The Regulatory Costs and Political Economy of Managing California's Groundwater [*]

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Abstract

We use California's Sustainable Groundwater Management Act (SGMA), a statewide framework for local groundwater management, to study the drivers of collective action, policy instrument choice, and the cost of groundwater regulation. Understanding the political economic forces that explain how, where, and why management is occurring is critical to both the long-run sustainability of groundwater-dependent regions and to the cost of regulation borne by present-day pumpers. First, we document patterns in policy instrument choice across local agencies and attempt to explain them through the lens of political economy. Then, we estimate the gross cost of agricultural groundwater regulation through changes in land values across agency borders. We find that by reducing the costs of collective action, SGMA caused a significant departure from the prior status quo of open access, with a majority of basins now proposing incentive-based policies for groundwater management. 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%.

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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). When surface water flows are lower than expected, groundwater resources provide an important reserve capable of decoupling agricultural production from year-to-year variation in rainfall (Tsur and Graham-Tomasi, 1991). This aspect of groundwater's value will only become more important as climate change continues to exacerbate droughts and the variability of precipitation. Despite a broad range of available regulatory solutions – from the formalization of property rights to pumping restrictions and volumetric fees – regulation remains rare. Challenges arise due to the high transaction costs associated with collection action and the difficulty in determining the optimal extent of groundwater regulation.

As with any common-pool resource dilemma, groundwater overdraft continues despite its resulting economic losses due to the difficulty of replacing open-access management with institutions designed to preserve aquifers' value. Examples of groundwater management do exist, ranging from quantity controls in parts of Kansas (Drysdale and Hendricks, 2018) to price controls in parts of Colorado (Smith et al., 2017) and California (Bruno and Jessoe, 2021). Groundwater basins that have instituted rules that bear resemblance to first-best policies have enjoyed greater economic returns from their water as a result (Hornbeck and Keskin, 2014; Edwards, 2016; Ayres et al., 2021). Understanding the political economic forces that give rise to collective action and policy instrument choice is critical to the sustained economic viability of groundwater-dependent regions in the face of climate change.

The focus of this paper is the abrupt change brought about by recent groundwater legislation in California that simultaneously affected hundreds of groundwater agencies in the nation's largest agricultural state. California's Sustainable Groundwater Management Act (SGMA) of 2014, arguably the biggest change in groundwater regulation in the U.S., is a statewide mandate for local institutional transition. SGMA required the formation of local Groundwater Sustainability Agencies (GSAs), formed by coalitions of pre-existing water and land management agencies like water districts, cities, and counties, each of which was charged with developing management actions to meet sustainability criteria. By mandating sustainability by 2040, the law forces parties to negotiate and therefore reduces barriers to collective action that would have persisted in the absence of SGMA. Several economic questions arise: where, how, and why is groundwater management occurring, and what are the costs?

California's SGMA offers a rare setting for observing changing institutions and investigating issues of collective action. First, the legislation is far reaching, covering all major agricultural areas in the state, which collectively account for over 90% of the state's groundwater pumping.[1] Second, SGMA provides a statewide framework with local authority and flexibility, while requiring that groundwater agencies engage with the public and document their governance structures and intended management actions. In essence, SGMA (1) reduces the transaction costs to bargaining over collective action, (2) empowers local water authorities to manage groundwater however they see fit, while (3) requiring that their processes and actions be recorded and made publicly available.

The nature of the implementation of SGMA also provides a unique opportunity to estimate the costs of groundwater regulation. The decentralized nature of the policy 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 a 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. We evaluate the effect of our 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.

In this paper, we first provide a broad assessment of how SGMA is unfolding, including an evaluation of policy instrument choice. We find that SGMA caused a significant departure from prior approaches to groundwater management. Agencies are tackling the sustainability mandate with substantial heterogeneity across the state by proposing a mixture of price and quantity instruments as well as a suite of other conservation incentive programs. The most common proposed policy change is the introduction of taxes or fees, for which 60% of management plans stated a plan to implement or consider implementing such a change. Almost half of the submitted plans include allocations to determine individual pumping amounts, but only two-thirds of the agencies setting allocations are considering trade. The most overdrafted basins are more likely to have plans to facilitate trade than basins closer to sustainable conditions.

We then estimate the gross cost of the policy by using spatial discontinuities in regulation stringency at the borders of management agencies. Since groundwater moves

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[1] Since groundwater makes up 40% of the agricultural water supply on average, a legislation with this coverage could have a significant impact to the nation's largest agricultural state.

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). Our estimates suggest the costs of groundwater regulation are large. Using a 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.

This paper reassesses the literature on how sustainable groundwater management institutions develop in light of new empirical evidence offered by SGMA. The literature describing the political economy of this institutional transition is thick, but many open questions remain due to the inherent difficulty of collecting adequate data in these contexts. Articles most closely related to this work are those by Leonard and Libecap (2019) and Ayres et al. (2018), both of which study institutional transitions of common-pool water resources and attempt to explain the economic characteristics that lead to the institutional change. We present new evidence on where, how, and why groundwater management is occurring in California with a novel dataset on the management choices and governing structures of 343 groundwater agencies following the passing of a statewide legislation that substantially altered the bargaining environment over collective action.[2]

This paper also 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 by providing estimates of the gross costs of groundwater regulation.

Finally, this paper 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.,

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[2] Our results also support a related literature that seeks to answer questions related to optimal policy instruments. 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).

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 costs.

The rest of the paper proceeds as follows. Section 2 provides background on SGMA and explains how sustainability is defined and implemented under the law. Section 3 analyzes the political economy of groundwater management and policy instrument choice under SGMA. We suggest ways in which SGMA altered the costs of collective action; we document the broad trends of how the GSAs are planning to meet the sustainability requirements; and we identify patterns and characteristics that predict the chosen strategies. Section 4 contains the estimation of the gross costs of groundwater regulation. The final section concludes.

2 Background

Groundwater serves as a critical buffer during periods of surface water scarcity, with average use in California increasing from 40 to 80% of the water supply during drought years. 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.

2.1 California's Sustainable Groundwater Management Act

The passing of California's Sustainable Groundwater Management Act (SGMA) in 2014 provides an ideal opportunity to study the implementation and cost of a sustainability policy. Passing during the peak of the state's last major drought, 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 form, reach, and maintain long-term stable groundwater levels.[3] 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 the 94 high- and medium-priority basins were required to be adopted by January 31, 2022. GSAs managing groundwater in high- and medium-priority basins subject to crit-

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[3] Oftentimes, multiple GSAs joined together to collaboratively develop one GSP and were thus treated as the same unit in our analysis.

ical conditions of overdraft had to adopt a GSP two years earlier, by January 31, 2020.[4] The state provided both advisory and monetary resources for the development of plans. Failure to comply will result in top-down state regulation as a backstop. SGMA created substantial variation in regulatory stringency, since basins with more overdraft must adopt greater pumping restrictions in order to achieve sustainability. Figure 1 shows the state-designated priority level, including which subbasins were deemed in conditions of critical overdraft.

