Regulating the Commons: Three Essays on Water Management*

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Abstract

The first chapter examines how groundwater users in California's Oxnard Basin voluntarily reallocate water under a quota-based system, forming informal, market-style coordination. Using well-level data from 1985 to 2020, it shows that multi-well operators shift water use internally while staying within their total allocation. Coordination is shaped by prior affiliation, geographical proximity, and heterogeneity in irrigation efficiency. These findings highlight the importance of considering existing coordination patterns and transaction costs when designing more centralized cap-and-trade programs.

The second chapter estimates the economic value of informal coordination. Using a hedonic pricing model, it links farmland values to groundwater allocation and well operation, capturing the welfare gains from collective action.

The third chapter evaluates Utah's irrigation conservation program. Using a novel method to estimate field-level water use with OpenET evapotranspiration data, this chapter evaluates the program's effectiveness and further examines how water rights seniority and baseline use affect program outcomes.

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1 Introduction

Climate change, population growth, and changes in land use have led to increasing scarcity and variability of freshwater resources (Swain et al., 2018, Rafiei-Sardooi et al., 2022). Over the past two decades, freshwater resources per person have declined by roughly 20 percent globally, posing challenges to the agricultural sector, which accounts for 72 percent of freshwater consumption in the world (Li, n.d.). More than 56 million acres of land depend on irrigation in the United States, with over 60 percent of the irrigation water drawn from underground aquifers (Siebert et al., 2010). Water is an especially critical input for both agriculture and regional economies in arid and semi-arid regions like the western United States. These challenges highlight the need for effective water management.

Water represents a classic resource management problem, as water is a common-pool resource, because of its non-excludable and rivalrous nature. Specifically, when one user pumps groundwater or diverts surface water, it can reduce the quantity or quality available to others. In Hardin's (1968) classic concept of the "Tragedy of the Commons", he proposed two ways to avoid overexploitation or depletion of the common-pool resources: privatizing the commons by assigning well-established property rights or regulating the commons under a centralized government.

Similar to other common-pool resources, such as fisheries, pastureland, and pollution, researchers investigate regulatory solutions to water resources such as legal entitlement of water rights (Bois, 1994), command-and-control quotas (Ayres et al., 2018, Valle-García et al., 2024), pricing water to internalize the externalities (Bruno and Jessoe, 2021b, Bruno and Jessoe, 2021a, Bruno et al., 2024), and environmental markets (Grafton et al., 2011, Kuwayama and Brozović, 2013, E. C. Edwards et al., 2016, Arellano-Gonzalez et al., 2021, Ayres et al., 2021, Bruno and Sexton, 2020, Bruno and Jessoe, 2024).

Ostrom (2015) introduced self-organizing collective actions under social cohesion and trust as another solution to govern the commons. Although less common in developed countries where property rights are more clearly defined and secured, Ostrom's work on self-regulating governance has been applied to water resource management as an alternative to formal institutional governance (Shalsi et al., 2022, Edwards and Leonard, 2025).

My dissertation contributes to the literature on common-pool resource governance by examining both decentralized and centralized approaches to groundwater management using empirical evidence in the Oxnard Basin, CA, and the Great Salt Lake, Utah. While many economists and policymakers have focused on formal mechanisms such as market-based trading and command-and-control regulations, there is a growing interest in how formal coordination and collective action emerge in practice in response to regulatory constraints. Water, in particular, presents unique challenges for resource governance: the diversion or extraction is difficult to monitor, the hydrology is temporally and spatially complex, and its management is typically fragmented across basins or water jurisdictions (Bruno and Jessoe, 2024). These features complicate the implementation of formal institutions and create potential for efficiency gains from informal coordination.

In the first chapter, I investigate how and why groundwater users voluntarily reallocate water among themselves under an individually binding allocation system using evidence from the Oxnard Basin, located in southern California. The basin has implemented formal pumping allocation at the operator level, which could capture one or more wells. Because the allocation is enforced at the operator level, well owners appear to engage in informal coordination by consolidating and reallocating water as a multi-well operator. Leveraging well-level extraction records in the Oxnard Basin between 1985 and 2020, I show that multi-well operators adjust water use internally while adhering to operator-level allocation enforcement. Coordination is more likely to be seen between wells that are located closer to each other and wells previously affiliated, such as belonging to the same family farm or agricultural association. Moreover, I find that the efficiency gains of the informal coordination come from water reallocation from wells exhibiting higher irrigation efficiency to others, instead of between heterogeneous wells in crop type and value.

The second chapter, following the first chapter, further evaluates the potential welfare gains from such informal reallocation using a hedonic analysis of land values, examining whether land parcels attached to wells that are being self-coordinated command a price premium. Together, these two chapters investigate self-organized coordination under a formal regulatory system while connecting to Ostrom's discussion on collective actions.

The third chapter turns to a different setting to evaluate Utah's irrigation conservation program. In 2019, Utah launched the Agricultural Water Optimization Program to support agricultural water conservation through allocating grants to farmers for water savings. With over $276 million in legislative appropriations to date, the program seeks to reduce consumptive water use while maintaining viable agriculture, but its effectiveness is difficult to assess due to limited monitoring of actual water use. To address this, we develop a methodology using OpenET's satellite-based evapotranspiration (ET) estimates to approximate field-level water use, enabling evaluation of water savings despite the lack of metered data. Our estimates allow us to construct historical baselines, compare outcomes across crops and regions, and assess whether publicly funded projects lead to measurable conservation. We aim to further apply this methodology to investigate how differences in water right characteristics, such as seniority and baseline consumptive use, reflect different effectiveness and value of conservation efforts. This chapter offers insights into the design of conservation programs under limited information.

Chapter 1: Do Groundwater Users Coordinate Under the Command-and-Control Regime? Evidence from the Oxnard Basin, CA

The Fox Canyon Groundwater Management Agency (FCGMA) established the first formal groundwater markets under California's Sustainable Groundwater Management Act (SGMA) as a market-based instrument to enhance more efficient water allocation, and the first trading started in 2020 (Heard et al., 2021). While this market was designed to allow for the trading of groundwater allocations among agricultural users with low information search and bargaining costs, observed trading volumes remained low. There were only 54 acre-feet of water being traded, recorded by the FCGMA[1]. At the same time, in the FCGMA Board Meeting in 2023, the GSA Board Member pointed out that the large operators were creating "private markets" outside of the formal trading platform. For example, they noticed that big strawberry packer-shipper operators consolidated a large number of wells into a operator code and transferred water in their "independent" market.[2] These observations motivated the central question of this chapter: Do groundwater users informally coordinate under a command-and-control (quota) regime, and if so, what affects the likelihood of acting collectively?

In the Oxnard Basin, agricultural pumpers have faced individual groundwater pumping limits since 1985. Although the limits are allocated per well, the punitive charges for excessive withdrawals are enforced at the operator level, and an operator can have multiple wells. Therefore, wells under the same operator code can potentially reallocate water among themselves. Using a stylized theoretical model, I show that with an individual binding allocation, pumpers are incentivized to consolidate into the same operator and reassign water to enhance efficiency, and water moves from lower marginal revenue farms to higher marginal revenue farms. In addition, heterogeneity in irrigation efficiency also incentivizes water reallocation, but whether water flows to more efficient wells is undetermined. Moreover, drawing on the literature on transaction and contracting costs, I also note that collective action may be obstructed by informational frictions and bargaining costs.

I use semi-annual extraction data at each agricultural well between 1985 and 2020, which captures the period after the quota was introduced and before the formal cap-and-trade program. Using the semi-annual data, I aggregate into annual data and construct an unbalanced panel with 7001 observations in total. This better aligns the analysis with the allocation being assigned yearly. I also supplement the primary data with the remote-sensed evapotranspiration (ET) data from the MODIS satellite products, the precipitation data from the PRISM weather group, the crop use and land classification data from LandIQ, crop data

[1] The market activity summary is provided by the FCGMA to the author upon public request.

[2] https://water.ca.gov/-/media/CWC-Website/Files/Documents/2023/06_June/June2023

from Ventura County's Crop and Livestock Report, and Agricultural Land & Weather Use Estimation from California Department of Water Resources. I find empirical evidence that wells under a multi-well operator reallocate water while following the operator-level allocation. While there is little evidence suggesting reallocation happens between wells irrigating different crops. I find that higher irrigation efficiency increases a well's likelihood of allocating water to other wells under the same operator code. I also find that transaction costs can have potential effects in shaping the pattern of well consolidation: well grouping is more likely with closer geographical distance and prior affiliation. Finally, I have a brief qualitative analysis on the formal market introduced to the Oxnard Basin in 2020, and discusses how lowering transaction costs in formal market design can potentially broaden participation and bring more efficiency in addition to existing coordination patterns.

The rest of the paper is structured as follows. Section 2 - 7 provide a more detailed discussion on the first chapter: Section 2 reviews relevant literature and highlights my contribution to the field, Section 3 introduces the study area and institutional background, Section 4 presents a theoretical framework for the empirical tests, Section 5 overviews the data and empirical strategies, Section 6 shows some primary results, and Section 7 concludes. Finally, Section 8 briefly touches on the other two chapters.

2 Literature Review

In environmental and natural resource economics, the common-pool resource (CPR) is a widely researched topic. CPRs are particularly vulnerable to overexploitation because CPR users cannot prevent others from using the resource (non-excludable) and compete over the limited stock (rivalrous/subtractable). In his influential work, Hardin (1968) states that such resources inevitably face depletion unless managed through privatization or centralized regulatory control. For example, as suggested by Pigou (1933), taxing the resources allows each resource user to take the liability for the negative externalities posed on others. On the other hand, imposing extraction limits through command-and-control regulations can also prevent overuse by aligning individual incentives with the socially optimal extraction level. This is largely applied in some fields such as fisheries and rangeland management. For example, in some regions, explicit rules have been set on who can fish, where and when to fish, and how many fish to catch (Acheson, 2006; Costello et al., 2008).

In addition to tax and quota, economists have also turned to environmental markets, which set the aggregate quota on extraction, distribute the extraction rights to individual users, and allow users to trade their allocation under supervision (Montgomery, 1972). Nowadays, some form of environmental market has been successfully established in practice. For example, individual transferable quotas (ITQs) are used in fisheries (Newell et al., 2005; Costello et al., 2016; Holland, 2016), and cap-and-trade programs are employed as an instrument to regulate greenhouse gas emissions (Newell and Stavins, 2003; Fowlie et al., 2012).

While groundwater shares some institutional and economic parallels with other CPRs, such as fisheries and air pollution control, it also presents several unique challenges based on its context. As Bruno and Jessoe (2024) discuss, lack of monitoring and enforcement for non-compliance, non-uniform marginal damages from groundwater extraction, disconnected hydrology that limits coordinated management across regions, high costs on transaction and obtaining information, and temporal dynamics of aquifer conditions all create challenges for policy design.

With considerations on these unique attributes of groundwater, relevant literature has accordingly looked at the potential of management strategies. Researchers have estimated the demand elasticity for agricultural groundwater by studying energy price, volumetric pumping price, self-imposed tax, and water market. These estimates range from -1.12 to -0.10 in different settings (Scheierling et al., 2006; Gonzalez-Alvarez et al., 2006; Wheeler et al., 2008; Hendricks and Peterson, 2012; Smith et al., 2017; Burlig et al., 2021; Bruno and Jessoe, 2021a). The estimated elasticities are then used to assess the efficiency gains and cost-effectiveness of market-based instruments for groundwater regulation (Bruno and Jessoe, 2021b).

A large body of groundwater-relevant literature simulates the substantial gains from the introduction of market-based approaches to manage groundwater. For example, Kuwayama and Brozović (2013) use data on irrigation wells in Nebraska to find that adopting spatially differentiated groundwater extraction rules allows sizable savings in total social costs. Palazzo and Brozović (2014), also studying Nebraska, find that groundwater trading reduces the costs of agricultural water use restrictions, highlighting the importance of institutional contexts and initial permit design, and show that initially unused permits create incentives for trade. Guilfoos et al. (2016) test a multi-cell hydrological model on one aquifer located in northwest Kansas to find that simple, uniform pricing, quota, or environmental market policies on groundwater management perform poorly unless improved by more localized policies. Bruno and Sexton (2020) apply an agricultural groundwater trade model to southern California and estimate that the benefits of allowing trade are up to 36% greater than the command-and-control regime, even with potential market power existing.

Despite the rich studies on modeling and simulating the performance of policies, market-based approaches to regulate groundwater extraction are rarely seen in practice. There are a few exceptions. For example, Fishman et al. (2016) show field evidence from a designed program implemented in Gujarat, India, to suggest that shifting to meter-based billing did not substantially change groundwater use. Smith et al. (2017) utilize a difference-in-difference framework to estimate that the self-imposed groundwater extraction fee in San Luis Valley, Colorado, had reduced the groundwater use by 33%. Ayres et al. (2021) look at the groundwater market in Mojave, California, and used a spatial regression discontinuity model to estimate that the environmental market increased land value by half compared to the open access regime.

Centralized regulation on groundwater and other types of common-pool resources, however, may not be able to achieve its first-best outcomes for several reasons. Researches have been looking at how the existence of market power (Hahn, 1984), transaction costs (Stavins, 1995; Williamson, 2010; Ayres et al., 2018) and other forms of barrier, such as implementation and enforcement costs, (Cropper and Oates, 1992) may prevent market-based instruments from successfully performing.

