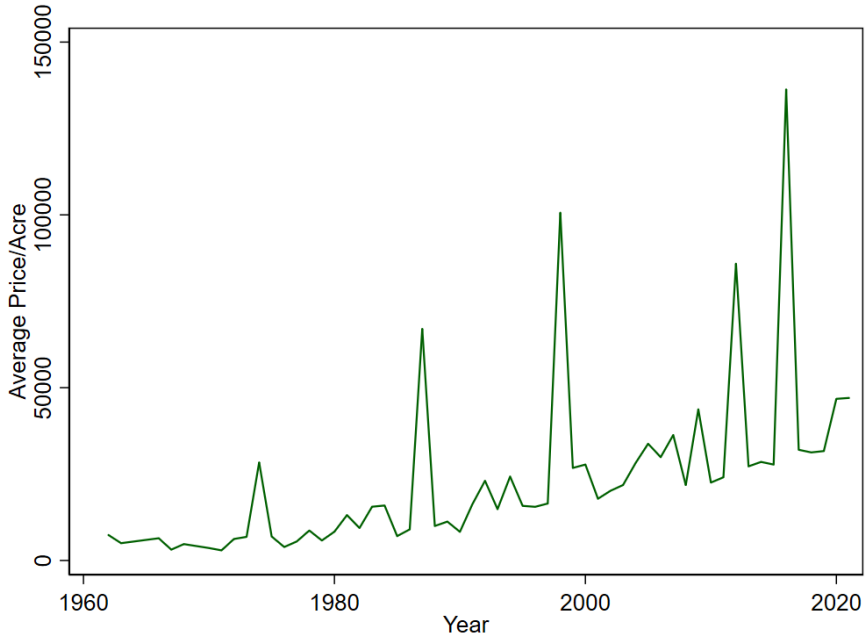
We will also consider the effects of groundwater regulation on land use. Our land use data consist of annual information on crops grown in the state at a 30-meter grid resolution spanning 2007-2020. We use the USDA's Cropland Data Layer, which is a remotely

Table 1: Descriptive Statistics

	Count	Mean	SD	Min	Max
Price	50,225	397,957.84	2,869,088.20	0	615,821,952
Price/Acre	50,132	35,802.63	1,098,728.45	0	171,520,672
Log(Price)	50,225	12.18	1.14	-1	20
Log(Price/Acre)	50,132	9.05	1.38	-6	19
Assessed Value	50,206	429,657.36	758,179.94	1	25,506,538
Improvement Value	50,225	309,669.64	785,647.64	70	61,419,454
Total Value	50,225	822,953.59	1,472,467.20	226	89,269,617
ParcelQuest Ratio	50,225	38.72	24.91	0	100
Lot Size (Acres)	50,132	51.42	97.20	0	9,072
Williamson Act Dummy	50,225	0.00	0.02	0	1

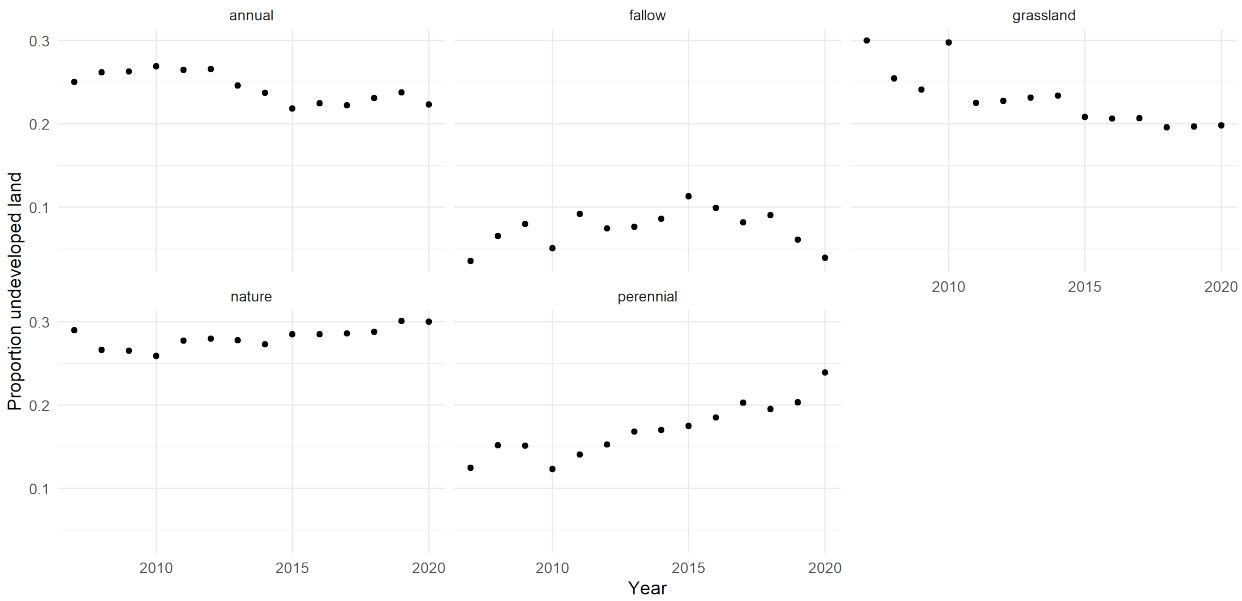
Notes: This table reports observations, means, standard deviations (SD), and min/max for parcel-level observables on the panel of ParcelQuest transaction data. Multi-parcel transactions have been removed.