Recognizing the institutional and policy path dependence in which SGMA emerged is important for characterizing the local developments and management strategies we observe. While historic in its nature to mandate groundwater management statewide, SGMA naturally built upon decades of previous water policies designed to support and encourage groundwater management (Ayres et al., 2018; Dennis et al., 2020). Its emphasis on local control, giving the newly formed GSAs the authority to leverage fees and facilitate trade, reflects a history of groundwater measurement and management at the local level. Prior to SGMA, the state provided funds to local water agencies to monitor groundwater and conduct studies, entrenching this idea of local control (Dennis et al., 2020). Some water agencies and irrigation districts took advantage of these incentives and others did not, placing agencies at different starting points when SGMA was passed.

2.2 Sustainability as Defined by the Law

Understanding how sustainability is defined and implemented under the law is important for interpreting what it means for farmers' 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.

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.

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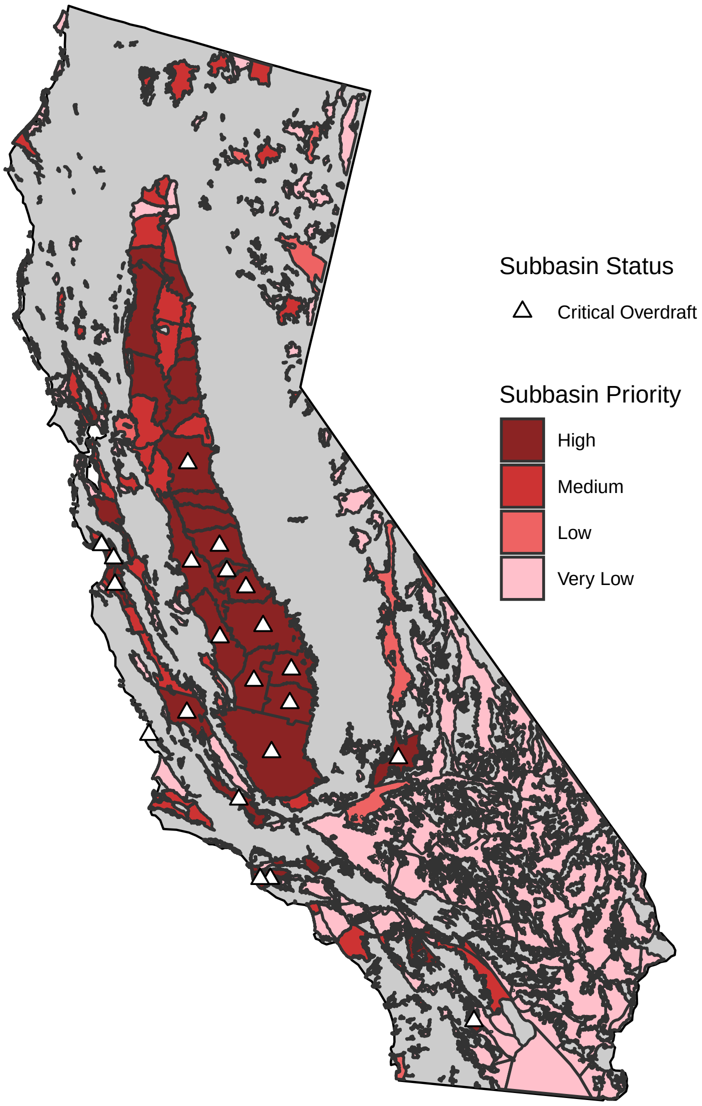
[4] Once they adopt, the plan goes into effect.

Figure 1: Priority and Overdraft Designation of California Groundwater Subbasins



Note: High- and medium-priority subbasins are subject to SGMA and must write GSPs. These are concentrated in the Central Valley. Critically overdrafted basins are subject to an earlier compliance timeline.

In defining what triggers an undesirable result, each GSP must establish minimum thresholds for each applicable sustainability indicator.[5] 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.[6] 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.

3 Political Economy and Instrument Choice

Our first goal is to characterize the conditions for which certain groundwater management strategies have emerged under SGMA and place these developments in the context of the literature. We provide a conceptual framework of SGMA through the lens of collective action and present data we collected from Groundwater Sustainability Plans to characterize trends in groundwater management, including where, how, and why groundwater management is occurring in the state.

3.1 Conceptual Framework

The basic problem facing groundwater management is a tragedy of the commons. With an unrestricted authority to pump from underlying aquifers, individual pumpers choose groundwater extraction based on their own private costs and benefits and ignore the external costs imposed on other basin pumpers through reduced aquifer storage. Choosing to extract additional water today imposes negative externalities on other users, reducing the amount available in the future, increasing pumping costs for neighboring pumpers, affecting groundwater quality, and inducing other spatial environmental effects. In the face of significant costs for bargaining over new management among users, economic theory predicts that individual pumpers will pump individually optimal but socially excessive amounts, leading to long-run drawdown of the aquifer.

Textbook treatments of the commons problem facing groundwater users elegantly describe how individually optimal extraction decisions can be socially suboptimal but over-

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[5] 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.

[6] 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.

simplify both the problems and remedies facing real-world basins. What prompts groundwater pumpers to attempt collective management, the factors influencing the success of those attempts, and what determines the choice of management instruments are all central questions in the political economy of groundwater management.

3.1.1 Gains from Management

To formalize this notion, consider a basin with many pumpers i, each of whom have a profit function $\pi_i(w_i(t), h(t))$ describing their profit from groundwater use as a function of the volume of water $w(t)$ pumped at time t and the height of the water table $h(t)$. The equation of motion for the height of the water table is $\dot{h}(t) = r(t) - \sum_i w_i(t)$, where $r(t)$ describes recharge.

A benevolent social planner would solve the problem:

$$\max_{\{w_i(t)\}} \int_0^\infty \sum_i \pi_i(w_i(t), h(t))\, dt$$

$$\text{s.t. } \dot{h}(t) = r(t) - \sum_i w_i(t),\ h(0) = H_0$$

which maximizes collective profits of pumpers on the basin subject to the constraint determining the rate of change in the height of the groundwater table. This is an extremely simple model, often referred to as the "bathtub" model of groundwater, that abstracts away from the concept of conductivity and other important spatial aspects of the hydrology of groundwater.

The seminal paper by Gisser and Sanchez using the "bathtub" model found the gains from optimal management to be negligible when extraction was small relative to the size of the aquifer, suggesting small stock externalities (Gisser and Sanchez, 1980; Brill and Burness, 1994). This approach assumes the absence of cones of depression around wells and the sizeable spatial pumping externalities that exist in many aquifers, which increase the gains from coordination and management (Brozović et al., 2010). It has been shown that high hydraulic conductivity and lower recharge are associated with higher relative land value increases when groundwater management is implemented (Edwards, 2016).

3.1.2 Costs of Collective Action

While the gains from management help to determine the likelihood of successful bargaining to end open access, a complete accounting includes the costs of bargaining as well. In principle, transitioning to a more efficient groundwater management policy should produce enough value to compensate any potential losers in the transition; this is the very definition of what it means to be efficiency improving. In practice, determining exactly how new property rights to groundwater ought to work and who should receive the gains and in what shares is a costly process that can spur deep disagreements among bargaining participants.