A different strand of the literature takes a more institutionalist perspective on CPR governance. After studying many cases of CPR management, Ostrom (1990) suggests that the resource users could themselves form a self-organized authority and manage the resource more effectively in the absence of a centralized government if certain institutional and social conditions are met. Libecap (1990) examines CPR governance through the lens of property rights negotiations, and he frames this as also a collective action problem that can be addressed through formal contractual agreements. While in Ostrom's theory, collective actions root in social norms and cohesion, Libecap states that informal institutions rely on clearly-designed property rights and negotiations. However, both highlight that groups with larger size and more heterogeneous attributes tend to face more challenges in collectively acting, and informational barriers can limit its scope(E. Edwards and Leonard, 2025).

Despite the richness of work grounded in empirical cases in regions with relatively weak central governance (Libecap, 1989; Agrawal and Goyal, 2001; Adhikari and Lovett, 2006; Ruttan, 2008), studies of collective action in CPRs remain relatively rare in the settings of developed countries where formal regulatory institutions and property rights are better established. In such contexts, governance tends to rely heavily on top-down mechanisms, with less attention paid to the informal arrangements and coordination that may occur among users within those systems. There are, however, a few exceptions. Lopez-Gunn (2003), Lopez-Gunn and Cortina (2006) study the example of the Groundwater User Associations in La Mancha aquifers, Spain, to explore the characteristics that guarantee the success of self-regulation and the complementary relationship between self-regulating water management and higher-level authorities. Shalsi et al. (2022) use the Angas Bremer irrigation district located in South Australia to show that the local collective action can lead to successful groundwater management even under the formal institutions.

Related insights on how collective action works under the management of a higher-level, more centralized institution can also be found in other fields of natural resources. In the case of fisheries, researchers have studied on community-based fishery management (Copes and Charles, 2004; Wiber et al., 2004), and the development of collective right-based management - "sectors"[3] - in New England. Sector management shows how collective action among fishermen under a catch share system can change their effort in fishing and shift the production frontiers (Huang et al., 2018). Similarly, under the Quota Management System (QMS) in New Zealand, transferrable catch allowances are allocated to New Zealand-owned fishing companies. The voluntary consolidation of quotas among firms resembles forms of collective action and bargaining (Yandle and Dewees, 2008). In the field of pollution management, Yoder (2019) also found that a shared pollution cap incentivized farmers in the Florida Everglades to cooperate and improve the water quality.

The first chapter of my dissertation contributes to the existing literature on common-pool resource governance by providing empirical evidence on whether and how resource users engage in collective action within the framework of a centralized, command-and-control system, focusing on the context of groundwater management in a developed country. While prior studies have extensively modeled and simulated the potential efficiency gains from market-based instruments in groundwater governance, empirical investigations remain scarce. Moreover, the observational facts from the existing market-based approach, as described in the previous introduction, highlight the need to study informal coordination under formal, centralized institutions. By situating the analysis in the Oxnard Basin, California, where the groundwater management agency imposes extraction limits, this chapter provides an empirical lens on how groundwater users respond to top-down regulatory frameworks while engaging in voluntary coordination, reflecting informal collective actions within the constraints of formal regulation. This chapter bridges the gap between the literature on CPR management,

[3]https://www.fisheries.noaa.gov/new-england-mid-atlantic/commercial-fishing/sector-management-northeast-multispecies-fishery

which often assumes full decentralization or centralized control, and the hybrid nature of CPR governance structures in the real world. Moreover, this chapter complements existing empirical research in fisheries and pollution control, showing that the collective action under formal property rights is also seen in groundwater management and offering new insights into how decentralized behaviors interact with top-down governance and implications for formal market design.

3 Study Area and Institutional Background

3.1 Oxnard Basin

Located in southern Ventura County, the Oxnard Basin spans approximately 58,000 acres and has an onshore storage capacity of about 7,140,000 acre-feet[4]. Five primary aquifers comprise the basin's groundwater production system, with an average extraction of roughly 69,000 acre-feet per year between 2015 and 2017[5]. Figure A1 shows a map of the underlying aquifers beneath the Basin. While the basin relies on a mix of surface water, groundwater, and treated or recycled water, groundwater supplies about 67% of its total water demand. The Oxnard Basin is one of the most productive agricultural regions in Ventura County, with the agricultural sector being the largest groundwater user. Irrigation accounts for approximately 60% of total groundwater use. The region's top cash crops include strawberries, raspberries, nursery stock, and some more water-intensive crops, such as avocado and leafy vegetables[6].

The Oxnard Basin falls under the jurisdiction of the Fox Canyon Groundwater Management Agency (FCGMA), which was established on January 1, 1983, through the passage

[4]The offshore storage capacity is approximately 3,360,000 acre-feet for all aquifers in the Oxnard Basin, but intrusion of saline water has been observed in some areas, such as the Port Hueneme and Point Mugu.

[5]California's Groundwater Bulletin. https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Groundwater-Management/Bulletin-118/Files/2003-Basin-Descriptions/4_004_02_OxnardSubbasin.pdf

[6]Groundwater Sustainability Plan for the Oxnard Subbasin. https://cawaterlibrary.net/document/groundwater-sustainability-plan-for-the-oxnard-subbasin/

of Assembly Bill 2995. The legislation granted FCGMA governmental authority to adopt ordinances for managing groundwater within its jurisdiction. In response to a series of severe droughts, California enacted the Sustainable Groundwater Management Act (SGMA) in 2014, which authorized the formation of a Groundwater Sustainability Agency for the Oxnard Basin. Due to its coastal location and long-term overdraft history, the Oxnard Basin is particularly vulnerable to seawater intrusion. After being designated as a critically overdrafted basin under SGMA, it was prioritized for management under a Groundwater Sustainability Plan.

To contextualize the past groundwater management strategies in the Oxnard Basin, I draw on the framework proposed by Edwards and Guilfoos (2021), which categorizes groundwater governance into five tiers of increasing regulatory control, transaction costs, and potential gains. The Oxnard Basin has experienced elements of each tier over time, reflecting a gradual shift from minimal limitation to more formalized regulation. Table A1 summarizes the groundwater management history in the Oxnard Basin.

3.2 Allocation System and Well Consolidation

I now turn to key institutional features in the Oxnard Basin that underpin my study: the extraction allocation (pumping caps) system and well consolidation. Individual extraction allocation in the basin has evolved through a series of ordinances adopted by FCGMA, beginning with Ordinance No. 5 on August 24, 1990. This ordinance established the goal of reducing extractions within the FCGMA's jurisdiction to a "safe yield" level of 120,000 acre-feet per year by 2010. To achieve this objective, FCGMA set the schedule which mandated a 25% total reduction through incremental five-percent steps. Under this system, each well received an annual groundwater allocation. For wells with a historical extraction record from 1985 to 1989, the annual allocation was calculated as a percentage of their average annual extraction during that baseline period, starting at 95% and decreasing over time to 75%. Wells drilled after 1989 were assigned annual allocations based on crop type, irrigated acreage, and engineering estimates of water needed for efficient irrigation.

This regulatory framework was further tightened on April 11, 2014, with the passage of Emergency Ordinance E in response to drought conditions. The historical allocation at the individual well level was recalculated using average extraction from 2003 to 2012, and the efficiency of water use for newly constructed wells was made more stringent. The Emergency Ordinance E aimed to reduce allocations by an additional 20% by 2016.

Most recently, the FCGMA Board adopted a new ordinance on March 27, 2024, amending key articles of the existing allocation structure to comply with a court ruling and ensure alignment with SGMA objectives for long-term basin sustainability. While this change in allocation assignment falls outside the temporal scope of my study, it reflects the continued evolution of more stringent groundwater governance in the region.

While groundwater allocations are calculated at the well level, enforcement occurs at the operator level, and the operator refers to "a person who either owns or operates a groundwater extraction facility with the written approval of the owner" (FCGMA Ordinance No. 05). An operator can oversee multiple wells, each with its individual extraction allocation. Still, when it comes to compliance, the FCGMA evaluates aggregate extraction across all wells linked to the same operator code at the end of each year to determine whether the extraction is subject to punitive surcharges. In the Ordinance, it explicitly states that "[w]here an operator operates more than one extraction facility, the extraction allocations for the individual facilities may be combined". The operator change or combination needs to be formally approved by the FCGMA before reporting water extraction, so ex-post manipulation of operational status is not expected. Figure A2 shows the trend of well consolidation in the Oxnard Basin between 1983 and 2019. Overall, a growing number of wells have transitioned from individual operation to being consolidated by multi-well operators, an increasing share of operators managing multiple wells, and an expansion of operator scale. Figure A4 shows the geographical distribution of agricultural wells within the Oxnard Basin and visualizes the distance between wells under the same operator. While a lot of multi-well operators operate wells within close geographical distance, there are a notable number of operators operating wells that span the basin. Comparing Panel A4a and Panel A4b, we can also see the increasing trend of operator scale.

This institutional setup creates a degree of flexibility for operators to effectively reallocate water from one well to another within their portfolio, which resembles a cap-and-trade style coordination. Moreover, this flexibility creates an incentive for wells to consolidate under a common operator with more stringent allocation assignments, allowing them to pool resources and manage water more efficiently under tightening pumping caps.

3.3 Comparison with Formal Cap-and-Trade

The operator-level flexibility described above represents a form of informal cap-and-trade, operating within the existing regulatory structure (fixed allocation) but without the infrastructure of a formal market. Operators can consolidate wells under a single code, internally reallocate water, and manage their aggregate extraction without engaging in formal transactions. In contrast, a formal groundwater market was introduced in the Oxnard Basin in 2017 under the SGMA framework and began trading in early 2020. This cap-and-trade program established well-defined water trading rules and tracking mechanisms. It enabled groundwater allocation to be traded across operators within the Oxnard Basin, introducing market-based incentives to reallocate the resource more efficiently at a broader scale. Although the internal coordination before 2020 and the formal cap-and-trade program implemented in 2020-2021 share common underlying principles, such as reallocating water among users to increase overall efficiency, there are differences in the settings and characteristics, as summarized in Table A2.

4 Theoretical Framework

Here, I present a simple framework to show that under the regulatory setting of the allocation system discussed in Oxnard, there is an incentive for individual wells to consolidate under a single operator code.

Benchmark. Assume there are two wells attached to two farms: one has a higher marginal revenue (H) and one has a lower marginal revenue (L) with respect to its groundwater input. Let x_i denote the groundwater input and $\mathbf{y}_i$ denote all other inputs besides groundwater in the farm's agricultural production for farm i, where $i \in \{H, L\}$. Taking the output price as given, the revenue for farm i is dependent on the agricultural inputs, and let $R_i(x_i, \mathbf{y}_i)$ denote the revenue function for farm i. The revenue will be increasing and concave in the farm's groundwater input, i.e., $\frac{\partial R_i(x_i,\mathbf{y}_i)}{\partial x_i} > 0$ and $\frac{\partial^2 R_i(x_i,\mathbf{y}_i)}{\partial x_i^2} \leq 0$. Assume farm H has higher marginal revenues with regard to groundwater input than farm L at any positive groundwater input level, and the empirical explanation for farm H's higher marginal revenue could be that it is growing less water-intensive crops, growing high-value crops, or some combination of both. At the benchmark stage, I assume that there is no conversion rate between groundwater extracted and applied, meaning all water extracted from wells is used in irrigation with no loss. I also assume there is a uniform, per-unit pumping charge for groundwater, denoted c, that stays constant over time[7], and the per-unit cost of all other inputs, denoted as $\mathbf{w}$, is exogenous. Finally, I assume there are two periods, $t \in \{0, 1\}$. In period 0, there are no pumping limits set for wells, so farms can optimize their extraction with no constraints; in period 1, groundwater extraction is subject to individual pumping caps, and the allocation is given at a certain percentage of the well's extraction in period 0.

Period 0 can be viewed as a common-property regime[8], where farms solve the optimization problem,

$$\max_{x_i, \mathbf{y}_i} \pi_i = R_i(x_i, \mathbf{y}_i) - cx_i - \mathbf{w}\mathbf{y}_i,$$

[7] In the Appendix, I discuss the scenario that pumping costs increase over time.

[8] Or referred as "open access" regime in many groundwater-related literature.

and following the first-order condition $\frac{\partial R_i(x_i,\mathbf{y}_i)}{\partial x_i} = c$, each can solve their optimal groundwater extraction $x_i^0(c,\mathbf{w})$ where the marginal revenue and the marginal cost of groundwater equalize. In period 1, with the introduction of individual pumping caps, farms are instead solving a constrained optimization problem,

$$\max_{x_i,\mathbf{y}_i} \pi_i = R_i(x_i,\mathbf{y}_i) - cx_i - \mathbf{w}\mathbf{y}_i \quad \text{s.t. } x_i \leq x_i^A,$$

and under the framework setting, the allocation is binding. Therefore, if no coordination happens between the two farms, their extraction under the command-and-control regime would be equal to x_i^A. Solving for the first-order conditions, we can derive the shadow price of groundwater extraction allocation to be $\lambda_i = \frac{\partial R_i(x_i^A,\mathbf{y}_i)}{\partial x_i} - c > 0$. When shadow prices for both farms differ, there is an incentive for the farm with the higher λ to purchase allocation from the farm with the lower λ until $\lambda_L = \lambda_H$.