Figure 2: Real Prices/Acre, 1960-2021



Note: Data come from ParcelQuest. Sales prices were adjusted for inflation. These trends exclude data from multi-parcel transactions.

Figure 3: Land Use, 2007-2020



Note: Data come from USDA's Cropland Data Layer. Land use was categorized into five groups and expressed as a fraction of undeveloped land in the GSA.

sensed data product of 119 distinct land-use classifications. Pixels are aggregated to farm fields as defined by quarter-quarter sections in the Public Land Survey System to reduce noise and computation time. Land use is classified into five categories: annual crops, perennial crops, fallowed/idled land, grassland, and nature. Land use presented in Figure 3 is expressed as a weighted average proportion of the undeveloped land in each GSA.

Our treatment variables are proxies for farmers' expectations of their future per-acre pumping restrictions. We collected measures of basin-level groundwater overdraft to proxy for the projected change in groundwater pumping expected under SGMA from two sources: Groundwater Sustainability Plans submitted by GSAs and the 1.0 version of the Fine Grid California Central Valley Groundwater-Surface Water Simulation Model (C2VSim), hydrologic model available from the California Department of Water Resources. We aggregate gridded values to GSAs by summing over all model grid cells whose centroid falls within each GSA boundary. The recent change in storage was compared to the average value of the change in storage from the 26 year period preceding SGMA – 1991 to 2015. Likewise, GSPs estimate and report overdraft, which we used in a similar fashion and assume farmers use this information to form expectations about future reductions in pumping required to achieve sustainability.

Our primary treatment variable is the plans' preferred measure of annual overdraft.

Secondary treatment variables are the plans' projected reduction in pumping and the model's estimate of overdraft. All treatment variables are divided by GSA cropland area to obtain per-acre volumes. Histograms of these three treatment variables are shown in Figure 4.

4 Empirical Approach

4.1 Conceptual Framework

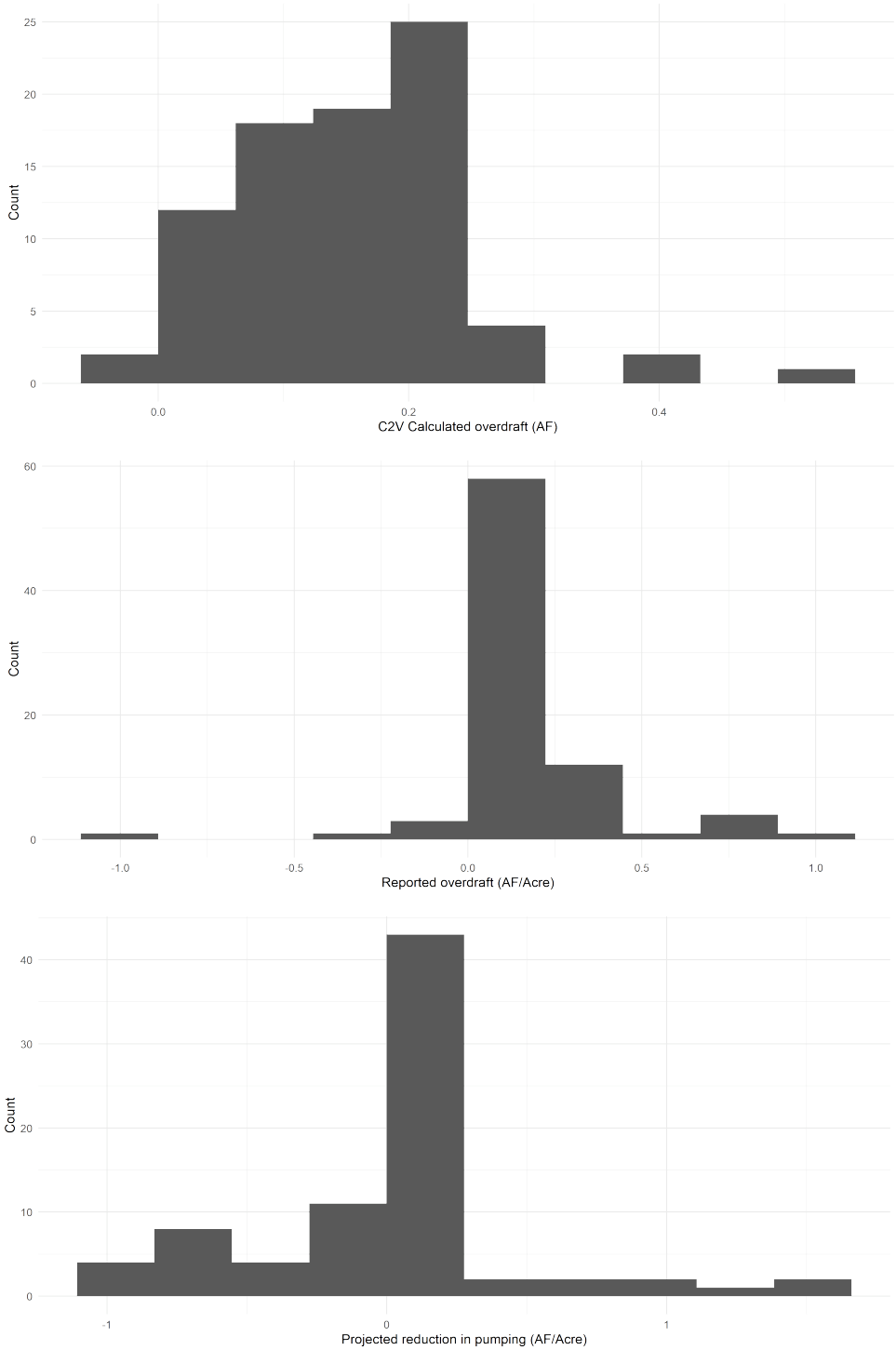
SGMA has created substantial variation in future regulatory stringency across groundwater basins in California. This variation provides an opportunity to learn about how future regulation affects decisions today.