Both the size and distribution of bargaining costs among users influence the likelihood of institutional change. Once at the negotiating table, users are constrained in what actions they can implement both by their ability to reconcile their heterogeneous preferences and the enforcability of their agreements. [7]

First, resource users need to agree upon baseline information about the nature of the groundwater resource and the value of individuals' claims. With imperfect scientific understanding of the groundwater resource, substantial disagreement over the rate of recharge, interactions with surface water flows, or the extent of hydraulic conductivity can easily spill over to disagreement over the best course of management action (Wiggins and Libecap, 1985; Ostrom, 1990, p. 33-34). Imperfect and asymmetric information regarding the value of water to different participants can also inhibit defining appropriate compensating transfers to smooth over disagreements (Wiggins and Libecap, 1985; Sallee, 2019). Outright deception in an asymmetric information bargaining environment (for the purpose of securing a larger allocation, for example) further aggravates these problems (Libecap, 1989, p. 26).

The number of bargaining parties also naturally raises the difficulty of reaching agreement. With few participants, norms of interpersonal conduct (Ellickson, 1991) or Coasean bargaining (Coase, 1960) can reliably encourage effective resource management. With larger groups, the complexity of negotiations increases and the scope of potential compensating transfer opportunities shrinks. In the context of settling disputed American Indian water claims, Sanchez et al. (2020) show that the number of bargaining parties increases the duration of negotiations. In the context of oil field unitization, which is highly similar to groundwater management in terms of relevant bargaining characteristics, Libecap and Wiggins (1984) find that only relatively concentrated fields are capable of reaching unitization agreements; fields with multitudes of smaller operators fail to reach agreement and continue overproducing.

Heterogeneity among resource users has a more contested influence over bargaining for collective action. Early treatments tended to treat heterogeneity as an unambiguous

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[7] A complete accounting of the variables influencing the endogenous management process would be beyond the scope of this paper—Ostrom (2009) identifies 53 unique variables important to understanding socio-ecological systems like groundwater.

drag on the bargaining process (Libecap, 1989, p. 22-23). When some users gain substantially from the status quo, disputes between incumbents seeking to maintain their privileges and burgeoning users desiring more equitable resource allocations can derail negotiations. Heterogeneity in terms of identity can also inhibit agreement—where negotiators bring existing socio-cultural resentments to the bargaining table, distrust further narrows the scope of achievable agreements. Varughese and Ostrom (2001) synthesize this literature and find that heterogeneity need not be a barrier to collective action. According to Ruttan (2008) heterogeneity in benefits of management can even facilitate transition to efficient management when "economically advantaged individual(s) gain from providing the collective good, and are thus willing to pay a greater share of the costs [and/or] where the actions of one or a few individuals provide sufficient positive externalities to provide the good for all."

Finally, the broader legal and political environment can both impose limitations and enable further progress on potential collective action agreements. While organizing for collective action completely outside the auspices of government is possible, recognition and support from formal authorities enables a broader suite of monitoring and enforcement possibilities.

3.1.3 Determinants of Instrument Choice

For basins in which the gains from management exceed the costs of collective action, the question becomes how to manage. The choice of policy instrument will depend on several political and economic factors. Major evaluation criteria discussed in the literature include the relative cost-effectiveness of different policies, the distribution of benefits and costs among users, and the minimization of risk associated with missing the policy target in the face of uncertainty (Baumol and Oates, 1988). The optimal policy instrument for a given basin will depend on the subjective weight placed on each dimension and the political feasibility of implementing a given strategy.

The cost-effectiveness advantage of incentive-based policies depends on the heterogeneity among regulated firms (Goulder and Parry, 2008). In the context of groundwater, we may expect to see markets emerge in places where variation in demand for groundwater is greatest. Heterogeneity in groundwater demand may stem from differences across users in the marginal value product of groundwater and the marginal cost to extract. Marginal value product will vary with the crops grown in the region and the presence or absence of urban water consumers while the marginal costs to extract will vary with the depth to groundwater. We can proxy for local heterogeneity in groundwater demand by considering the variation in crops grown in a given region, the density of public supply wells, and the variance in groundwater levels.

3.1.4 Changes to the Bargaining Landscape

The passing of SGMA changed the bargaining landscape in several important ways that are relevant for the emergence of collective action. Prior to the passing of SGMA, active groundwater management was only occurring in a small number of adjudicated basins (Ayres et al., 2018), implying that in most cases the transaction costs of bargaining outweighed the gains from management, despite stark declines in groundwater reserves in many regions.[8] We see SGMA serving to enable less costly institutional transitions, pulling some basins into collective action and active groundwater management. We anticipate that GSAs will introduce meaningful groundwater management where the transaction costs associated with bargaining over collective action are now smaller than the gains from management.

SGMA has altered the bargaining environment in four key ways. First, SGMA serves to lessen information asymmetries and incomplete information by requiring hydrologic modeling and the development of a detailed water budget that must be consistent with other GSPs in the same subbasin. It also requires the establishment of a monitoring network of wells to track key sustainability indicators. Combined with its requirements to conduct public outreach and stakeholder engagement, this likely reduced information barriers to collective action.

Second, SGMA generates a new role for the state to act as a backstop if plans are insufficient, altering the policy default, and reducing the likelihood of management plans that lack teeth. By imposing a 2040 sustainability mandate, SGMA restricts the set of potential collective agreements, eliminating the possibility that parties come together and decide that business-as-usual is their mutual best interest.[9]

Third, SGMA broadens the jurisdiction and power of local agencies by giving them the new authority to monitor and meter wells, levy taxes, and facilitate groundwater trade. It empowers GSA board members to agree on management actions as representatives of the interests in the region, thereby limiting the number of bargaining parties directly involved, and bolstering their ability to conduct effective monitoring and enforcement. Even

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[8] Given that court adjudication is often a decades-long and highly litigious process, this may not be surprising.

[9] We note that DWR cannot perfectly observe or predict whether a given plan will actually achieve sustainability, meaning the state is only likely to reject plans that fail to target sustainability by a large and apparent margin. For this reason, we may expect subbasins where bargaining costs continue to outweigh the gains from management to propose only a minimal set of actions to appease state regulators.

some "very low priority" basins are forming GSAs and writing GSPs, even though they are not required to do so, implying that these shifts in the bargaining environment have been significant even in instances where there is no new binding sustainability mandate.

Finally, SGMA sinks many transaction costs by mandating the development of plans, which forces negotiation among GSA board members, and by providing direct financial support for plan development.

3.2 Data

The primary data we use for characterizing groundwater management under SGMA is GSA-level data on who controls governing board seats and GSP-level data on demand management and efficiency programs under consideration, including information on which GSAs are involved in them.[10] These data are supplemented by district-level data on suffrage, i.e., the law enabling the formation of the district and how voting works withing it, and subbasin-level data from the DWR on priority status, including whether or not each basin is critically overdrafted. These data were collected for all 343 groundwater agencies formed and all 107 groundwater plans that were submitted to the DWR. The 94 medium- and high-priority basins, on which 236 GSAs formed to collectively write and submit 102 GSPs, were the only areas mandated to do so under the law. An additional 5 very low priority basins voluntarily submitted plans which were included in our analysis.

Table 2 provides a descriptive overview of the variables collected, including the unit, number of observations, interpretation, and source. The data comprise a cross sectional snapshot of how SGMA is unfolding.