Figure 1 visualizes this framework where we can see at the allocation x_H^A, x_L^A, farm H has a higher shadow price for groundwater because $MR_H(x_H^A) - c > MR_L(x_L^A) - c$, and therefore, these two farms will have an incentive to consolidate under the same operator code so that farm L can reallocate some groundwater to farm H to achieve (1) $MR_H(x_H^1) = MR_L(x_L^1)$ and (2) $x_H^1 + x_L^1 = x_H^A + x_L^A$.

Difference in irrigation efficiency. When groundwater is applied to farms, a portion of it is typically lost due to inefficiencies in irrigation or loss during transfer. As a result, the amount of water consumed by crops is less than the total volume extracted from wells. To account for this, I incorporate irrigation efficiency, defined as the ratio of crop-consumptive water use to total groundwater extraction, into the farm's optimization problem:

$$\max_{x_i,\mathbf{y}_i} \pi_i = R(x_i,\mathbf{y}_i) - c\frac{x_i}{\alpha_i} - \mathbf{w}\mathbf{y}_i \quad \text{s.t. } x_i \leq \alpha_i x_i^A,$$

where $\alpha_i \leq 1$ captures the irrigation efficiency[9]. I also assume the farms are growing the

[9]In the long run, the irrigation efficiency would not be fixed, as farms could invest in new agricultural

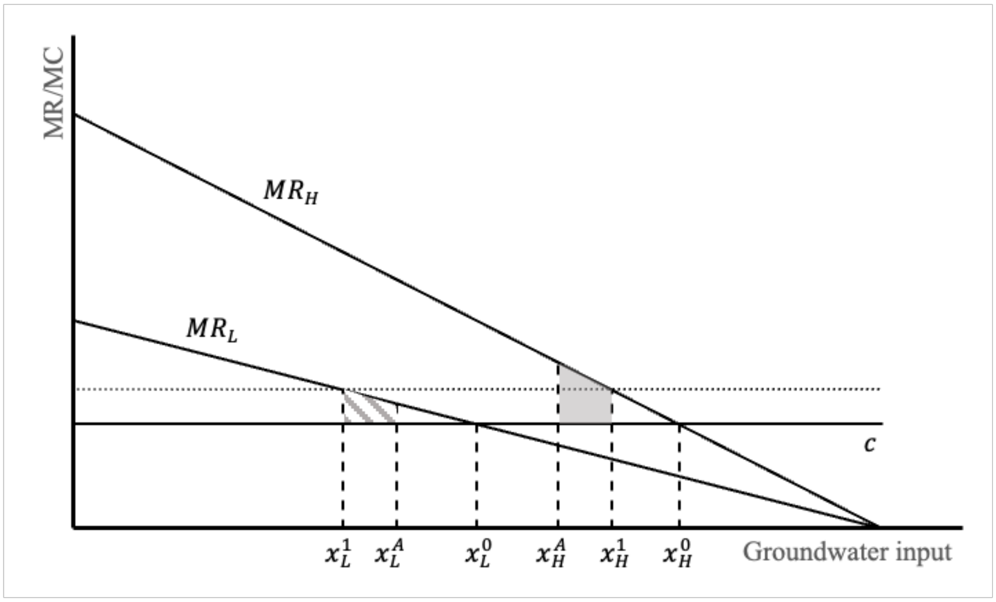


Figure 1: Incentive to reallocate under individual allocation. The optimal reallocation under the allocation would be that farm H extracts x_H^1 and farm L extracts x_L^1, and the gain from trade would be the fully shaded area minus the dashed area shown in the figure.

same crop with the same production function, so the revenue function $R(x_i, \mathbf{y}_i)$ is the same for both farms. Therefore, the only difference between the two farms is irrigation efficiency. Denote the farm with higher irrigation efficiency as farm H and the farm with lower irrigation efficiency as farm L, and $\alpha_L < \alpha_H \leq 1$. In period 0 where there is no binding allocation constraint, both farms would extract groundwater to satisfy $\frac{\partial R(x_i, \mathbf{y}_i)}{\partial x_i} = \frac{c}{\alpha_i}$, therefore, the optimal extraction for farm L is lower than farm H, i.e., $x_L^0 < x_H^0$, because they have the same decreasing marginal revenue function, and $\frac{c}{\alpha_H} < \frac{c}{\alpha_L}$. In period 1, where the individual pumping allocation is introduced, both farms should reduce their groundwater extraction by the same percentage, so farm L is receiving a lower allocation, i.e., $x_L^A < x_H^A$.

Solving for the first-order conditions of the constrained maximization problem, we can derive the shadow price of groundwater extraction allocation to be $\lambda_i = \frac{\partial R(\alpha_i x_i^A, \mathbf{y}_i)}{\partial x_i} - \frac{c}{\alpha_i} > 0$.

practices or innovative technologies to increase their irrigation efficiency, especially when they face a cap. However, in my model specification, I focus on a relatively short period (2 periods), so α remains fixed for both farms.

The difference between the shadow value of the two farms is

$$\begin{aligned}
\lambda_H - \lambda_L &= \frac{\partial R(\alpha_H x_H^A, \mathbf{y}_H)}{\partial x_H} - \frac{c}{\alpha_H} - \frac{\partial R(\alpha_L x_L^A, \mathbf{y}_L)}{\partial x_L} + \frac{c}{\alpha_L} \\
&= \left(\frac{\partial R(\alpha_H x_H^A, \mathbf{y}_H)}{\partial x_H} - \frac{\partial R(\alpha_L x_L^A, \mathbf{y}_L)}{\partial x_L} \right) + \left(\frac{c}{\alpha_L} - \frac{c}{\alpha_H} \right) \\
&= \left(\frac{\partial R(\alpha_H x_H^A, \mathbf{y}_H)}{\partial x_H} - \frac{\partial R(\alpha_L x_L^A, \mathbf{y}_L)}{\partial x_L} \right) + c \left(\frac{\alpha_H - \alpha_L}{\alpha_H \alpha_L} \right)
\end{aligned}$$

The first term captures the difference in marginal revenues in groundwater and is always negative because $\alpha_L x_L^A < \alpha_H x_H^A$ and the marginal revenue is decreasing in groundwater output. The second term captures the difference in marginal costs of groundwater and is positive. Therefore, the sign of $\lambda_H - \lambda_L$ is ambiguous, and we cannot have a clear prediction on the direction of how heterogeneity in irrigation efficiency drives groundwater reallocation.

Transaction costs. While the flexibility to consolidate wells under a single operator creates the potential for cap-and-trade style coordination, the actual extent of consolidation is constrained by transaction costs. In a world without transaction costs, one might expect that as long as wells have heterogeneous shadow values of groundwater, consolidation would naturally occur. Operators would group wells strategically to reallocate water under the aggregate allocation cap, and in the most extreme case, all wells within the Oxnard Basin could form a single operator code to create a basin-wide market.

However, in practice, several types of transaction costs can also limit the formation and scope of such informal coordination. First, information search costs can be nontrivial. Different well owners lack information about others' extraction behavior and cropping patterns, making it difficult for them to identify consolidation partners. Second, bargaining costs arise from the need to negotiate collaboration. Third, contract enforcement can deter consolidation. Maintaining private agreements may involve contracting, ongoing coordination, and the burden of filing legal documentation.

In *Contracting for Property Rights*, Libecap (1990) views heterogeneity within a group through the lens of transaction costs. The costs of reaching a common agreement are higher for groups whose members have more heterogeneity in potential costs and benefits when making collective decisions. Collective action can be obstructed by transaction costs, as even if there are aggregate benefit gains as a group, individual gains can differ across group members, so "some may resist collective action" (Ayres et al., 2018). Therefore, while the simple theoretical framework suggests that heterogeneity in costs and benefits can drive reallocation and generate efficiency gains through reallocation, in practice, such heterogeneity also raises transaction costs, limiting the extent to which these gains are realized. Transaction costs in informal coordination influence who chooses to consolidate and with whom, shaping the patterns of group formation.

5 Data and Empirical Strategy

5.1 Data

The primary dataset used in this study comprises well-level groundwater extraction records maintained by the Fox Canyon Groundwater Management Agency (FCGMA). These data span from 1983 to 2024 and include semi-annual extraction volumes in acre-feet self-reported by well operators. Every groundwater extraction facility, as requested by the FCGMA, installs at least one water meter to keep a record of groundwater extraction through the well, and this is regularly supervised by the FCGMA. Each record in the dataset is associated with a unique State Well Number (SWN) which identifies the well, a Combined Code (CombCode) which identifies the operator, the semi-annual extraction, and other associated attributes such as well status, use purpose (in my study, I select only groundwater extraction for agricultural purposes) and operator's name. The georeferenced location of each well is identified by the centroid of the corresponding quarter-quarter section, as designated by the Public Land Survey System (PLSS), based on the coding rules of SWN[10].

I also supplement the primary dataset with the evapotranspiration (ET) data from the

[10]The Well-Numbering System. https://ca.water.usgs.gov/mojave/pdfs/well-diagram_mojave2.pdf

MODIS satellite products, which provide remote-sensed estimates of actual crop evapotranspiration at a high spatial and temporal resolution[11], the precipitation data from the PRISM weather data[12], the crop use and land classification data from LandIQ to enable identification of crop heterogeneity, crop revenue from Ventura County's Crop and Livestock Report[13], and California Department of Water Resource Agricultural Land & Water Use Estimates[14].

5.2 Empirical Strategies

Following the theoretical framework presented in Section 4, I make these hypotheses that could be empirically tested on:

1. Internal reallocation. Wells under the same operator code are jointly subject to an aggregate allocation, creating incentives for internal reallocation of groundwater among them. Even without direct observations of private water trading quantities and prices, such reallocation can be inferred from well-level extraction patterns over time. While all wells are expected to follow the mandated allocation reductions at the operator level, wells under multi-well operators (i.e., groups) should exhibit greater variance in extraction patterns as a result of internal reallocation.

2. Source of efficiency gains. Groundwater reallocation has potential efficiency gains because it allows the water to move from wells that exhibit lower marginal profits to higher marginal profits, or between wells that have different irrigation efficiency in an undetermined direction.

3. Transaction costs and consolidation. When transaction costs are relatively low, wells are more likely to consolidate under the same operator and collectively act to reallocate water. The transaction costs cannot be directly observed but can be proxied using geographical

[11]The ET data is obtained using the tools from the operational Simplified Surface Energy Balance (SSEBop) Earth Resources Observation and Science Center (EROS) Science Processing Architecture (ESPA) Open Source project. https://www.usgs.gov/software/ssebop-espa-open-source

[12]PRISM Climate Group. https://prism.oregonstate.edu/recent/

[13]https://www.ventura.org/agricultural-commissioner/reports/

[14]https://water.ca.gov/Programs/Water-Use-And-Efficiency/Land-And-Water-Use/Agricultural-Land-And-Water-Use-Estimates

proximity and prior affiliation. A closer physical distance reduces coordination costs, and prior affiliation, such as historical joint operations or shared ownership, lowers informational and trust barriers. Both increase the likelihood of wells grouping under the same operator, thereby facilitating collective action and internal water reallocation.

5.2.1 Internal Reallocation

The first empirical test aims to examine whether reallocation of groundwater occurs within groups of wells managed under the same operator code. While water reallocation records are not observable at the well level, the regulatory structure allows wells grouped under the same CombCode to aggregate their total extraction and allocation. This setting allows a local cap-and-trade system within the same CombCode. The data is trimmed into the 1992-2019 period because 1992 was the year that the quota took place, and 2020 was the year that the formal cap-and-trade program was initiated.

To empirically test the hypothesis that wells under multi-well operators exhibit greater variation in extraction due to internal reallocation, I construct a cross-sectional dataset that includes all wells observed at any point during the study period. The primary outcome variable is the coefficient of variation (CV)[15] of each well's annual groundwater extraction, capturing the degree of variability in its extraction pattern over time. This metric serves as a proxy for the potential reallocation activity within operator groups.

I estimate this equation:

$$CV_i = \beta_0 + \beta_1 GroupYear_i + \mathbf{X}_i'\gamma + \epsilon_i, \tag{1}$$

The explanatory variable $GroupYear_i$ is the number of years that well i has been operating under the multi-well operator. Because this is an unbalanced panel with wells exiting before the end of the study period or wells constructed after the beginning of the study

[15]The coefficient of variation is calculated as $CV = \frac{\text{standard deviation}(s)}{\text{mean}(\mu)}$.

period, I normalize this metric by dividing the number of years a well is part of a multi-well group by the total number of years it appears in the data. Control variables include average field-level evapotranspiration (ET) and average precipitation over the well's observed years. These account for the variation in water demand and supply across wells, isolating the effects from hydrological dynamics on extraction patterns. With the hypothesis that wells under multi-well operators (i.e., groups) exhibit greater variance in extraction patterns as a result of internal reallocation, we should expect β_1 in equation (1) to be positive.