Hedonics and welfare. The ability to pump groundwater is bundled with land ownership in California under both open access and future regulatory regimes under SGMA. Hedonic valuation can therefore recover the marginal willingness to pay for differing characteristics of groundwater access across land parcels. This includes both present characteristics (such as groundwater levels) and expected future characteristics (such as future pumping restrictions and future groundwater levels), in present discounted value terms.

Hedonic valuation of agricultural land will capture the welfare impacts of future regulations to agricultural producers under the assumptions that market participants are appropriately forward-looking and the farmland market is competitive and frictionless, which we treat as useful approximations. We expect welfare effects to be largest for agricultural producers, since they consume the vast majority of groundwater. However, welfare effects of groundwater regulation may also accrue elsewhere: to municipal and industrial users of groundwater, rural households who rely on wells for domestic water, those affected by land subsidence, and people and sectors affected by riparian and wetland ecosystems. Most of these aspects are beyond the scope of this paper, though a future version of this paper will study the effects on residential property values.

Benefits and costs. Pumping restrictions under SGMA will bring both costs and benefits to agricultural landowners. The cost is that they will face new constraints on their pumping quantities, beginning in the next few years and continuing indefinitely. The benefit is that groundwater levels will be higher in future years, as a result of reduced pumping by themselves and by nearby landowners. Higher levels reduce both the energy costs of

Figure 4: Three Treatment Variables



Note: Three treatment variables were constructed to capture the expected reduction in pumping at the GSA level: (1) estimated overdraft from the hydrologic model, C2VSim, (2) reported overdraft from GSPs, and (3) reported differences between current and future pumping from GSPs. The figure plots the distribution of these estimates (acre-feet per undeveloped acre per year) for each treatment variable.

pumping and the costs of drilling and deepening wells. There may also be benefits from the potential ability to sell pumping rights to other users such as municipal water agencies, but we believe these are negligible. SGMA does not prescribe a formal adjudication process, and few GSPs include plans to define and assign property rights strong enough to trade across sectors.

Spatial incidence. What allows us to separately identify the costs and benefits on property values is that the incidence of costs and benefits varies spatially. First, as a benchmark, consider a GSA with an aquifer that is perfectly connected within its boundaries but perfectly isolated from the outside world, such that any differences in groundwater levels immediately equalize throughout the GSA but do not affect (and are not affected by) neighboring aquifer levels. In this "bathtub" model, all land within the GSA shares equally in both the costs and the benefits of groundwater regulation.

Next, consider two neighboring GSAs with a permeable boundary, which describes all major agricultural regions of California. Pumping restrictions apply to all users within each GSA, so the costs are shared equally throughout a GSA, stopping immediately at the boundary. Groundwater levels, however, equalize across the boundary between the two GSAs. If one GSA has higher average groundwater levels than the other, groundwater levels will follow a smooth gradient such that the difference in groundwater levels between the GSAs is greatest furthest from the border and zero at the border itself.

This scientific understanding motivates our two empirical strategies. We identify the net benefits of groundwater regulation by making comparisons between GSAs that are not hydraulically connected to each other. If two such GSAs have different pumping restrictions but are otherwise identical, the difference in property values includes the value of both the costs and benefits of the restrictions.