GSPs include lists of management actions that the GSA is considering to achieve sustainability. These vary a great deal in terms of specificity and certainty. Though the majority of management actions listed in GSPs are supply augmentation and conservation projects conducted by GSAs themselves, we focus exclusively on management actions that alter the pumping incentives of groundwater end users. We characterized these management strategies in each GSP by recording the intentions of GSAs to set allocations or pumping restrictions, allow trade, set taxes or fees, or provide incentives for conservation and efficiency improvements. The presence or absence of a given strategy was characterized as "Yes," "No," or "Maybe" to reflect the natural uncertainty at this early stage of SGMA development. If plans stated that a given strategy would be developed or implemented, regardless of the degree of detail described, we marked them as a "Yes." Plans

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[10] In cases where smaller GSAs joined to form a larger GSA (e.g. the Northern Delta GSA), we count only the smaller, individual GSAs.

Table 1: Variables Collected

Data	Interpretation	Primary Source
District Level		
Enabling Act	Law under which district formed	(California State Controller, 2013)
Suffrage	Basis of district votes: universal, landownership, acreage, or assessed value	(California Department of Water Resources, 1994)
GSA Level (343 obs, 236 signatory to a "High" or "Medium" Priority GSP)		
Board Seats	List of districts, cities, etc. with board representation	GSA Formation Documents, GSA websites
Single Agency	Is GSA a single agency? (As opposed to MOU, JPA)	From Board Seats
Landowner Majority	Are the majority of GSA board seats controlled by districts with landownership, acreage, or assessed value based suffrage? Y/N	From District Suffrage
GSP Level (106 obs, 102 "High" or "Medium" Priority)		
GSA Participants	List of GSAs included in GSP	GSP Submissions
Landowner Majority	Are the majority of GSAs signatory to the GSP made up of landowner majority boards?	From GSA Landowner Majority
Allocations	Does GSP include making an “allocation”? Y/M/N	GSP Submissions
Trading	Does GSP allow trading of allocations? Y/M/N	GSP Submissions
Taxes or Fees	Does GSP impose taxes or fees? Y/M/N	GSP Submissions
Tax Base	What is the tax based on? Acreage, extraction, not specified	GSP Submissions
Rate Structure	How is the tax structured? Tiered, flat, not specified	GSP Submissions
Pumping Restrictions	Does the GSP impose other restrictions on pumping? Y/M/N	GSP Submissions
Restriction Description	Open field describing pumping restrictions	GSP Submissions
Efficiency Incentives	Does GSP offer incentives for conservation/efficiency? Y/M/N	GSP Submissions
Incentive Description	Open field describing conservation/efficiency incentives	GSP Submissions
Subbasin Level (515 obs, 94 "High" or "Medium" Priority)		
Priority	DWR-assigned priority for SGMA compliance	DWR
Critical Overdraft	Is basin in critical overdraft?	DWR
Prioritization Data	All data used for prioritization by DWR	DWR

Notes: Gaps in district-level data were filled manually. GSA formation documents and GSP submissions are accessible at https://sgma.water.ca.gov/portal/

were given a “Maybe” designation with language such as “we may adopt” or “we may consider implementing” a certain strategy.[11]

Each category of management action that we record is an abstraction that captures many varied management responses. Here, we give further detail about the definitions of each management action variable recorded.

Allocations

Adjudication has long been an available but costly option for California groundwater basins seeking to establish formalized property rights to water. Without undergoing adjudication, California law prevents a clear, simple groundwater entitlement allocation, so these policies look a little different but function basically as allocations. For example, it is not uncommon to see a two-tier block rate structure where the first rate is basically free and the second rate is prohibitively expensive. In this way, the usage level of the tier jump basically constitutes an allocation. Other plans discuss allowing farmers to generate groundwater “credits” by pumping below some expected/allowable level which can be sold to other users. Not all GSPs that discuss allocations specify how the allocations will be made; among those that do, allocations based on either historic pumping or owned acreage are common.

Trading

This variable is only relevant for GSAs making (or at least considering making) allocations and includes any procedure whereby allocation owners can trade their allocations to other groundwater users in cash sales. Trading schemes often come with restrictions, including bans on exporting water outside the subbasin or volumetric limits. We do not include individual banking and borrowing (trading across time periods rather than across users) in this variable.

Taxes or Fees

New authority to levy taxes on groundwater extraction is a major new power bestowed on GSAs by SGMA. This variable includes new taxes that affect agricultural production decisions on some margin (i.e. not completely flat fees imposed on every property owner). For taxes and fees that specify their tax basis (groundwater extraction, irrigated acreage,

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[11] Levels of both specificity and certainty vary substantially between GSPs; where one plan may include a throwaway line about potentially considering a pumping charge, another may set out a multi-page plan for a specific groundwater allocation and market development scheme, perhaps even with results from a pilot.

or acreage), we record this as well. This variable does include the tiered extraction taxes that make up some of the allocation schemes as described earlier. Among the GSPs that specify a tax structure, all plans involve tiered (as opposed to flat) rates. Most plans leave the specific monetary level of the tax to future determination.

Pumping Restrictions

While all of the above can be considered "pumping restrictions" in some sense, we reserve this variable for outright bans on pumping in certain circumstances or geographies. These restrictions generally take the form of conditional restrictions that are triggered in event of a drought declaration, for example. Many GSPs receive a "Maybe" in this category for the inclusion of a vague sentence alluding to the potential need to consider outright pumping restrictions in the event that the remainder of the GSP management actions are insufficient for achieving sustainability. Other examples include geographic pumping bans to prevent specific undesirable outcomes like seawater intrusion or impacts on groundwater-dependent ecosystems.

Efficiency Incentives

Of all the variables, this captures the broadest diversity of policies. Examples include payments for fallowing, switching to less water-intensive crops, investments in more water-efficient irrigation infrastructure, and payments for residential rainwater harvesting, lawn removal, or appliance efficiency. Importantly, this variable does not include descriptions of existing water utility efficiency programs (they must be new), programs offering merely education or technological support without direct monetary incentives, or efficiency improvements made only to the infrastructure directly controlled by the agencies forming the GSA, e.g., canal lining.

3.3 Results: Trends in Groundwater Demand Management

We document the broad trends of how the GSAs are planning to meet the sustainability requirements of SGMA, with a focus on the demand-side strategies, and identify patterns and characteristics that predict the proposed strategies. A tabulation of the number of plans that suggest a given policy is reported in Table 2.

Our count of reported management strategies reveals both substantial variation in the approaches taken by local agencies and a substantial deviation from pre-SGMA management strategies. Notably, 17 plans report the establishment of individual groundwater

Table 2: Tabulation of Management Actions

	Number of GSPs	
Policy	Yes	Maybe
Allocations	17	33
Trading	5	26
Taxes/Fees	18	46
Pumping Restrictions	8	30
Efficiency Incentives	19	33

Notes: Detailed definitions of each variable are provided in the text of the paper. Data were collected manually from 107 Groundwater Sustainability Plans submitted to the Department of Water Resources, available on the online SGMA Portal.