As an alternative to using the coefficient of variation, I examine the year-to-year change in extraction and the absolute value of the extraction change as outcome variables to capture different groundwater extraction patterns for wells under multi-well and individual-well operation. The key explanatory variable is a binary indicator, $Group_{it}$, equal to 1 if the well belongs to a multi-well operator and 0 if it is operated individually. I also include the count of wells within the same CombCode, $WellCount_{it}$, to capture the extent and flexibility of internal coordination, year-fixed effects to account for common shocks, and control variables $\mathbf{X}_{it}$, such as subsection-level evapotranspiration and precipitation. The estimation equations are specified as

$$\Delta Extraction_{it} = \alpha_0 + \alpha_1 Group_{it} + \alpha_2 WellCount_{it} + \mathbf{X}'_{it}\gamma + \delta_t + \epsilon_{it}, \tag{2}$$

$$|\Delta Extraction_{it}| = \beta_0 + \beta_1 Group_{it} + \beta_2 WellCount_{it} + \mathbf{X}'_{it}\gamma + \delta_t + \epsilon_{it}. \tag{3}$$

If grouped wells internally reallocate water while maintaining compliance with their shared allocation, then increases at some wells may be offset by decreases at others. This would result in no systematic difference in the average year-to-year change compared to ungrouped wells. Thus, if both grouped wells and ungrouped wells comply with the operator-level allocation in the same manner, we should not expect α_1 in equation (2) to be statistically different from zero. On the other hand, in equation (3), the outcome variable captures the size of the change regardless of direction. If grouped wells are reallocating water internally, we expect them to show higher variability in extraction than ungrouped wells that can only adjust their use individually, and this would imply $\beta_1 > 0$. Moreover, a statistically significant positive β_2 is expected because more wells within the operator imply more flexibility in reallocating water, thus more variability in extraction.

Together, these tests provide reduced-form evidence on the existence of informal water reallocation across wells under the same operator, despite the lack of formally recorded water trades.

5.2.2 Source of efficiency gains

To understand what drives efficiency gains in water reallocation within multi-well operators, I first classify wells as net sellers or buyers based on comparison between observed groundwater extraction and allocation. Allocation is constructed using historical extraction-based rules. Specifically, for each well i in year t, I classify it as a seller if its observed extraction is below its allocation, and as a buyer otherwise. This proxy classification reflects the assumption that under-utilization of allocation signals a well selling its excess water, while over-extraction signals buying to cover the gap. However, if the initial allocation is not binding or there is non-compliance, the seller/buyer status could be misclassified. Therefore, further robustness checks are needed. I focus on the subset of data in 2014, 2016, 2018, and 2019 because these are the only years for which LandIQ crop use data is available.

Crop choice reflects both the revenue potential and the sensitivity of farm output to water input. I use spatially resolved crop data from LandIQ and match each well i with the dominant crop c grown in its surrounding area in year $t \in \{2014, 2016, 2018, 2019\}$. For each crop, I compute its value-to-irrigation ratio (VIR). See Appenidx for details.

In addition to crop choice, I also investigate whether irrigation efficiency affects reallocation patterns. I use the evapotranspiration (ET) estimates, precipitation, and extraction data to construct the irrigation efficiency of the parcel where a well is located. See Appendix for the detailed construction of irrigation efficiency.

With the VIR and irrigation efficiency, I estimate a probability model where the outcome is the probability of being a seller under the multi-well operator:

$$\Pr(Seller_{igt} = 1) = f(VIR_{it}, IrrEfficiency_{it}, \mathbf{X}_{it}, \delta_t, \alpha_g), \tag{4}$$

where $Seller_{igt}$ is an indicator variable equal to one if well i under operator o in year t is a net seller using the classification rule described above. I include year fixed effects (δ_t) to control for annual groundwater conditions, and group (operator) fixed effects (α_g) because I am interested in comparing sellers and buyers within the same operator.

5.2.3 Transaction Costs and Consolidation

To examine the role of transaction costs in shaping wells' consolidation, I use two observable proxies. First, geographical proximity between wells serves as a natural measure of coordination costs - wells that are closer together are likely easier to manage jointly, gather information, and enforce private contracts. Second, organizational affiliation can be inferred by examining well owners' names. Wells that appear to belong to the same family farm, agricultural alliance, or entity may face lower information and bargaining costs when coordinating.[16] Geographical proximity and prior affiliation are used to proxy for the unobserved costs of forming and maintaining a grouped operator structure.

I first estimate a probability model, specified in equation (5), where the outcome variable is whether two wells (i, j) are observed under the same operator code in a given year t.

$$\Pr(Grouped_{ij,t} = 1) = f(\log(Distance_{ij}), Affiliated_{ij}, \mathbf{X}_{ij}, \delta_t) \tag{5}$$

$$\Pr(Grouped_{ij,t} = 1 | Grouped_{ij,t-1} = 0) = f(\log(Distance_{ij}), Affiliatedij, \mathbf{X}_{ij}, \delta_t) \tag{6}$$

$$\Pr(Grouped_{ij} = 1) = f(\log(Distance_{ij}), Affiliated_{ij}, \mathbf{X}_{ij}) \tag{7}$$

[16] An example of well affiliation observed in the data is several wells under the name of XXX Sod Farms were filing the extraction report individually under operator names XXX-1, XXX-2, etc., but consolidated to the same operator code XXX-COMBINED in 2014. In my data, I will then mark these well pairs to be "affiliated".

$Distance_{ij}$ is the Euclidean distance between well i and well j, $Affiliated_{ij}$ is a binary indicator equal to 1 if the two wells are plausibly owned by the same entity based on owner name clustering. $\mathbf{X}_{ij}$ includes other time-invariant pair-level characteristics, such as the difference in soil quality and the difference in crop type, and year-fixed effects absorb shocks that might bias the comparison, i.e., if a well pair can be grouped in some years but not others. A negative coefficient on $Distance_{ij}$ and/or a positive coefficient $Affiliated_{ij}$ would indicate that lower transaction costs are associated with a higher probability of consolidation.

Next, I apply a conditional probability model specified in equation (6), which estimates the conditional probability that a pair of wells (i, j) consolidates in year t, given that they were not grouped in the prior year. This specification focuses more on new groups' formation instead of group persistence over time.

Finally, as an alternative, I also implement a pooled cross-sectional model, collapsing the outcome to a single binary indicator for whether the two wells were ever observed to consolidate under the same CombCode during the observation window (equation 7). This specification is useful for identifying long-run associations between transaction costs and consolidation probability.

6 Results and Discussion

Internal reallocation. After collapsing the unbalanced panel data into cross-sectional, there are a total of 328 wells being observed during the observation period. Four wells appear only once in the dataset, so their standard deviations of extraction are unavailable. Table A3 shows the summary statistics of the cross-sectional data.

Table 1 presents the results from estimating equation (1), where the coefficient of variation (CV_i) is the outcome variable, and the main explanatory variable is $GroupYear_i$, the ratio of years the well operated as part of a group (under a shared operator code) to its total years of operation, which ranges from 0 to 1 and captures the intensity of a well's exposure to collective management. Column (4) in Table 1 adds the number of years a well is operating within the observation period as an additional covariate. In addition to CV, I also estimate the same model using the mean and standard deviation of extractions as alternative outcomes. This allows me to disentangle whether increased CV among grouped wells is driven primarily by higher volatility (standard deviation), lower average use (mean), or both.

The results show a positive and statistically significant coefficient on $GroupYear$ across all three outcome variables. In the main CV specification, the estimated coefficient on $GroupYear$ is 0.264, indicating that wells with more exposure to group-based operation tend to exhibit greater relative variation in extraction. Columns (1) and (2) show that wells with more exposure to group-based operation tend to have a higher volatility, but also a higher average extraction at the same time.

	$Mean$	$St.Dev.$	CV	
Variable	(1)	(2)	(3)	(4)
$GroupYear$	118.568 ***	79.235***	0.264*	0.288**
	(22.017)	(15.296)	(0.104)	(0.103)
$Precipitation$	0.846***	0.440***	-0.005***	0.004***
	(0.160)	(0.119)	(0.001)	(0.001)
ET	0.361***	0.138**	-0.001***	-0.001**
	(0.076)	(0.053)	(0.000)	(0.000)
$YearOperating$				-0.015**
				(0.005)
Observation	328	324	324	324
R^2	0.1918	0.1196	0.1387	0.1627
Adjusted R^2	0.1843	0.1114	0.1306	0.1523

$*** : p < 0.001; ** : p < 0.01; * : p < 0.05$

Table 1: Coefficient of variation

Table A8 reports the results from estimating equations (2) and (3), which test for evidence of groundwater reallocation within operator groups. The regressions are based on well-level panel data spanning from 1992 to 2019, the period between the introduction of extraction quotas and the formal implementation of the cap-and-trade program in the Oxnard Basin. A summary statistics of this panel, with grouped versus ungrouped observations, can be found in Table A4.

Column (1)-(3) of Table A8 represents results using the raw year-to-year change in groundwater extraction as the dependent variable. The coefficient on the multi-well group indicator is estimated to be -4.398 (4.915) acre-feet, and is statistically insignificant. This result suggests that, on average, wells operated under multi-well groups do not adjust their total extraction more or less than individually operated wells. Moreover, the coefficient on the number of wells under the same operator is not statistically significant. This finding is consistent with the idea that all operators, regardless of group size, are responding similarly to aggregate binding constraints under the shrinking allocation regime.

Column (4)-(6) of Table A8 uses the absolute value of extraction change as the dependent variable. The coefficient on the group indicator is estimated to be 18.490 (4.407) acre-feet, and is positive and statistically significant. This indicates that wells within multi-well operators exhibit greater variation in year-to-year extraction levels compared to single-well operators - some wells reduce extraction while others increase, in a manner that preserves the overall allocation at the operator level. In addition, the coefficient on well count is also significantly positive at 9.104 (0.863) acre-feet, implying that internal reallocation is more noticeable for operators with more wells, consistent with the hypothesis that increased group size facilitates greater flexibility in water use. As a robustness check, columns (7)-(9) re-estimate equation (2) using the logarithm of the absolute extraction change as the dependent variable. The results remain consistent, reinforcing the interpretation that reallocation behavior is more prevalent among multi-well operators with larger group sizes.

To emphasize the heterogeneous effect of operational grouping on groundwater extraction and reallocation pattern across different operator sizes, I adjust the specification to be

$$
\begin{aligned}
Y_{it} = \alpha_0 &+ \beta_1 \cdot Group_{it} + \beta_2 \cdot Group_{it} \times \mathbf{1}(WellCount_{it} = 2) \\
&+ \beta_3 \cdot Group_{it} \times \mathbf{1}(WellCount_{it} = 3) + \beta_4 \cdot Group_{it} \times \mathbf{1}(WellCount_{it} = 4) \\
&+ \mathbf{X}'_{it}\gamma + \delta_t + \epsilon_{it},
\end{aligned}
$$

where $Y_{it} \in \{\Delta Extraction_{it}, |\Delta Extraction_{it}|\}$, $\beta_1 + \beta_n$ captures the marginal effect of grouping for wells under operators having n wells, and β_1, as the baseline, describes the marginal effect of grouping for wells under operators having more than four wells. I show the summary statistics of observations with different well counts in Table A5.

In Figure A5, Panel A5a presents the estimated marginal effect of being in a group (multi-well operation) on extraction change across the operator size categories. The results suggest that the coefficients are statistically insignificant across all categories, indicating operators generally comply with extraction allocations in a uniform way, regardless of size. In contrast, Panel A5b shows the marginal effect of grouping on absolute extraction change increases with operator size, suggesting that larger operators - those managing more wells - experience greater flexibility in reallocating water within their portfolios of wells.

Overall, these results provide reduced-form evidence supporting the hypothesis that informal water reallocation occurs within operator groups. While total extraction does not differ systematically between wells under groups and individually operated wells, the pattern of individual well-level adjustments reveals greater redistribution flexibility among multi-well operators.

Source of efficiency gains. To explore the role of shadow price heterogeneity in water reallocation within multi-well operations, I estimate the probability that a well is classified as a seller in a given year using data from 2014, 2016, 2018, and 2019. The sample consists of 565 well-year observations. Table A3 shows the summary statistics of the data.

The dependent variable is an indicator of whether a well is a net seller of water. The key explanatory variables are the value-to-irrigation ratio (VIR), which proxies for crop water productivity, and irrigation efficiency. I estimate both a linear probability model and a logistic regression, controlling for year fixed effects and operator fixed effects. The inclusion of operator fixed effects is crucial, as water reallocation can only occur within operators instead of across operators, so I want to identify patterns of *within-operator* variation in water trading.

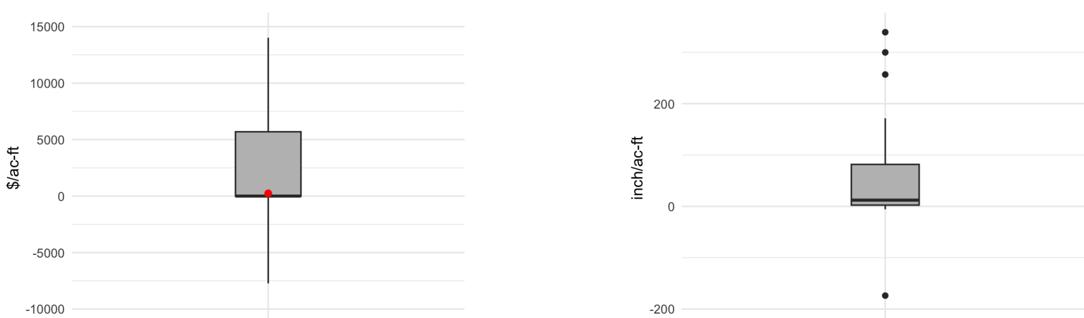
The results in Table 2 show that the coefficient on VIR is statistically insignificant across both model specifications, suggesting that heterogeneity in crop value per unit of water does not systematically affect a well's likelihood of being a seller. In contrast, the coefficient on irrigation efficiency is positive and statistically significant, indicating that wells with higher efficiency are more likely to reallocate surplus water to other wells.