Then, we identify the gross costs of groundwater regulation by making comparisons at the immediate boundary between neighboring GSAs. Two properties directly across a GSA boundary from each other are subject to different pumping restrictions, depending on which GSA they fall into. But because groundwater levels equalize across the boundary, they face identical benefits of groundwater regulation, no matter how different their pumping restrictions. Cross-border differences in property values therefore reveal the value of only the costs of groundwater regulation, not the benefits.

4.2 Estimating Net Benefits

To estimate the net benefits of groundwater regulation, we use a difference-in-differences approach, comparing outcomes across GSAs subject to greater or lesser future pumping restrictions, before and after the restrictions became known. To select time periods for the before-after comparison, we want to isolate periods that are completely unaffected by SGMA, and those during which the future pumping restrictions are clear. Since SGMA passed in mid-2014, we define the pre-period as ending in 2013. GSAs were initially formed in 2017, but it was not until 2018 that sustainability plans were drafted and public hearings held. Therefore, we exclude the period 2014-2018 and define the post-period as 2019 onward.

Because economic and growing conditions vary significantly across the state, we are reluctant to use a standard two-way fixed effects regression, which compares each GSA to all other GSAs in the state. Instead, we use a stacked event study approach following Cengiz et al. (2019), which allows for more transparent and theory-driven comparisons. Because the timing of our treatment variable is simultaneous across all units, we avoid many of the problems identified in the recent literature on difference in differences (Baker et al., 2021).

For each GSA, we construct a comparison group of other GSAs (with different future pumping restrictions) to serve as a counterfactual. In selecting comparison groups, we need to balance two considerations. On one hand, GSAs geographically closer to each other seem more likely to be similar in unobservable ways. On the other hand, comparisons between GSAs very close to each other are likely to be contaminated by spillovers, since the policies adopted by one GSA are likely to affect the groundwater levels of its neighbors. Our solution is to include within the comparison group all GSAs whose centroids fall within 50 km of the index GSA's boundary, except for immediate neighbors. To further avoid picking up spillovers across GSA boundaries, we also restrict the sample to focus on observations in the interior of each GSA, excluding observations within each GSA that fall within 4 km of the exterior boundary.

Conceptually, we compute the before-after difference in mean outcomes in each comparison group, subtract it from the before-after difference in the index GSA, and divide that by the relative difference in the treatment variable (pumping restrictions) between the index GSA and its comparison group. This yields a treatment effect for each index GSA, which we pool across GSAs to obtain an average causal effect.

Mechanically, we estimate a stacked regression on the datasets corresponding to each of the index/comparison groups of GSAs, treating each group as a separate event. We

regress the natural log of property values (for parcel i within GSA j in year t for event c) on a measure of the expected future pumping restrictions T_{gc} interacted with an indicator for the post-period:

$$\log SalesPrice_{igtc} = \alpha_{gc} + \lambda_{tc} + \beta T_{gc} Post_t + \Pi_c X_{igtc} + \varepsilon_{igtc} \tag{1}$$

Our parameter of interest β captures the average effect of greater pumping restrictions. It is the only parameter pooled across events; all other parameters are estimated separately within each event. The post-period indicator is $Post_t = 1(t \geq 2019)$, and the sample excludes the years 2014-2018. Fixed effects control for time-invariant parcel-level characteristics (α_i) as well as annual shocks shared by each GSA and its comparison group (λ_{tc}). We also control for a vector of parcel-level covariates X_{itgc}, including the natural log of both acres and the assessed value of improvements on the property, and indicator variables for the use type of the parcel.

The identification assumption is that in the absence of the sustainability mandate, differences in land value between the treated and counterfactual comparison groups would have remained constant over time.

We cluster standard errors by GSA to allow for both serial and spatial correlation and to correct for the double-counting of observations across events. We omit parcel-level fixed effects since we observe repeated sales for only a small fraction of our sample. A future version of this paper will check for robustness using parcel fixed effects in this repeat-sales sample.

4.3 Estimating Gross Costs

To estimate the gross costs of groundwater regulation, we use a stacked spatial regression discontinuity design. We identify 744 pairs of GSAs that neighbor each other, set up a regression discontinuity between each pair p, and stack the data into a single regression, pooling the coefficient of interest θ across all RD pairs. Our main specification for a single year is:

$$\log SalesPrice_{igp} = \theta T_{gp} + \alpha_p + f_p(DistanceBorder_{igp}) + \Pi X_{igp} + \varepsilon_{igp}. \tag{2}$$

The parameter θ captures the average effect of expected future pumping restrictions T_{gc}. The running variable $DistanceBorder_{igp}$ is the perpendicular distance to the nearest point along the border between the pairs of GSAs. Running variable terms and intercepts (α_p) are estimated separately for each GSA pair. We also control for a vector of

parcel-level covariates, X_{igc}, including the natural log of both acres, the assessed value of improvements on the property, and indicator variables for the use type of the parcel.