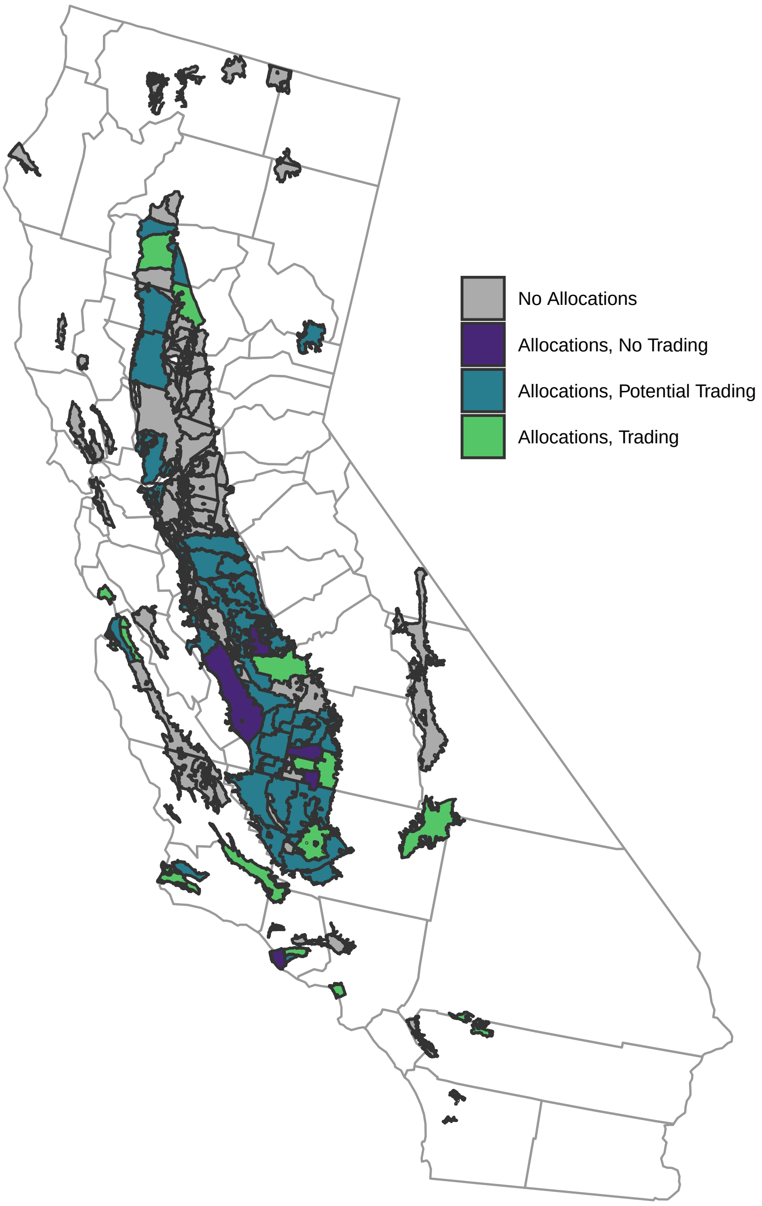
pumping allocations, with another 33 plans considering setting such allocations. Prior to SGMA, this type of quantification was only achieved through a costly adjudication process. A smaller subset of these plans are developing groundwater markets (5) or considering the development of markets (26) to facilitate trade of these newly defined allocations.

The establishment of taxes or fees on groundwater extraction or land use represents another departure from the previous status quo where groundwater pumpers faced only the energy costs to extract groundwater from below. Taxes and fees represent one of the most common demand-side management actions proposed by GSAs with 18 GSPs outlining definite plans and another 46 with possible plan to institute a tax, together representing 60% of the plans in our data.

Of the 107 GSPs submitted to DWR, 19 of them exclude mention of any demand-side strategy, and are likely relying exclusively on supply-side strategies to correct overdraft and achieve sustainability. These supply-side strategies include importing additional surface water supplies for in-lieu groundwater recharge, artificial groundwater recharge with excess winter flood flows, and recycled water programs. While these programs may help achieve the goal of slowing or stopping groundwater drawdown, they also impose costs on the district that must be recuperated. Rather than aligning the individual and social costs of pumping, these projects drive a larger wedge by socializing the costs of finding additional water sources when groundwater is over-extracted.

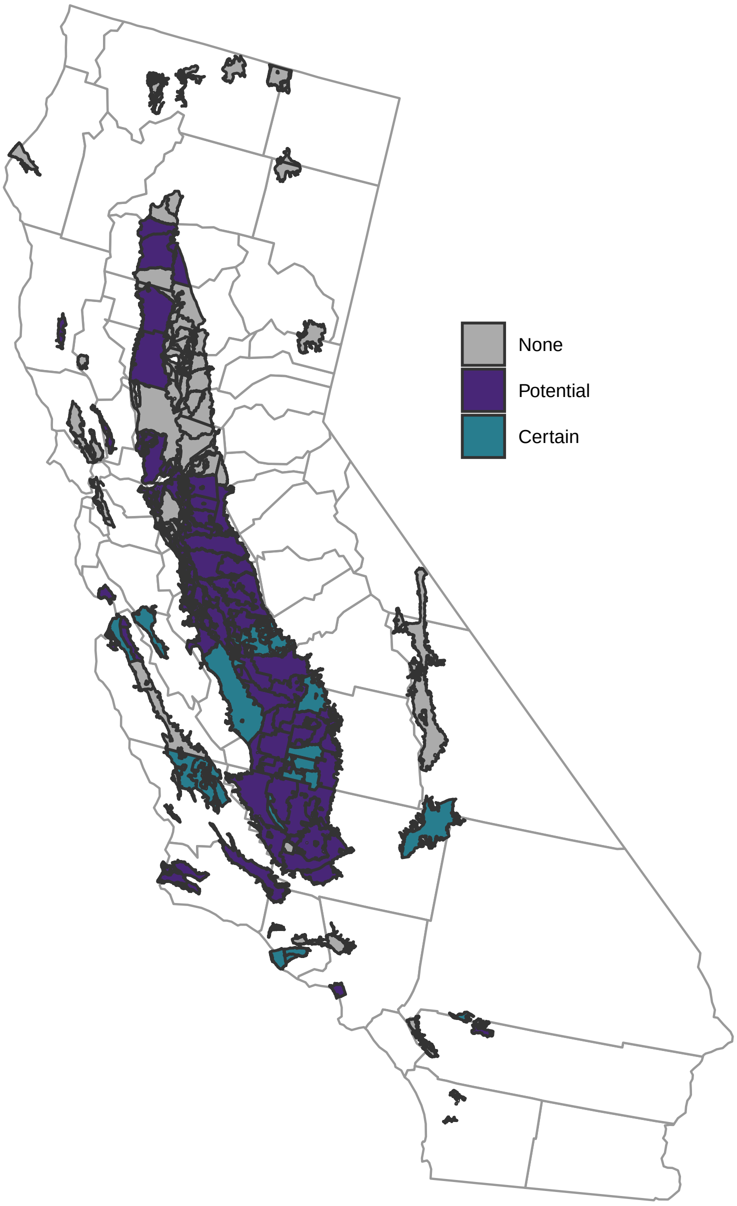
Figures 2 and 3 show the spatial distribution of (1) allocations and trading and (2) taxes and fees, respectively, with definite and potential proposals shown separately. A look at the spatial spread reveals a concentration of these policies in the Tulare Lake region of the southern Central Valley where the majority of critically overdrafted basins reside.

Figure 2: Allocation and Trading Programs



Note: Both certain and potential allocations are included in this map. Data were collected manually from Groundwater Sustainability Plans submitted to the Department of Water Resources, available on the online SGMA Portal.