Variable	$\Pr(Seller_{it} = 1)$ (1) LPM	(2) LPM	(3) Logit	(4) Logit
VIR	1.407e-03	5.855e-04	9.381e-03	-3.686e-03
	(1.069e-03)	(1.221e-03)	(6.661e-03)	(1.005e-02)
$IrrEfficiency$	1.616e-05**	2.899e-05***	7.169e-05*	5.328e-02***
	(5.243e-06)	(6.332e-06)	(3.135e-05)	(1.059e-02)
$Precipitation$	-9.466e-04***	-7.258e-04***	-7.856e-03***	-5.463e-03**
	(1.734e-04)	(1.8838e-04)	(1.524e-03)	(1.969e-03)
Year FE	Yes	Yes	Yes	Yes
Operator FE	No	Yes	No	Yes
Observation	565	565		
R^2	0.0810	0.2622		
AIC			581.54	503.18

$*** : p < 0.001; ** : p < 0.01; * : p < 0.05$

Table 2: Probability of being a net seller

In addition, I match the net sellers and net buyers within the same operator and the same year, and compare the differences in their value-to-irrigation ratio and irrigation efficiency. I calculate the difference using the average of net sellers minus the average of net buyers for each CombCode in each year, pool all values, and use Figure 2 to visualize the difference. Panel 2a displays the distribution of differences in the value-to-irrigation ratio (VIR), defined as crop revenue per unit of water applied, in dollars per acre-foot. Panel 2b shows the difference in estimated irrigation efficiency in inches per acre-foot. The distributions of VIR difference are centered around zero, and a majority (25th to 100th percentile) of the differences are positive. This pattern suggests that wells being classified as sellers tend to have a higher crop revenue per unit of water applied compared to their matched buyers. The distribution of irrigation efficiency differences is skewed positively, with a positive median and most observations above zero, although a few negative outliers exist. These findings suggest that there are potential efficiency gains when groundwater moves from more efficient irrigation to others. One possible explanation is that the allocation constrains is less binding for wells with a higher irrigation efficiency.



(a) Difference in Value-to-Irrigation ratio (b) Difference in irrigation efficiency

Figure 2: Difference in crop water productivity (panel a) and irrigation efficiency (panel b) between sellers and buyers of groundwater under the same CombCode in the same year. The y-axis shows the VIR/irrigation efficiency difference calculated by seller minus buyer, and the box plot shows the span, median, and quantile of the difference across all CombCodes in all years.

There are some possible reasons to explain why the difference in value-to-irrigation ratio may not be a driver of water reallocation. Heterogeneity in crop types can hinder agreement on what constitutes optimal or efficient water use. When individual wells within a group are associated with farms growing different crops, the variation in crop water needs and profitability can make it more difficult to align incentives and reach consensus on how water should be reallocated. The lack of common ground may constrain the potential for collective action. In contrast, in later empirical results, I show that wells with prior affiliation, often tied to farms growing similar crops, are more likely to coordinate, as the shared production practices and water demands reduce negotiation friction and facilitate internal reallocation. Moreover, the value-to-irrigation ratio is constructed based on the crop choice, and it is a proxy for *average* revenue in groundwater input instead of *marginal* revenue in groundwater input. Therefore, a high VIR does not necessarily imply a higher marginal return that would incentivize selling. On the other hand, I find that the heterogeneity in irrigation efficiency can be an important driver of internal groundwater reallocation. While the direction is ambiguous from the theoretical prediction, the empirical evidence suggests that wells with higher irrigation efficiency have a higher probability of selling the water on average.

Transaction costs and consolidation. I construct a well-pair data to list every unique combination of two wells, i and j in year t. Table A7 shows the summary statistics. I estimate three sets of models described in equations (5), (6), and (7) to investigate the role of transaction costs in shaping well consolidation decisions. The dependent variable in each model captures a different aspect of well group formation: (1) the probability of two wells (i, j) being jointly operated in a given year t ($\Pr(Grouped_{ij,t} = 1)$, (2) the conditional probability of new group between well i and well j given the pair was not previously grouped ($\Pr(Grouped_{ij,t} = 1 | Grouped_{ij,t-1} = 0)$), and (3) a pooled indicator of whether a well-pair is ever observed as grouped ($\Pr(Grouped_{ij} = 1)$). For each dependent variable, I estimate both linear probability models (LPMs) and logit models, and report estimated coefficients and robust standard errors clustered at the well-pair level in Table 3.

Across all models, I find consistent evidence that geographic proximity and organizational affiliation are significantly correlated to the probability of consolidation. The coefficient on

$\log(Distance_{ij})$ is significantly negative in every specification, indicating that wells located closer together are more likely to consolidate. For example, a one percent increase in the Euclidean distance between well i and well j is associated with decreased odds of these two wells newly grouping by a factor of 0.88. I also find that the coefficient on $Affiliated_{ij}$, which indicates whether the two wells appear to be part of the same organizational entity (e.g., same family name or agricultural group), is positive and statistically significant across all specifications. For example, in the conditional probability logit model, the odds of group formation increase by a factor of 127.49 for affiliated well pairs.

	$\Pr(Grouped_{ij,t} = 1)$		$\Pr(Grouped_{ij,t} = 1 \mid Grouped_{ij,t-1} = 0)$		$\Pr(Grouped_{ij} = 1)$	
Variable	(1) LPM	(2) Logit	(3) LPM	(4) Logit	(5) LPM	(6) Logit
$\log(Distance)$	-0.011^{***}	-0.192^{***}	-0.001^{***}	-0.129^{***}	-0.010^{***}	-0.140^{***}
	(0.001)	(0.014)	(0.000)	(0.017)	(0.001)	(0.007)
$Affiliated$	0.328^{***}	6.480^{***}	0.032^{***}	4.848^{***}	0.525^{***}	5.058^{***}
	(0.015)	(0.157)	(0.002)	(0.112)	(0.016)	(0.082)
Year FE	Yes	Yes	Yes	Yes	No	No
Observation	821676		753844		67896	
R^2	0.3537		0.0229		0.3241	
AIC		26383		5296.1		6439.3

$*** : p < 0.001; ** : p < 0.01; * : p < 0.05$

Note: The standard errors reported here are robust standard errors clustered at the well-pair level.

Table 3: Transaction costs and consolidation probability

The results are robust across model specifications and the three dependent variable definitions. In particular, the conditional probability, which focuses on new group formation by restricting to well-pairs not previously grouped, emphasizes the role of transaction costs at the point of group formation rather than the persistence of joint operation. The significant effects of geographical proximity and affiliation support the hypothesis that lower information search costs, bargaining costs, and coordination costs facilitate consolidation among wells.

7 Conclusion and Policy Implications

This study examines whether wells consolidate and coordinate informally under a command-and-control regulatory setting, but exhibiting cap-and-trade style flexibility. Theoretically, multi-well operators are allowed to internally reallocate water among wells, effectively operating under shared caps, while single-well operators remain constrained by well-specific quotas. Empirical evidence suggests that multi-well operators do engage in within-group reallocation, while following the aggregate quota in the same manner as a single-well owner. Moreover, the flexibility of intra-operator reallocation increases with the operator size. Further analysis highlights the role of transaction costs in shaping well consolidation: both geographic proximity and prior affiliation influence the formation of well groups, with family-run farms, agricultural alliances, and water companies serving as common forms of well consolidation. Finally, while variation in crop type does not appear to drive intra-operator allocation, differences in irrigation efficiency within operators emerge as a key factor behind water movement among wells.

While this study provides some insights for well owners' decision making, limitations remain. The static framework does not capture the dynamic nature of water use decisions and information updating under regulatory changes. Future research could explore long-term behavioral responses, incorporate crop-level panel data to examine crop switching resulting from groundwater management, and simulate counterfactual scenarios to evaluate the efficiency gains of expanding the formal market under alternative policy designs. Moreover, while the informal reallocation is observed from the data, and the mechanism of such reallocation is partially explained in my analysis, it does not provide implications for welfare change, which is essential in evaluating the collective actions. Therefore, I follow the analysis in this chapter with my second chapter, which explores the welfare change given by the informal coordination.

Policy implication. In 2020, the formal groundwater cap-and-trade program in the Oxnard Basin recorded a total of 54 acre-feet of water traded, involving only three distinct sellers and three buyers. Although this marked the first operational year of a regulated groundwater market under SGMA, the volume and participation were notably limited. Taking a closer look at the transaction records gives important insights:

1. Besides one seller, all agents trading in this formal market are single-well operators, and these agents had no prior affiliation suggested by the names of well owners.

2. Figure A6 shows the geographical distribution of sellers and buyers on the map. While the three buyers are situated in the northern part of the Oxnard Basin, buyers and sellers are not geographically clustered, indicating limited spatial proximity between trading entities.

3. Sellers in the formal market are attached to farms having higher values of irrigation, such as flower nurseries and cole crops, while buyers grow more water-intensive crops: citrus and field crops. In addition, sellers in the formal market tend to have higher irrigation efficiencies than buyers.

The observed features of the 2020 formal cap-and-trade market highlight key policy implications when compared to existing informal coordination. First, the formal market expands the scope of water reallocation from intra-operator to inter-operator transfers, enabling participation by single-well operators who are typically excluded from internal water transfer strategies. Second, unlike formal coordination, which often occurs within affiliated wells, the formal market facilitates transactions among unaffiliated entities. The broader participation allows the market to capture potential efficiency gains not only from differences in irrigation efficiency, as seen in formal reallocation, but also from transferring water across farms with different crop choices. Although intra-operator coordination may have internalized some of the gains from reallocating water based on irrigation efficiency, the formal market still holds promise for enhancing efficiency through cross-crop water transfers.

It is important for policymakers to think about the existing regulatory settings and whether voluntary coordination and collective actions have already internalized some potential efficiency gains from the formal environmental market. In addition, when designing formal markets, reducing transaction costs, especially those related to information search and bargaining, is essential to broaden participation and enhance market efficiency.

8 Subsequent Chapters

Chapter 2

The first chapter of my dissertation documents patterns of informal coordination among groundwater users within California's Oxnard Basin. The empirical analysis signals that some agricultural well owners within the basin collectively reallocate their assigned water under the shared cap by grouping with others and forming multi-well "operators". The observed reallocation suggests that some groundwater users are not acting as isolated, individual agents who respond to regulation independently but rather as members of loosely coordinated networks. Moreover, the patterns of such group forming align with findings in other literature that informational barriers limit the scope of collective actions (Ostrom, 1990; Libecap, 1990; Edwards and Leonard, 2025). While self-managing reallocation among groundwater users is empirically observable, it naturally raises further questions, which motivate my second chapter: What are the economic implications given by the informal coordination among resource users? To what extent does it enhance welfare outcomes relative to uncoordinated or purely individualistic behavior? Are there any distributional changes in welfare outcomes to different types of groundwater users?

Understanding the welfare implications of informal coordination is particularly important in the context of groundwater management under regulatory regimes like California's Sustainable Groundwater Management Act (SGMA). Policymakers are increasingly interested in using individual binding caps and groundwater markets to achieve sustainable extraction goals. Yet the effectiveness and distributional outcomes of these policy instruments depend not only on their design but also on how groundwater users respond to such policies. If informal coordination allows more efficient reallocation of water that moves water to higher-valued uses, it may offer a hidden efficiency gain. Alternatively, such informal coordination might have distributional effects on different resource users. Therefore, evaluating the welfare consequences is crucial to understanding the role of collective actions in resource management policies.

Measuring welfare gains from informal coordination, however, is empirically challenging. The marginal values of additional groundwater are difficult to observe because of the lack of a competitive water market that reflects groundwater users' valuation. Even when there is informal water trading, transaction prices are not observable.

A common way economists propose to measure the implicit value of natural resources or environmental goods is the revealed-preference approach. This approach infers value from actual choices made in markets, especially when explicit prices are absent. One widely used revealed-preference method is the hedonic property value model, which decomposes land prices into the value of their attributes, such as access to water, institutional regimes, and environmental amenities.

In the context of groundwater, Faux and Perry (1999) show that by including other land value determinants, such as soil quality, hedonic price analysis could be applied to agricultural land sales to reveal the implicit market price of irrigation water, and the value of irrigation water is estimated from $9 to $44 per acre-foot depending on the land productivity. Schlenker et al. (2007) also find that water availability is strongly capitalized into land value. Focusing on the case of the Kansas High Plain Aquifer, Addicott and Fenichel (2019) and Sampson et al. (2019) have both used land value of irrigated versus non-irrigated parcels to capture the groundwater valuation, highlighting the importance of taking spatial heterogeneity into account. Edwards et al. (2024) further study how different attributes of groundwater, such as access, allocation, and seniority, were capitalized into agricultural land values in the High Plains Aquifer. Leggett and Bockstael (2000) and Walsh et al. (2017) have both looked at how property prices revealed the economic effects of water quality. Ayres and

Meng (2018) use a hedonic approach with a spatial regression discontinuity to measure the welfare impacts of moving from the open access regime of groundwater to the environmental market, emphasizing the value of secured property rights.