We also estimate versions of the specification above that pool data across multiple years. In those cases, all parameters are estimated separately by year t except for θ.

We use local linear regression for the running variable, estimating separate slopes on each side of each border, limiting the sample to a window of observations close to the border and using triangular kernel weights (following Cattaneo et al. (2019)). We show results using a range of bandwidths that balance the goals of comparing observations close to each other in space and preserving statistical power. Although optimal bandwidths can be calculated in a basic RD setting, we are not aware of an algorithm available for a stacked spatial RD design that accounts for spatial correlation, a multidimensional cutoff, and pooling across comparisons.

We again cluster standard errors by GSA, the unit of treatment, which allows for both serial and spatial correlation and corrects for the double-counting of observations across events.

A key identifying assumption for this approach is that all other pre-treatment factors change continuously at the GSA boundaries. The validity of this design also rests on the assumptions that the discontinuity be known, precise, and free of manipulation.

5 Results

We present preliminary results on the costs of groundwater regulation from the estimation of the stacked regression discontinuity design presented in the previous section. Results from the estimation of net benefits are in progress. The next version of this manuscript will present estimates from the stacked difference-in-differences framework.

We begin by showing graphical evidence of the regression discontinuity results. Graphs in Figure 5 plot average agricultural property values by distance to the boundary by pairs of groundwater sustainability agencies. Pairs are arranged such that the GSA with greater reported overdraft appears on the right-hand side in positive distances. Since farmland near the boundary is very similar other than the change in expected future pumping restrictions, we can interpret any discontinuous change in sales prices observed near the border as the effect of these future pumping restrictions. Pair fixed effects and covariates are partialed out from the variables before plotting, so the graphs show the average patterns across individual RD comparison. Plotted points are not raw data but rather binned means within quantile bins of distance to the border.

In the period before SGMA (top panel), we fail to visually detect changes in property

values at the borders of GSAs. The local linear trend lines suggest that, if anything, property values were higher in the districts that went on to report greater overdraft in their sustainability plans.

In the period after SGMA plans clarified (bottom panel), we begin to see some visual evidence that property values may have declined in response to greater reported overdraft after SGMA was introduced. Due to sampling noise, however, the graphical evidence is inconclusive, and so we turn to regressions.

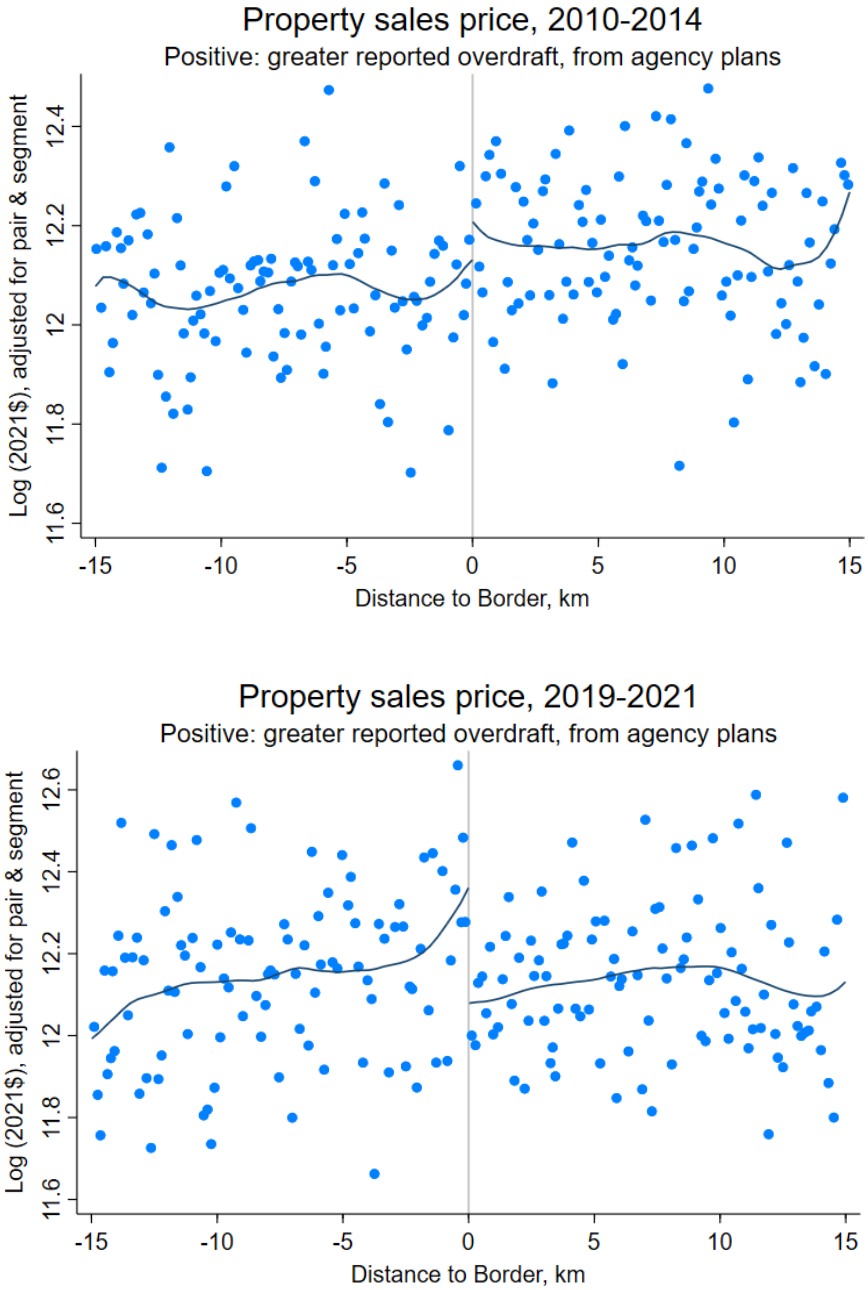
Table 2 reports corresponding estimates from RD regressions of the form presented in Equation 2. Effects are estimated separately for three RD bandwidths: 15km, 10km, and 5km. Larger bandwidths can improve precision and the influence of observations close to the border, but smaller bandwidths can reduce concerns about omitted variables. The literature does not offer clear guidance on the optimal choice of bandwidth in this setting due to three complicating factors relative to the basic RD setting: the existence of spatial autocorrelation, the fact that the distance cutoff is not one dimensional in space, and because discontinuities are stacked to estimate the average effect. We proceed by selecting a range of empirically reasonable bandwidths and evaluating the sensitivity of our results to these choices.