Figure 3: Proposed Fees



Note: Map shows which Groundwater Sustainability Agencies submitted Groundwater Sustainability Plans include fees on extraction, irrigated acreage, or some other measure of water intensity. Data were collected manually from Groundwater Sustainability Plans submitted to the Department of Water Resources, available on the online SGMA Portal.

We next explore how collective action and policy instrument choice correlate with different features of the localities in which they emerge. Table 3 reports these associations, restricting the sample to only GSPs that report definite plans to proceed with a given management strategy. Not surprisingly, the presence of a demand management strategy (allocations, taxes, pumping restrictions, or conservation incentives) being implemented with confidence is positively correlated with a subbasin being designated as high priority or critically overdrafted. Medium-priority basins are less likely to propose demand management strategies of any kind. This is consistent with the expectation that collective action is more likely to occur where the gains from management are greatest.

Column (2), which considers plans that are developing markets to trade allocations, is restricted to the subset of plans that are proposing allocations. High-priority and critically overdrafted basins are more likely to facilitate trade, conditional on setting allocations, than medium- or low-priority basins.

The next two variables – the number of GSAs coordinating on one GSP and the number of board seats governing GSAs involved in the GSP – proxy for the number of bargaining actors. We anticipate that a larger number of players reduces the likelihood of collective action. Comparing across columns, plans with a larger number of coordinating GSAs are more likely to propose pumping restrictions and efficiency incentives than allocations, trading, or taxes.

The final set of attributes, which describe the representation on the board, proxy for whose interests are dominating. Many local water and land use agencies elected to partner with other organizations and form multi-agency GSAs. GSAs pursuing this route formed boards, with substantial leeway to design board size and representation. Some GSAs granted board seats to non-agency partners, like water companies, private well stakeholders, or environmental organizations. The majority of GSA board seats are held by special districts and local water agencies. Special districts, including reclamation, water, and irrigation districts, are local government entities created under state law to administer specific public services. An irrigation district, for instance, maintains irrigation canals and distributes surface water. We largely anticipate that special districts are aligned with the incentives and priorities of farmers and agribusiness in their jurisdictions.

Cities and counties are also common board seat holders in collaborative GSAs that are motivated to maintain groundwater supplies for community water systems. Counties have an extra role under SGMA implementation to fill in as the GSA representative for any basin areas left unmanaged by the formation of other GSAs.

Table 3: Correlation Coefficients Between Policy Choice and GSP Attributes ("Yes" Only)

	(1) Allocations	(2) Trading*	(3) Taxes or Fees	(4) Pumping Restrictions	(5) Efficiency Incentives
Critically Overdrafted	0.331	0.323	0.406	0.208	0.127
	(0.008)	(0.018)	(0.008)	(0.009)	(0.009)
High Priority	0.311	0.213	0.325	0.238	0.19
	(0.009)	(0.019)	(0.009)	(0.009)	(0.009)
Medium Priority	-0.276	-0.203	-0.289	-0.215	-0.149
	(0.009)	(0.02)	(0.009)	(0.009)	(0.009)
Number of GSAs	-0.071	-0.033	-0.107	0.035	0.119
	(0.009)	(0.02)	(0.009)	(0.01)	(0.009)
Number of Seats in GSAs	0.036	-0.219	-0.172	-0.067	0.241
	(0.01)	(0.019)	(0.009)	(0.009)	(0.009)
Share of Seats - Special Districts	0.01	0.173	0.121	-0.013	-0.141
	(0.01)	(0.02)	(0.009)	(0.01)	(0.009)
Share of Seats - Cities/Counties	-0.106	-0.064	-0.089	0.107	0.015
	(0.009)	(0.02)	(0.009)	(0.009)	(0.01)

Notes: The table presents correlations between management actions and GSP attributes. We focus here on management plans that are considered definite and exclude management plans that are simply under consideration ("Yes" only). Standard errors are reported in parentheses. For counting seats, single-agency GSAs are considered to have a single seat controlled by the forming agency. *When considering how trading correlates with GSP attributes, we restrict the sample set to only plans that are setting allocations.

Table 4: Correlation Coefficients Between Policy Choice and GSP Attributes (“Yes” and “Maybe”)

	(1) Allocations	(2) Trading*	(3) Taxes or Fees	(4) Pumping Restrictions	(5) Efficiency Incentives
Critically Overdrafted	0.229	0.257	0.581	0.17	0.092
	(0.009)	(0.019)	(0.006)	(0.009)	(0.009)
High Priority	0.227	0.099	0.438	0.175	-0.053
	(0.009)	(0.02)	(0.008)	(0.009)	(0.009)
Medium Priority	-0.178	-0.136	-0.369	-0.184	0.115
	(0.009)	(0.02)	(0.008)	(0.009)	(0.009)
Number of GSAs	-0.095	0.321	-0.013	-0.07	0.084
	(0.009)	(0.018)	(0.01)	(0.009)	(0.009)
Number of Seats in GSAs	0.074	0.142	0.042	-0.048	0.063
	(0.009)	(0.02)	(0.01)	(0.01)	(0.009)
Share of Seats - Special Districts	0.107	0.373	0.205	-0.048	0.147
	(0.009)	(0.018)	(0.009)	(0.01)	(0.009)
Share of Seats - Cities/Counties	-0.137	-0.178	-0.169	0.046	-0.188
	(0.009)	(0.02)	(0.009)	(0.01)	(0.009)

Notes: The table presents correlations between management actions and GSP attributes. Here we consider management plans that are both definite and potential (“Yes” and “Maybe”). Standard errors are reported in parentheses. For counting seats, single-agency GSAs are considered to have a single seat controlled by the forming agency. *When considering how trading correlates with GSP attributes, we restrict the sample set to only plans that are setting allocations.

A look at the last two rows of Table 3 shows that GSPs where the governing boards feature a higher share of seats held by special districts are more likely to propose allocations and taxes and less likely to impose pumping restrictions and efficiency incentive programs. The opposite is true for GSPs with a greater fraction of seats held by cities and counties. These results are suggestive of the hypothesis that unobserved interests of governing parties plays a role in policy instrument choice.

Table 4 presents the same set of correlations but this time inclusive of potential plans to implement a given policy. Results are consistent between these two samples in terms of both direction and magnitude when considering prioritization of the basin and the share of seats held by different entities. Differences emerge when considering associations between management policies and the number of GSAs or number of board seats.

4 Costs of Groundwater Regulation

The cost of agricultural groundwater regulation is affected by policy instrument choice and the degree of regulatory stringency. In this section, we estimate the gross cost of the policy by exploiting spatial discontinuities in implementation across agency borders.

4.1 Conceptual Framework

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.

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 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 from benefits 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.

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 Data

The primary data for the analysis of the gross costs of SGMA consist of annual basin-level groundwater overdraft volume estimates and parcel-level sales transaction history of agricultural land in California subject to SGMA. Secondary data were collected from GSPs. GSAs exclusively covering cities were removed from our sample.

4.2.1 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 available to us.

Our first treatment measure comes from output from 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. 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 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. 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.[12] 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.

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[12] 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.

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.[13] 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.

Our treatment variables are all proxies for farmers' expectations of their future per-acre pumping restrictions. 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.