Hedonic methods are also found in other fields besides groundwater, especially when valuing the environmental amenities. By looking at the relationship between air quality and housing market, Chay and Greenstone (2005) estimate that the housing price is negatively correlated to the particulate matter concentration, and the economic improvement from cleaner air was high. Analysis of housing prices around hazardous waste sites reveals that the cost of the Superfund Program clean-ups is largely understated (Greenstone and Gallagher, 2005).

Following the rich literature in environmental and resource economics that uses land markets to infer the value of unpriced or hidden attributes, the second chapter uses a revealed-preference approach based on the farmland value to capture the economic gains from informal coordination and groundwater reallocation. If formal coordination maintains long-term agreements that shape groundwater use and improve productive efficiency, those benefits may be capitalized into land values. Moreover, even the possibility or expectation of coordination may generate welfare gains through reduced uncertainty, which can also be reflected in land prices.

This chapter proceeds in two parts. First, it evaluates basin-level effects by comparing land values across groundwater basins that are similar in observable characteristics but differ in the extent of allowing pumping allocation transfer.[17] This comparative approach captures the broader institutional value of enabling collective actions by resource users, including expectations or option values associated with the potential to coordinate, even if it is not actively exercised by all landowners.

Second, this chapter explores within-basin heterogeneity in the distribution of welfare

[17]For example, the Mid-Kaweah Subbasin also adopts pumping allocation to manage its groundwater use and allows allocation transfer but limits the transfer within 5 miles, which constrains the scope of coordination. Similarly, The Madera Subbasin allows allocation to be shared within designated farm units.

gains from informal coordination. Building on the previous chapter's finding that coordination tends to occur among wells that are geographically proximate or previously affiliated, such as those sharing similar cropping patterns or agricultural operations, this chapter investigates whether welfare gains are concentrated among parcels with more clustered wells or those operated by larger entities. By examining how land values vary with the extend of coordination across parcels, while controlling for soil quality, crop type, and other factors that may affect land values, the analysis sheds light on whether informal groundwater reallocation disproportionately benefit larger or more interconnected farming operations.

Together, these approaches provide both a broad measure of the institutional value of enabling coordination. The analysis uses data on assessed value and sales value of agricultural lands obtained from the Ventura County Tax Assessor and supplemented by the 2014 Tenure, Ownership, and Transition of Agricultural Land (TOTAL) survey. The agricultural groundwater extraction report described in the first chapter will continue to be used for determining well location, coordination, and operation status. Soil quality (Soil Survey Geographic Database/SSURGO) and high-resolution land use maps (LandIQ) provide important determinants of land value and will be used to link land characteristics to the parcel value.

Chapter 3

Irrigation water conservation programs have been widely implemented across arid and semi-arid regions, especially in the western United States, where the agricultural sector is the main user of water and prolonged droughts have limited the water supplies. For example, at the federal level, the Natural Resource Conservation Service administers the Environmental Quality Incentives Program to help farmers, ranchers, and forest owners integrate conservation into working lands. In addition to federal efforts, substantial funding has been directed to state and local initiatives, such as the Agricultural Water Optimization Program in Utah, the State Water Efficiency and Enhancement Program in California, the Water Conservation and Infrastructure Initiative in Nevada, and the Water Irrigation Efficiency Program in

Arizona. These programs aim to reduce agricultural water use through grants for improved agricultural infrastructure or more efficient irrigation strategies.

However, a persistent concern with such conservation programs is the irrigation efficiency paradox or rebound effect, that improving irrigation efficiency does not always reduce overall water consumption, as the "conserved" water may instead be used to expand irrigated acreage, switch to more water-intensive crop, or increase irrigation intensity (Lankford, 2023). This paradox highlights the importance of evaluating not just technological upgrades but actual changes in consumptive use.

Therefore, a growing body of research looks at whether the irrigation efficiency paradox exists or what the magnitude of rebound effect is, and they find mixed results. Burt et al. (1997) provided early scientific evidence that increases in irrigation efficiency rarely translate into greater water availability at the system or basin level. Perry (2017) similarly finds that while water conservation may appear substantial at the on-farm scale, they often leads to increased total water consumption at basin level. Grafton et al. (2018) highlight that increases in irrigation efficiency must be accompanied by robust water measurement, a cap on total extractions, recognition of uncertainties, and trade-offs that account for water users' behaviors and incentives. More recent empirical work by Cameron-Harp and Hendricks (2025) applies a dynamic estimator and finds no significant evidence of rebound effect in improved irrigation efficiency.

While these studies have looked at the effect of technology development on water consumption, most rely on self-reported or administrative water withdrawal data, which can be inaccurate or unavailable in other regions, including Utah. The limited data on water consumption makes it difficult to assess whether public grants achieve the intended conservation outcomes. Therefore, developing an empirical approach to estimate consumptive water use, especially at the field level, offers a promising way to address the gap and generate policy-relevant evidence even in the absence of direct monitoring.

In my third chapter, I will address these research questions: How can we evaluate the water consumption outcomes of irrigation conservation programs in the absence of direct water use monitoring? What can estimates of field-level consumptive use tell us about the effectiveness and design of conservation policy?

Our project proposes a more accurate and scalable framework to assess policy effectiveness across diverse settings. We use remote-sensed evapotranspiration (ET) data from OpenET.[18] By comparing the methods from other relevant literature that derive actual ET estimates into field-level consumptive water use (Snyder et al., 2012; Mathbout et al., 2018; Boser et al., 2024; Huntington et al., 2025), we specify the approach that we think best capture the hydrological and agricultural conditions in our setting. With our specified approach, we can estimate the agricultural water consumption and construct a baseline for both field-level and basin-level estimates of historical water use and average water use by crop or region. The ability to generate both micro-level (field) and macro-level (basin) consumptive water estimates makes this methodology particularly relevant for researchers and policymakers seeking to understand how conservation programs affect consumptive water use across different spatial scales.

Specifically, we aim to evaluate the effectiveness of Utah's Agricultural Water Optimization Program, a state-led initiative designed to enhance water resilience while maintaining a viable agricultural sector. Initiated in 2019 with an initial $3 million legislative appropriation, the program aims to support projects that reduce consumptive water use, adopt innovative agricultural practices, and fund new and updated infrastructure. By 2023, this program had received over $276 million in total funding and was institutionalized further through the establishment of the Agricultural Water Optimization Committee. In addition to the initial objectives, this program further enabled saved water to be recognized as a beneficial use and emphasized improved water quantification and accountability.[19]

We combine the monthly and growing season evapotranspiration (ET) by field, precipi-

[18]OpenET is a non-profit that produces publicly accessible evapotranspiration estimates. They aggregate existing ET estimates (such as the SSEBop model) and also provide an "ensemble" model, which is a method that aggregates and weights existing ET models to produce ET measurements.

[19]https://ag.utah.gov/wp-content/uploads/2024/11/Water-Opt-Strategic-Plan-FINAL.pdf

tation from PRISM, Cropland Data Layer for crop pattern and land use[20], and water rights in Utah[21] to construct the data used in this project. Table A9 summarizes the data sources.

We plan to use a field-level difference-in-difference model as the benchmark empirical framework to estimate the effect of enrolling in the conservation program after constructing the field-level, irrigation-related ET. The model allows us to evaluate the program's effect on consumptive water use and other behavioral responses by farmers. The specification is in the Appendix.

Beyond quantifying water consumption outcomes, we also want to apply this methodology to further explore how institutional and hydrological characteristics, such as water seniority and baseline consumptive use, shape the effectiveness of conservation efforts. The methodology and the findings of this project are going to contribute to broader policy discussions about how to evaluate or design agricultural water conservation programs under limited data.

[20] https://opendata.gis.utah.gov/datasets/utah-water-related-land-use/about

[21] https://www.waterrights.utah.gov/wrinfo/query.asp

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Appendix

Chapter 1: Increasing Pumping Costs

In the benchmark setting, I assume that groundwater pumping costs remain constant over time, and the groundwater cost is uniform for every unit extracted. Under this assumption and in the absence of allocation constraints, the optimal groundwater input for a farm would remain unchanged across periods. However, due to the subtractability of groundwater, the groundwater pumping costs are likely to increase over time, because the extraction reflects in a lower water table and thus higher pumping costs, such as energy costs. Given that the marginal revenue from groundwater use is decreasing in quantity, an increase in the marginal cost leads to a downward adjustment in the optimal groundwater extraction level. This ensures that the farm's optimal groundwater input satisfies the first-order condition that marginal revenue equals marginal cost.

The pumping cost increase can generate different responses from farms, depending on its magnitude. If the new optimal groundwater input under the higher pumping cost is still above the allocated amount, the allocation constraint remains binding, as the right panel in Figure 3 suggests. In this case, operators may still benefit from reallocating water within a group of wells to equalize their marginal returns. However, if the cost increase is large enough that the unconstrained optimal extraction level falls below (or exactly equal to) the allocation, the allocation constraint is no longer binding. The left panel in Figure 3 visualizes this, and in this case, there are no potential gains from consolidating wells or reallocating water, disincentivizing well owners' coordination. Overall, the discussion on pumping costs highlights that declining allocation and increasing pumping costs may have offsetting effects on the incentive for coordination among wells under the same operator.

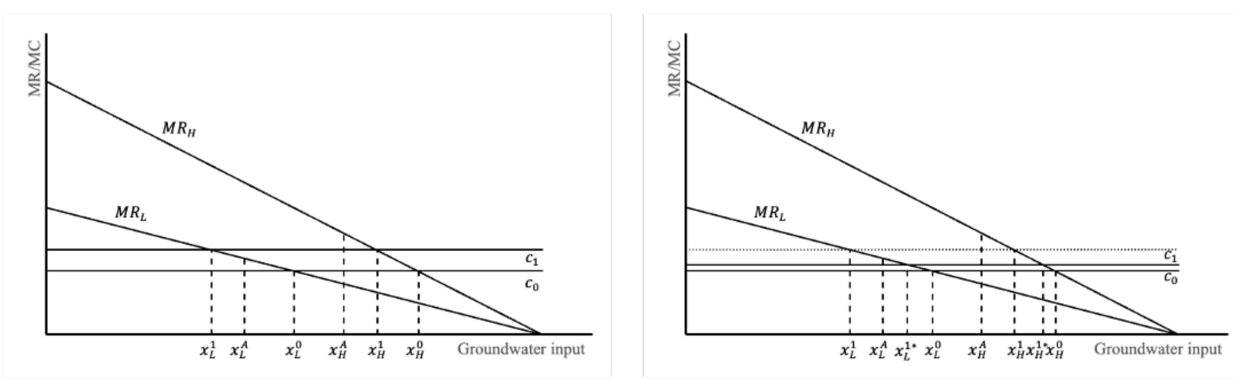


Figure 3: Reallocate under individual allocation and MC increase

Chapter 1: Value-to-Irrigation Ratio

I compute a crop c's value-to-irrigation ratio (VIR) as:

$$VIR_{ct} = \frac{\text{Revenue per Acre}_{ct}}{\text{Applied Water}_{ct}},$$

where Revenue per Acre$_{ct}$, reported in dollars per acre of land, is the county-average agricultural revenue of crop c in year t, which was reported in Ventura County's Crop and Livestock Report. Applied Water$_{ct}$ refers to the estimates of applied water in the California Department of Water Resources (DWR) Agricultural Land & Water Use Estimates. DWR estimates applied water for the top 20 crop categories between 1998 and 2020. I use the DWR estimates of average potential evapotranspiration in unit value (acre-feet per acre of land) for crop c in 2014, 2016, 2018, and 2019 in Ventura County to construct the value-to-irrigation ratio. The VIR essentially captures how much revenue one acre-foot of water can create on average. Table A6 reports the county average crop revenues, applied water, and the estimated VIR for all crop types grown in the Oxnard Basin.

Chapter 1: Irrigation Efficiency

I construct the irrigation efficiency as

$$IrrEfficiency_{it} = \frac{ET^c_{it}}{Extraction_{it}} = \frac{\sum_{m \in t}(ET_{im} - EffPrecipitation_{im})}{Extraction_{it}},$$

where ET_{im} is the actual ET estimates from MODIS in millimeters for well i in month t, and $EffPrecipitation_{im}$ is the effective precipitation derived from PRISM monthly precipitation data in millimeters for well i in month t. I first estimate the efficient precipitation of well i in month m as

$$EffPrecipitation_{im} = \begin{cases} ET_{im} & \text{if} \quad Precipitation_{im} \geq ET_{im} \\ 0.75 \times Precipitation_{im} & \text{if} \quad Precipitation_{im} < ET_{im} \end{cases}.$$

When precipitation in month m around well i exceeds actual ET, then I expect no irrigation water is applied to the farm, so irrigation-related ET ET^c_{im} is expected to be zero. On the other hand, when precipitation is below actual ET, then irrigation water is being applied to the farm, and the effective precipitation would be less than actual precipitation due to the water storability of the soil. Figure A3 shows the monthly average of actual evapotranspiration, precipitation, and computed irrigation-related evapotranspiration. The precipitation pattern in the Oxnard Basin aligns with California's climate, which is humid in winter and dry in summer, and there is more irrigation water applied in summer.