Columns (4) through (6) present results from the post-treatment period of 2019-2021 while varying bandwidths. Across specifications, coefficient estimates are similar and suggest that GSAs with more reported overdraft experienced lower property values. As the bandwidth shrinks and the number of observations declines, estimates become less precise, however magnitudes of estimates are not statistically different from each other. Our preferred estimate, reported in column (5) of Table 2, corresponds to a bandwidth of 10km. It suggests that each 1 acre-foot per acre of expected future pumping restrictions reduces land values at the border of a GSA in the post-treatment period by 0.8 log units – about 55%, or $4,300 for a typical acre.

In aggregate, the preliminary estimate from column (5) implies that the statewide costs of SGMA are large and totaling $1.1 billion. However, it is important to keep in mind that this RD design fails to capture any benefits of the policy. An understanding of the full welfare effects of SGMA to agricultural producers is incomplete without an estimate of the benefits.

One concern in this spatial RD setting is that GSA boundaries may reflect other regulatory or growing conditions that may influence agricultural land values. It is possible that GSA boundaries were not drawn exogenously but coincide with other boundaries like those of surface water districts. The concern here is that, as a result, these boundaries may reflect other discontinuities that influence property values such as differences in surface

Figure 5



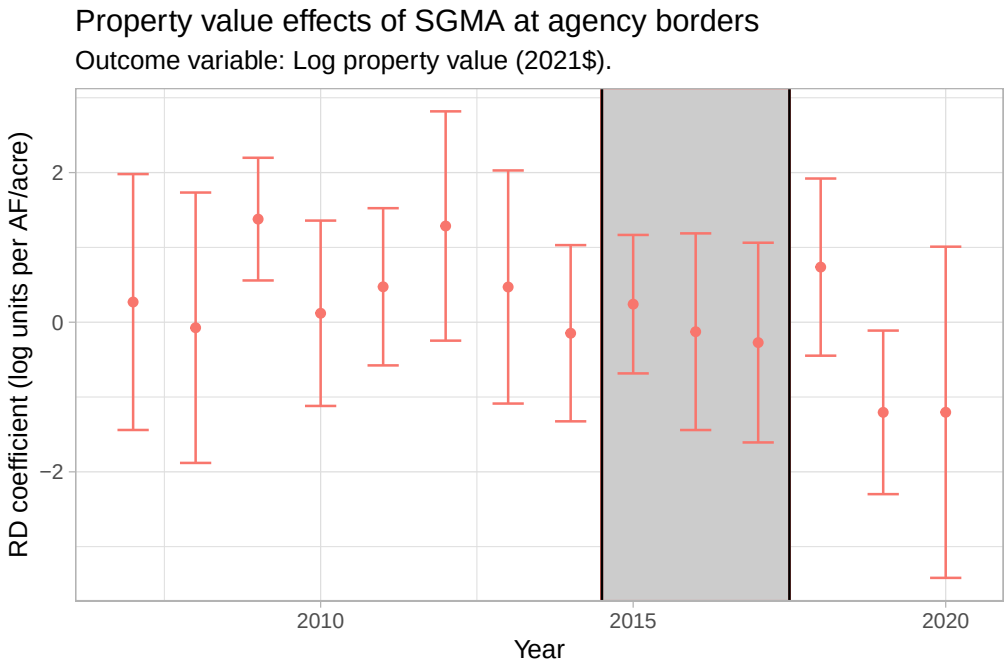
Note: Graphs show the mean sales price for agricultural properties subject to SGMA within each quantile bin of distance to the border between a pair of neighboring groundwater sustainability agencies (GSAs). Each pair of GSAs is ordered such that the GSA with greater reported overdraft (and greater expected future pumping restrictions) is on the right with positive distance values in kilometers. In the top panel, outcomes represent means over the pre-treatment period spanning 2010 to 2014. In the bottom panel, outcomes present means over the post-treatment period spanning 2019 to 2021. Nonparametric trend lines are plotted separately on each side of the border using local linear regression. District pairs are centered before plotting by partialing out covariates, subtracting the midpoint of each pair's means, and adding the sample grand mean.