4.2.2 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 expectations 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

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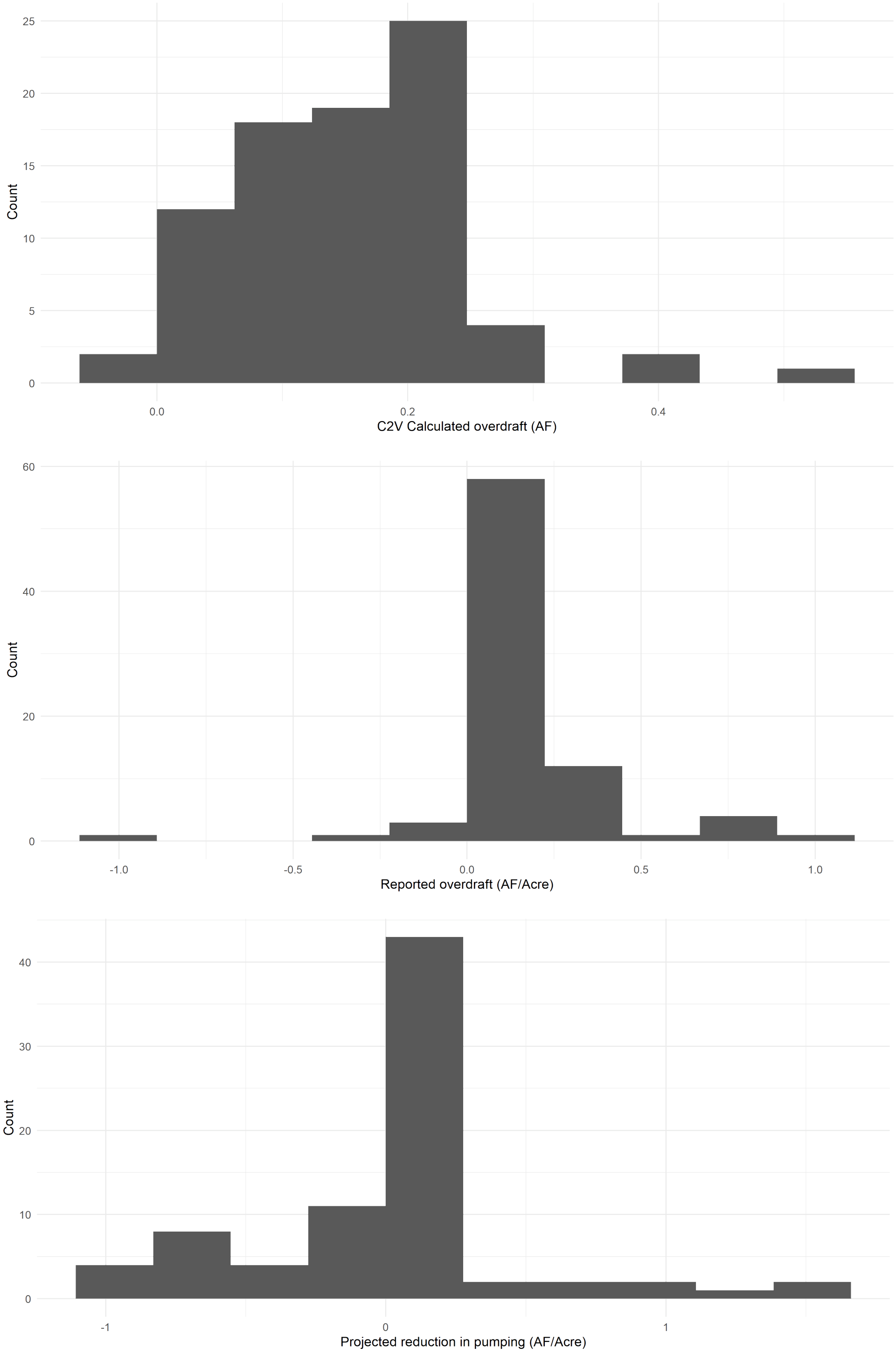
[13] Storage and overdraft are conceptually very similar, however one incorporates lateral flow. Overdraft tells us the difference between pumping (out) and recharge (in), net of lateral flows.

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.

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.

4.2.3 Land Values and Other Observables

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 5 shows the average price per acre, adjusted for inflation, from 1960 to 2021. Descriptive statistics on parcel-level property characteristics are reported in Table 5.

Table 5: Descriptive Statistics

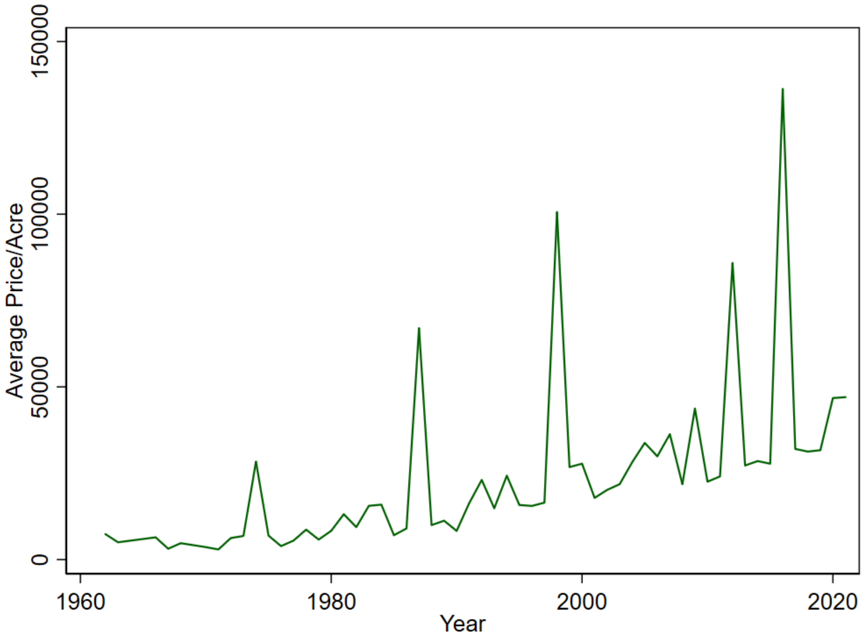
	Count	Mean	SD	Min	Max
Price	50,225	397,957.84	2,869,088.20	0	615,821,952
Price/Acre	50,132	35,802.63	1,098,728.45	0	171,520,672
Log(Price)	50,225	12.18	1.14	-1	20
Log(Price/Acre)	50,132	9.05	1.38	-6	19
Assessed Value	50,206	429,657.36	758,179.94	1	25,506,538
Improvement Value	50,225	309,669.64	785,647.64	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.

4.3 Empirical Approach

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

Figure 5: Real Prices/Acre, 1960-2021



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

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:

$$\log SalesPrice_{igp} = \theta T_{gp} + \alpha_p + f_p(DistanceBorder_{igp}) + \Pi X_{igp} + \varepsilon_{igp}. \qquad (1)$$

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 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.

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.

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.