Both ET and precipitation are spatially matched to the Public Land Survey System (PLSS) quarter-quarter section in which well i is located. I simply subtract the effective precipitation from the actual ET to obtain the irrigation-related ET ET^c_{im} for well i in month m. Then I aggregate the irrigation-related ET across all months in year t to obtain the annual irrigation-related ET around well i to proxy for the consumptive water use for agriculture. Finally, the irrigation efficiency is calculated by dividing the irrigation-related ET in year t by the groundwater extraction of well i in year t. If two wells have similar irrigation-related ET, the well with less groundwater extraction tends to have a higher irrigation efficiency.

Chapter 3: Difference-in-difference Model Specification

The empirical model is specified as

$$Y_{fct} = \beta_0 + \beta_1 \text{Treatment}_f + \beta_2 \text{Post}_t + \beta_3 \text{Treatment}_f \times \text{Post}_t + \mathbf{X}'_{fct}\gamma + \lambda_f + \delta_{ct} + \epsilon_{fct},$$

where Y_{fct} is the outcome of interest for field f, in county c, and in year t. This outcome variable can be evapotranspiration (ET), crop choice (e.g., an indicator for whether a farm switch to a more water-intensive crop), or other water-related outcomes. Treatment_f is an indicator for whether field f participated in the conservation program, and Post_t is an indicator for post-treatment years. $\mathbf{X}_{fct}$ includes time-varying covariates such as precipitation. We also control for field-level fixed effect and year-by-county fixed effect in the diff-in-diff model.

Table

	Category	Description	Timeline
Tier I	Open access	Minimal limitations on new well drilling; no oversight on groundwater extraction	Before 1983
Tier II	Management entity	FCGMA being established and granted governmental authority	1983.1.1 -
Tier III	Well monitoring	Water meter and semi-annual extraction report required for each water extraction facility	1983.7.1 -
	Local uniform rule	Per-unit pricing for groundwater extraction implemented uniformly	1983.5.27 -
Tier IV	Individual pumping caps	Individual pumping allocation assigned to each water extraction facility	1992.1.1 -
	Penalty enforcement	Penalty for excessive water withdrawals over the allocation	1992.1.1 -
Tier V	Groundwater markets	A pilot cap-and-trade program allowing transfer of water allocation	2017.11.13 -2021.9.30

Table A1: Groundwater management in the Oxnard Basin

Feature	Informal coordination	Formal cap-and-trade
Unit of allocation	Well-level	Well-level
Enforcement level	Operator-level	Operator-level
Transfer Mechanism	Internal reallocation across wells under same operator code	Across operators
Administrative costs	Low - no documentation needed	High - need the FCGMA to approve and need formal changes in initial allocation
Information search costs	Vary - depend on how wells consolidate	Low - sellers and buyers submit their excessive/needed allocation to a third-party broker
Bargaining costs	Vary - depend on how wells consolidate	Low - sellers and buyers submit their excessive/needed allocation to a third-party broker
Geographic scope	Within one operator's wells	Within the Oxnard Basin
Third party involvement	No	Yes
Inventive to consolidate	Incentive to group wells under the same operator code	Less dependent on operator identity

Table A2: Comparison between informal coordination and formal cap-and-trade

Variable	mean	s.d.	median	min	max	n
Mean of Extraction (ac-ft)	161.44	162.01	113.05	0.07	840.95	328
St. Dev. of Extraction (ac-ft)	99.35	105.99	73.14	0.18	819.92	324
Precipitation (mm)	329.33	51.70	335.40	111.68	578.53	328
Evapotranspiration (mm)	309.16	108.81	311.06	52.17	671.65	328
$GroupYear$	0.67	0.38	0.86	0.00	1.00	328
CV	0.91	0.73	0.66	0.02	3.65	324
Seller	0.24	0.43	0.00	0.00	1.00	565
VIR ($1000/ac-ft)	24.83	17.02	25.27	0.00	57.53	628
Irrigation Efficiency	508.29	3169.84	2.63	0.10	34572.80	628
Precipitation (mm)	324.03	191.24	252.90	71.62	1339.62	628

Table A3: Summary statistics of the cross-sectional data

	All Observations					
Variable	mean	s.d.	median	min	max	n
Extraction (ac-ft)	165.75	222.43	93.65	0.00	3338.55	7001
ΔExtraction (ac-ft)	-1.68	156.42	0.00	-2979.11	3313.17	6615
$\|\Delta$Extraction$\|$ (ac-ft)	68.02	140.87	22.94	0.00	3313.17	6615
Precipitation (mm)	329.55	175.40	300.76	2.00	1454.92	7001
Evapotranspiration (mm)	311.03	152.49	298.24	12.01	1231.17	7001
	Ungrouped Wells					
Variable	mean	s.d.	median	min	max	n
Extraction (ac-ft)	121.48*	135.51	80.15	0.00	1169.98	2143
ΔExtraction (ac-ft)	-0.28	81.11	0.00	-553.81	934.75	2010
$\|\Delta$Extraction$\|$ (ac-ft)	43.66*	68.35	16.84	0.00	934.75	2010
Precipitation (mm)	347.57*	179.51	316.76	2.48	1454.92	2143
Evapotranspiration (mm)	297.19*	143.62	289.26	23.79	1019.03	2143
	Grouped Wells					
Variable	mean	s.d.	median	min	max	n
Extraction (ac-ft)	185.28*	248.92	103.63	0.00	3338.55	4858
ΔExtraction (ac-ft)	5.46	95.44	4.22	-399.22	511.66	4605
$\|\Delta$Extraction$\|$ (ac-ft)	72.56*	62.24	57.16	0.00	511.66	4605
Precipitation (mm)	321.60*	172.98	299.11	2.00	1339.62	4858
Evapotranspiration (mm)	317.14*	155.87	301.87	12.01	1231.17	4858

Table A4: Summary statistics for pooled observations, observations under single-well operators (ungrouped wells), and observations under multiple-well operators (grouped wells). The star shows that the mean values for grouped and ungrouped wells are statistically different, according to the Welch two-sample t-test.

	Well Count = 2					
Variable	mean	s.d.	median	min	max	n
Extraction (ac-ft)	129.53	163.74	74.00	0.00	2031.80	2142
ΔExtraction (ac-ft)	5.28	91.14	5.50	-399.22	414.55	2021
|ΔExtraction| (ac-ft)	68.15	60.72	53.12	0.00	414.55	2021
Precipitation (mm)	321.24	175.88	299.93	2.28	979.37	2142
Evapotranspiration (mm)	292.56	157.60	277.35	14.69	1231.17	2142
	Well Count = 3					
Variable	mean	s.d.	median	min	max	n
Extraction (ac-ft)	167.80	200.91	110.63	0.00	1881.18	1041
ΔExtraction (ac-ft)	11.20	92.73	11.72	-333.76	351.78	982
|ΔExtraction| (ac-ft)	72.65	58.67	61.06	0.00	351.78	982
Precipitation (mm)	324.63	169.01	300.99	2.00	956.90	1041
Evapotranspiration (mm)	317.14	144.89	310.42	12.01	918.04	1041
	Well Count = 4					
Variable	mean	s.d.	median	min	max	n
Extraction (ac-ft)	209.96	250.41	127.50	0.00	1282.20	560
ΔExtraction (ac-ft)	2.56	137.09	0.00	-487.63	781.79	539
|ΔExtraction| (ac-ft)	74.46	115.09	25.44	0.00	781.79	539
Precipitation (mm)	294.93	159.16	282.19	21.63	1004.65	560
Evapotranspiration (mm)	349.69	161.95	329.34	45.11	978.90	560
	Well Count ≥ 5					
Variable	mean	s.d.	median	min	max	n
Extraction (ac-ft)	296.31	361.33	166.96	0.00	3338.55	1115
ΔExtraction (ac-ft)	-4.95	309.54	0.00	-2979.11	3313.17	1063
|ΔExtraction| (ac-ft)	157.52	266.47	63.70	0.00	3313.17	1063
Precipitation (mm)	332.87	176.46	299.62	2.49	1339.62	1115
Evapotranspiration (mm)	347.99	150.96	325.98	14.56	1153.95	1115

Table A5: Summary statistics for observations under different operational scales.

Crop	Revenue per acre ($)	Applied water (AF)	VIR ($)
Year 2014			
Flowers and nursery	54269.09	3.2	16959.09
Strawberries	53995.18	2.11	25590.14
Young perennials	52643.99	2.11	24949.76
Bush berries	51292.81	2.11	24309.39
Miscellaneous truck	31760.44	2.11	15052.34
Peppers	15456.80	2.11	7325.50
Citrus	15189.92	4.14	3669.06
Cole crops	9128.24	2.11	4326.18
Avocados	6493.38	4.14	1568.45
Carrots	5757.89	2.11	2728.86
Beans (dry)	2933.17	1.31	2239.06
Miscellaneous grasses	269.28	4.34	62.05
Year 2016			
Strawberries	64017.79	1.84	34792.28
Flowers and nursery	63643.08	3.2	19888.46
Greenhouse	63643.08	3.4	18718.55
Bush berries	38969.60	1.84	21179.13
Peppers	17596.66	1.84	9563.40
Citrus	15572.28	3.66	4254.72
Miscellaneous truck	13590.90	1.84	7386.36
Cole crops	9572.74	1.84	5202.57
Avocados	6978.25	3.66	1906.63
Miscellaneous grasses	301.47	4.23	71.27
Year 2018			
Strawberries	73632.23	1.28	57525.18
Flowers and nursery	62378.13	3.2	19493.16
Greenhouse	62378.13	3.4	18346.51
Bush berries	43617.11	1.28	34075.87
Lettuce/Leafy greens	19545.40	1.28	15269.84
Citrus	15335.34	3.52	4356.63
Miscellaneous truck	14382.97	1.28	11236.70
Cole crops	9941.34	1.28	7766.67
Avocados	6032.48	3.52	1713.77
Miscellaneous grasses	409.25	4.25	96.29
Year 2019			
Flowers and nursery	60278.78	3.2	18837.12
Greenhouse	60278.78	3.4	17729.05
Strawberries	58520.89	1.3	45016.07
Bush berries	48755.40	1.3	37504.15
Miscellaneous truck	18350.12	1.3	14115.48
Peppers	16460.65	1.3	12662.04
Citrus	12667.86	3.54	3578.49
Cole crops	11175.51	1.3	8596.55
Avocados	7093.63	3.54	2003.85
Miscellaneous grasses	416.80	4.05	102.91
Grain and hay	409.25	4.05	101.05

Note: Revenue per acreage for a certain crop (Column 2) is calculated by dividing the total revenue by the total acreage grown in Ventura County. The acreage and revenue data come from Ventura County's Crop and Livestock Report in 2014, 2016, 2018, and 2019. Applied water by crop in acre feet per year (Column 3) comes from Agricultural Water Use Data for Ventura County, estimated by the California Department of Water Resources, except the applied water to flowers, nurseries, and greenhouses comes from the Crop Year Irrigation Allowance listed by the FCGMA. Revenue per acre-foot of water, referred to as VIR in my paper (Column 4), is calculated by dividing per-acre revenues by the average AF of applied water.

Table A6: Crops Grown in the Oxnard Basin

	Grouped = 0					
Variable	mean	s.d.	median	min	max	n
Distance (km)	7.29	3.88	7.27	0.01	18.37	896551
Affiliated	0.01	0.11	0.00	0	1.00	815693
	Grouped = 1					
Variable	mean	s.d.	median	min	max	n
Distance (km)	2.30	3.08	0.91	0	13.58	6232
Affiliated	0.87	0.33	1.00	0	1.00	5983

Table A7: Summary statistics for well pairs

	$\Delta Extraction$			$\|\Delta Extraction\|$			$\log(\|\Delta Extraction\|)$		
Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$Group$	-2.995	-4.975	-4.398	11.982**	18.135***	18.490***	-0.101	0.219***	0.231***
	(4.836)	(4.918)	(4.915)	(3.205)	(4.407)	(4.407)	(0.059)	(0.058)	(0.058)
$WellCount$	0.381	0.9115	0.629	8.890***	9.374***	9.104***	0.120***	0.105***	0.096***
	(0.939)	(0.956)	(0.962)	(0.833)	(0.857)	(0.863)	(0.011)	(0.011)	(0.011)
ET			0.034*			0.033*			0.001***
			(0.014)			(0.013)			(0.000)
$Precipitation$			0.061**			0.014			0.001*
			(0.023)			(0.021)			(0.000)
Year FE	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Observation	6615	6615	6615	6615	6615	6615	6615	6615	6615
R^2	0.00006	0.03981	0.04217	0.02978	0.0493	0.05048	0.01901	0.1087	0.1154

$*** : p < 0.001; ** : p < 0.01; * : p < 0.05$

Note: When transforming the dependent variable $|\Delta Extraction|$ to the logarithm form, I add an arbitrarily small value to address the existence of zero value in absolute extraction change.

Table A8: Well-level groundwater extraction change

Data	Source	Description
Land use	Utah Automated Geographic Reference Center	Yearly feature layer of agricultural and other water-related land use and crop types in and around Utah 2023. Crop type comes from Cropland Data Layer (CDL).
Evapotranspiration	OpenET	Monthly and/or growing season ET by field.
Precipitation	PRISM at Oregon State	High-resolution, spatially interpolated climate estimates on monthly precipitation based on point measurements, digital elevation models, and other spatial datasets.
Water rights	The Utah Division of Water Rights	Documentary file for each water right in the State of Utah.