Table 2: Impact of Expected Future Pumping Restrictions on Log of Agricultural Property Values, Before and After SGMA

	Pre-treatment, 2010-2014			Post-treatment, 2019-2021		
	(1)	(2)	(3)	(4)	(5)	(6)
Bandwidth	15 km	10 km	5 km	15 km	10 km	5 km
Reported Overdraft	0.472**	0.507*	-0.0752	-0.597**	-0.783*	-1.303
	(0.198)	(0.282)	(0.317)	(0.280)	(0.426)	(0.890)
Constant	12.07***	12.06***	12.16***	12.89***	12.92***	12.98***
	(0.0367)	(0.0517)	(0.0563)	(0.0501)	(0.0744)	(0.154)
Year × Pair	✓	✓	✓	✓	✓	✓
Year × Pair × Dist	✓	✓	✓	✓	✓	✓
Year × Pair × Dist × More	✓	✓	✓	✓	✓	✓
Year × Covariates	✓	✓	✓	✓	✓	✓
Observations	7,607	4,945	2,277	3,758	2,387	1,152
Clusters	30	29	28	31	30	28

Note: Table reports impact of reported overdraft on the log of sales prices before and after SGMA varying bandwidths. Slopes of the running variable are estimated separately for GSA neighbor pair in each year, on each side of the border. Covariates (also estimated separately in each year) consist of the log of acres, the log of the assessed value of improvements, and indicator variables for parcel use code. Standard errors are reported in parentheses. *, **, *** denote significance at the 10%, 5%, and 1% levels.

Figure 6



Note: Figure plots stacked spatial regression discontinuity coefficients over time from the estimation of Equation 2 in each year, using a 10-km bandwidth. The years 2015-2017 are shaded gray to highlight the implementation period after SGMA passed and before expectations about future groundwater pumping are likely to have formed.

water deliveries.

To shed light on this concern, we check for preexisting discontinuities at these boundaries in the pre-treatment period of 2010 to 2014 and report results of the RD from the same range of bandwidths. These estimates are presented in columns (1) - (3) of Table 2. We find a meaningful and statistically significant difference at larger bandwidths, but one that is indistinguishable from zero at the smallest bandwidth. If pre-treatment differences exist, they appear to be in the opposite direction of our post-treatment results, suggesting that areas with greater reported overdraft were experiencing higher land values at the border before SGMA. If these preexisting difference exist, they suggest that the estimates we report in the columns (4) - (6) may underestimate the true treatment effect.

If there are pre-existing differences at the borders of GSAs, the treatment effect of SGMA can still be causally identified under a "difference-in-discontinuities" design. For this design, we need the equivalent of a parallel trends assumption: that pre-existing differences would have remained stable over time absent SGMA.

While we cannot provide direct evidence of this assumption, we can use the long panel of pre-treatment data to examine whether there are time trends in the border differences over the 8 years prior to the passage of SGMA. Figure 6 plots our regression discontinuity coefficients in each time period. Prior to the announcement of SGMA, coefficients remain stable around zero. Border discontinuities are generally not significantly different from zero for either the pre-SGMA period (2007-2014) or the implementation period (2015-2018), before the GSA plans were announced. This result is reassuring for the idea that even if GSA boundaries coincide with other meaningful boundaries, those other factors are not driving the large, negative coefficients estimated for the post-period.

6 Conclusion

The Sustainable Groundwater Management Act of 2014 is a landmark legislation that is substantially altering the time path of groundwater consumption in California, the largest agricultural state in the United States. The comprehensiveness of the policy, affecting over 90% of the agricultural groundwater pumping in the state, is particularly remarkable given the fact that groundwater use is largely unregulated and undocumented. According to the U.S. Department of Agriculture, only 36% of groundwater wells in the U.S. have flow meters installed (U.S. Department of Agriculture, 2019).