4.4 Results: Gross Costs of Groundwater Regulation

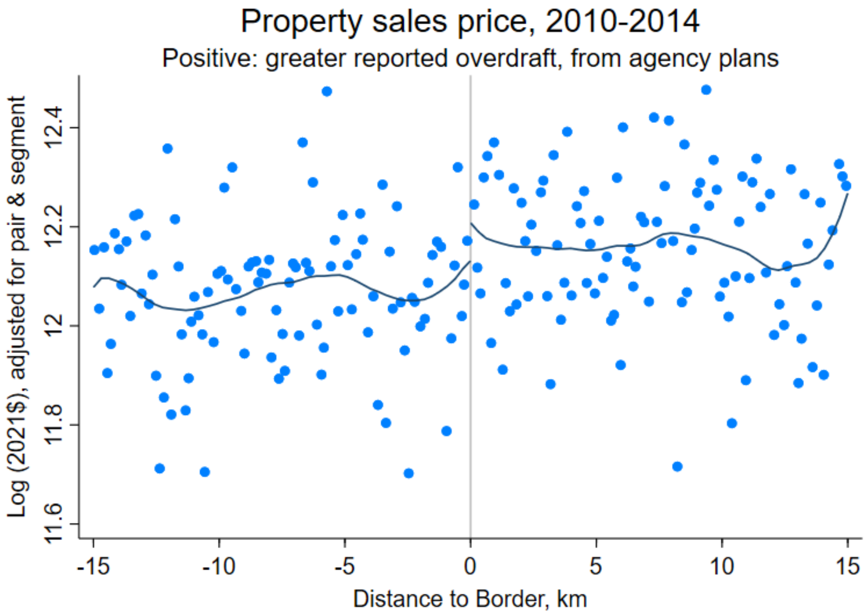
We begin by showing graphical evidence of the regression discontinuity results. Graphs in Figure 6 plot average agricultural property values by distance to the boundary by pairs of groundwater sustainability agencies. Pairs are arranged such that the GSA with greater reported overdraft appears on the 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 comparisons. Plotted points are not raw data but rather binned means within quantile bins of distance to the border.

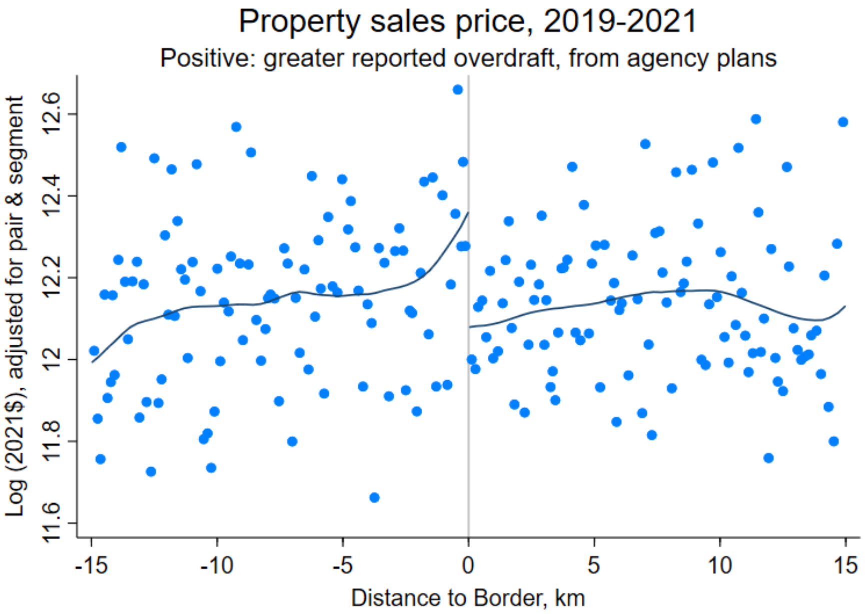
In the period before SGMA (top panel), we fail to visually detect changes in property values at the borders of GSAs. The local linear trend lines suggest that, if anything, property values were higher in the districts that went on to report greater overdraft in their sustainability plans.

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 6 reports corresponding estimates from RD regressions of the form presented in Equation 1. 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.

Figure 6





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.

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 6, 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 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 6. 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.

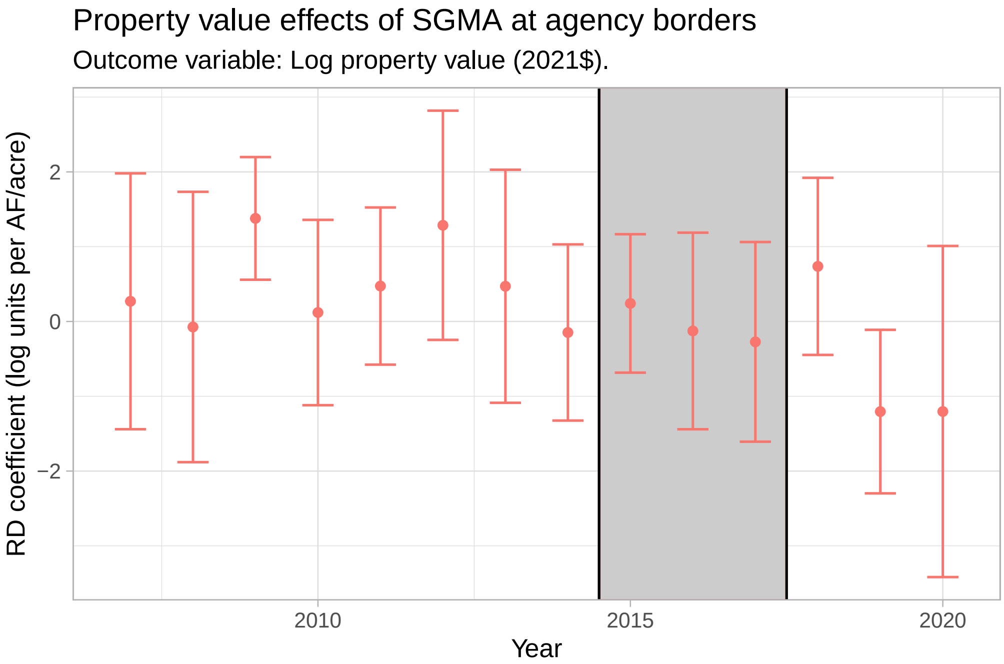
If there are pre-existing differences at the borders of GSAs, the treatment effect of

Table 6: 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 7



Note: Figure plots stacked spatial regression discontinuity coefficients over time from the estimation of Equation 1 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.

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 7 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.

5 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 was largely unregulated and undocumented prior to its passing.

In this paper, we sought to add to the debate about optimal groundwater management by contributing empirical estimates of the gross costs of a comprehensive groundwater policy in the context of California agriculture. We were 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. Our 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, estimates suggest that, in aggregate, the statewide costs of SGMA may total $1.1 billion.

Through a comprehensive assessment of policy instrument choice under SGMA, we also were able to shed light on the ways in which SGMA reduced barriers to collective action and brought about active groundwater management in the state, which carries implications for other groundwater-dependent regions. Open-access issues around groundwater will become even more critical to resolve as climate change causes higher temperatures, alters the frequency and severity of droughts, and shifts the precipitation regime. Our assessment of California's Sustainable Groundwater Management Act has shown that efforts by a centralized government to reduce transaction costs over bargaining can drive local management. In other groundwater-stressed regions of the world characterized by many competing actors and large transaction costs, policy changes that reduce information asymmetries and force negotiation may be fruitful avenues for collective action in the face of climate change.

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