Table A9: Data description

Figure

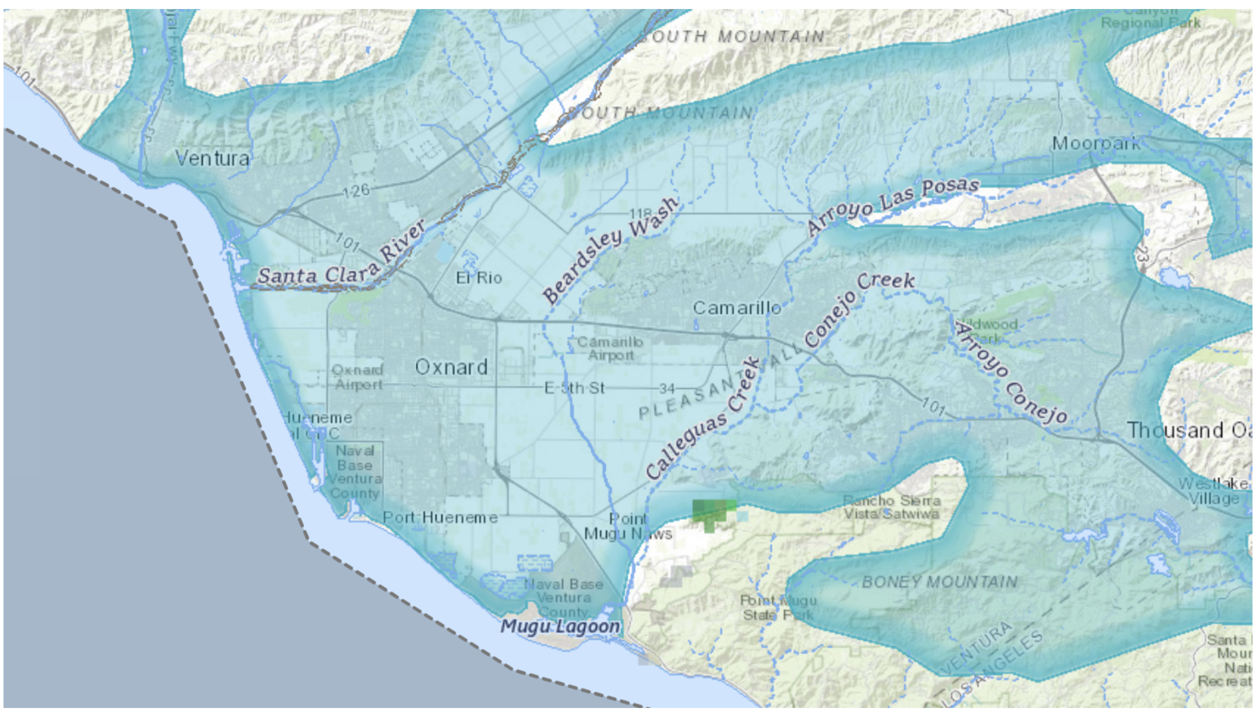
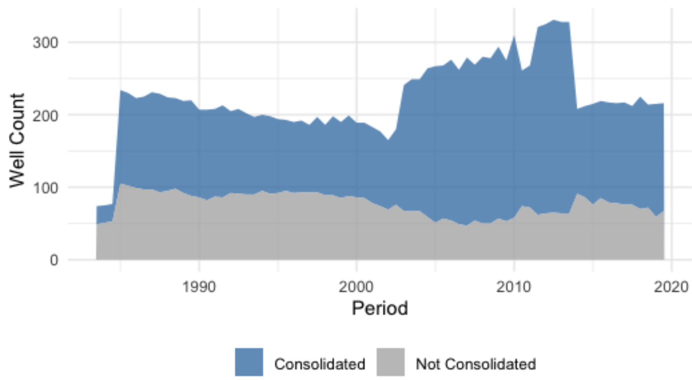
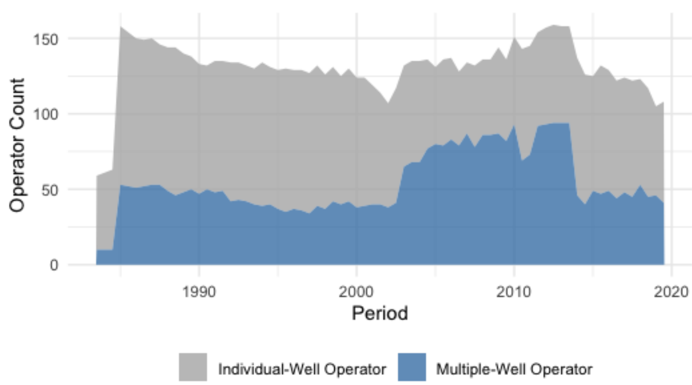


Figure A1: This figure shows the underlying aquifers beneath the Oxnard Basin and the surface water sources in the region. The information is obtained from the USGS National Water Dashboard. Source: https://dashboard.waterdata.usgs.gov/app/nwd/en/



(a) Stacked chart of well count across time. The gray part corresponds to the number of wells that individually operate without jointly operating with other wells. The blue part shows the number of wells that are within an operation group that contains more than two wells. Note that there is a large drop in numbers of operating wells around 2013-2014, which may be caused by the severe drought in California from 2012, that decreased groundwater levels impacted well operations. Meanwhile, new drilling of wells was temporarily halted.



(b) Stacked chart of operator count across time. The gray part corresponds to the number of operators that have only one well under their operation. The blue part shows the number of operators that have more than one well under their operation.

Figure A2: Well and operator trends in the Oxnard Basin.

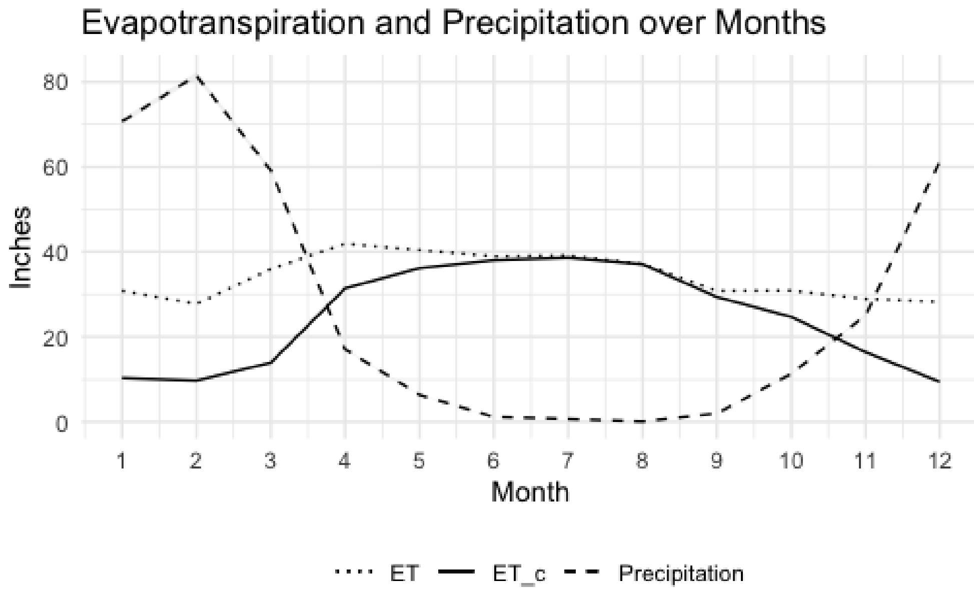
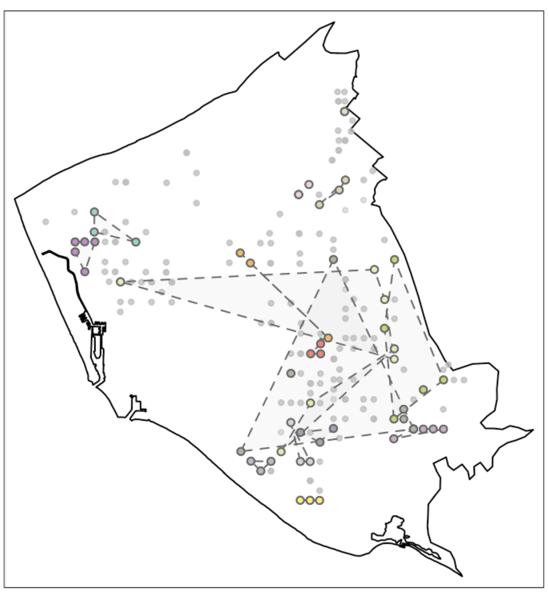
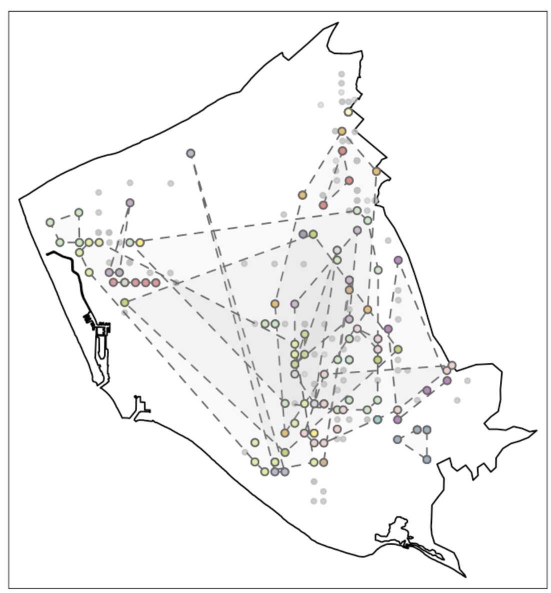


Figure A3: This figure shows the monthly average actual ET, precipitation, and computed irrigation-related ET across 1992-2019.

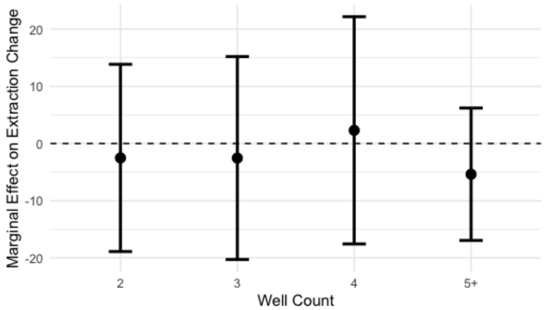


(a) Agricultural wells in 1991.

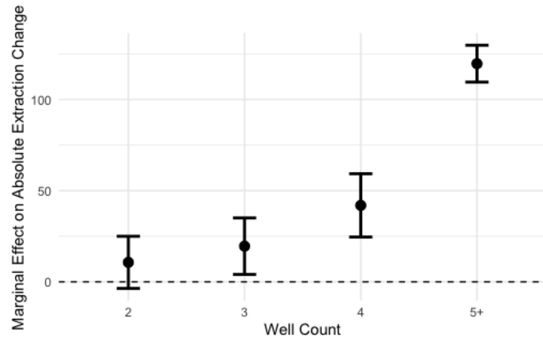


(b) Agricultural wells in 2019.

Figure A4: The gray dots represent all AG wells operating within the Oxnard Basin in 1991. The location of wells is identified at the centroid of the PLSS quarter-quarter section. The dashed box, together with the colored dots, represents wells under the operators having $n \geq 5$ wells.



(a) Extraction change



(b) Absolute extraction change

Figure A5: Heterogeneous effect of being under multi-Well operators across operator size

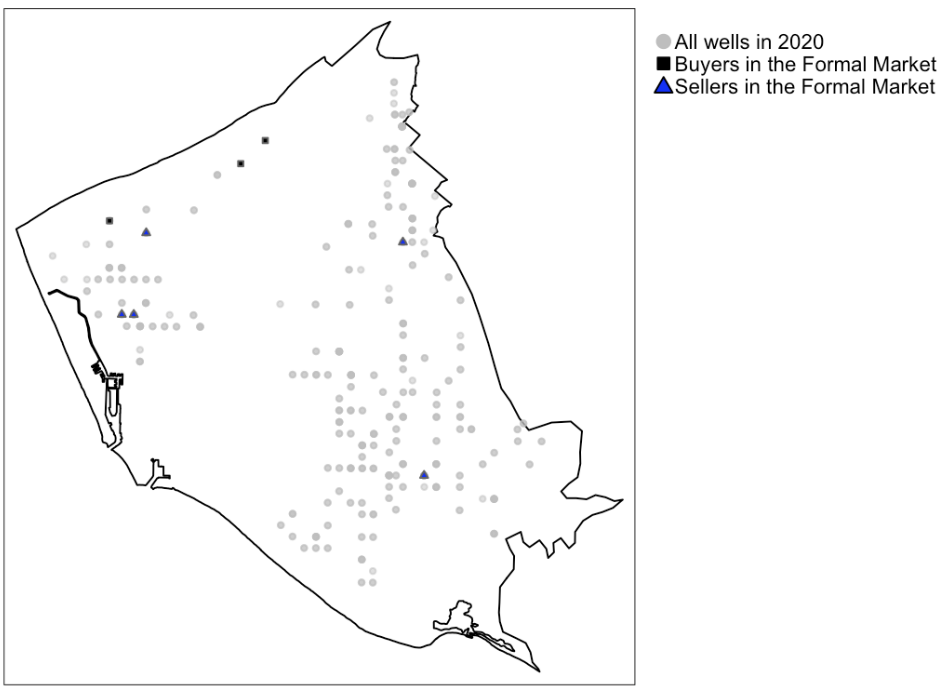


Figure A6: Agricultural wells in 2020, sellers and buyers in the formal cap-and-trade market.