In this paper, we seek to add to the debate about optimal groundwater management by contributing empirical estimates of the welfare effects of a comprehensive groundwater policy in the context of California agriculture. We are able to do so by utilizing land value data for all agricultural parcels subject to the legislation and estimating how farmland markets respond to changes in future pumping access. The decentralized nature of the mandate led to large variation in expected future pumping restrictions across the state, creating a policy experiment to study questions about sustainable use and the welfare effects of groundwater regulation. Determining if groundwater regulation in California is privately efficient has potential to inform policy design and implementation for groundwater sustainability elsewhere in the U.S. and groundwater-dependent regions worldwide.

Our preliminary estimates of gross costs, derived from border comparisons between groundwater agencies with greater or lesser pumping restrictions, suggest that the costs of the sustainability mandate are large. In fact, preliminary estimates suggest that in aggregate the statewide costs of SGMA may total $1.1 billion. Our next step is to empirically estimate net benefits, back out gross benefits, and compare how each welfare term changes over time. Estimates of net benefits are in progress, and full results will be available by the time of the conference. Our next immediate steps also include evaluating the impacts

of overdraft on land use which may reveal mechanisms regarding land value change and have implications for the resiliency of agriculture in the face of water scarcity.

References

Ayres, A. B., Meng, K. C., and Plantinga, A. J. (2021). Do environmental markets improve on open access? Evidence from California groundwater rights. Journal of Political Economy, 129(10):2817–2860.

Baker, A., Larcker, D. F., and Wang, C. C. (2021). How much should we trust staggered difference-in-differences estimates? Working Paper SSRN 3794018.

Brill, T. C. and Burness, H. S. (1994). Planning versus competitive rates of groundwater pumping. Water Resources Research, 30(6):1873–1880.

Brozović, N., Sunding, D. L., and Zilberman, D. (2010). On the spatial nature of the groundwater pumping externality. Resource and Energy Economics, 32(2):154–164.

Bruno, E. M. and Jessoe, K. (2021). Missing markets: Evidence on agricultural groundwater demand from volumetric pricing. Journal of Public Economics, 196:104374.

Bruno, E. M. and Sexton, R. J. (2020). The gains from agricultural groundwater trade and the potential for market power: Theory and application. American Journal of Agricultural Economics, 102(3):884–910.

Buck, S., Auffhammer, M., and Sunding, D. (2014). Land markets and the value of water: Hedonic analysis using repeat sales of farmland. American Journal of Agricultural Economics, 96(4):953–969.

Burlig, F., Preonas, L., and Woerman, M. (2019). Spatial Externalities in Groundwater Extraction: Evidence from California Agriculture.

California ASFMRA (2021). Trends in agricultural land & lease values.

Cattaneo, M. D., Idrobo, N., and Titiunik, R. (2019). A practical introduction to regression discontinuity designs: Foundations. Cambridge University Press.

Cengiz, D., Dube, A., Lindner, A., and Zipperer, B. (2019). The effect of minimum wages on low-wage jobs. The Quarterly Journal of Economics, 134(3):1405–1454.

Drysdale, K. M. and Hendricks, N. P. (2018). Adaptation to an irrigation water restriction imposed through local governance. Journal of Environmental Economics and Management, 91:150–165.

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

Faux, J. and Perry, G. M. (1999). Estimating irrigation water value using hedonic price analysis: A case study in Malheur County, Oregon. Land Economics, pages 440–452.

Gisser, M. and Sanchez, D. A. (1980). Competition versus optimal control in groundwater pumping. Water Resources Research, 16(4):638–642.

Hagerty, N. (2021). The Scope for Climate Adaptation: Evidence from Water Scarcity in Irrigated Agriculture.

Hornbeck, R. and Keskin, P. (2014). The historically evolving impact of the Ogallala Aquifer: Agricultural adaptation to groundwater and drought. American Economic Journal: Applied Economics, 6(1):190–219.

Ifft, J., Bigelow, D. P., and Savage, J. (2018). The impact of irrigation restrictions on cropland values in Nebraska. Journal of Agricultural and Resource Economics, 43(1835-2018-2978):195–214.

Merrill, N. H. and Guilfoos, T. (2017). Optimal groundwater extraction under uncertainty and a spatial stock externality. American Journal of Agricultural Economics, 100(1):220–238.

Pfeiffer, L. and Lin, C.-Y. C. (2012). Groundwater pumping and spatial externalities in agriculture. Journal of Environmental Economics and Management, 64(1):16–30.

Sampson, G. S., Hendricks, N. P., and Taylor, M. R. (2019). Land market valuation of groundwater. Resource and Energy Economics, 58:101120.

Smith, S. M., Andersson, K., Cody, K. C., Cox, M., and Ficklin, D. (2017). Responding to a groundwater crisis: The effects of self-imposed economic incentives. Journal of the Association of Environmental and Resource Economists, 4(4):985–1023.

U.S. Department of Agriculture (2019). 2018 Irrigation and water management survey.

Wada, Y., Van Beek, L. P., Van Kempen, C. M., Reckman, J. W., Vasak, S., and Bierkens, M. F. (2010). Global depletion of groundwater resources. Geophysical Research Letters, 37(20).