The Dynamic Impacts of Pricing Groundwater*

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June 28, 2023

Abstract

This paper evaluates own-price dynamics in taxing environmental externalities. We exploit a natural experiment that exposed some firms to a large and persistent price increase for groundwater, a setting characterized by incomplete markets. Using five years of post-treatment data on farm-level water use, we find that water conservation doubles between the first and fifth year of the tax. Failure to account for dynamics in policies designed to manage groundwater will mischaracterize the price elasticity of demand and introduce efficiency costs.

JEL: D62; H23; Q15; Q25
Keywords: environmental regulation; market-based approaches; groundwater; agriculture; dynamic effects

*The authors thank Nicholas Brozović, Nick Hagerty, Koichiro Ito, Yusuke Kuwayama, Pierre Mérel, Taro Mieno, Petra Moser, Mar Reguant, Molly Sears, Richard Sexton, Aaron Smith, Matt Woerman, David Zilberman, and seminar participants at Carnegie Mellon, Oregon State University, Colorado School of Mines, California Polytechnic State University, University of Chicago, University of Massachusetts Amherst, University of Pittsburgh, University of Arizona, Montana State University, University of Nevada Reno, and Pennsylvania State University for helpful discussions and comments. A special thanks goes to Brian Lockwood, Marcus Mendiola, and Casey Meusel at the Pajaro Valley Water Management Agency for sharing data and institutional knowledge. This project has also benefited from the excellent research assistance of Jack Gregory, Lucy Hackett, Luna Yue Huang and the technical support of Eric Lehmer at the Geospatial Innovation Facility at UC Berkeley. Funding and support for this research comes from: the National Bureau of Economic Research, the California Institute for Water Resources, and the UC Water Security and Sustainability Research Initiative funded by the UC Office of the President (Grant No. MR-15-328473).

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1 Introduction

A classic distinction in economic theory is that factors treated as fixed in the short run may become choices under a longer time horizon (Samuelson, 1947). With few exceptions, making the empirical distinction between short and long run effects has proven more difficult (Hornbeck, 2012; Burke and Emerick, 2016; Deryugina, MacKay and Reif, 2020; Hagerty, 2021). Researchers are often faced with the choice between credible short-run estimates or longer-run estimates that lean on less tenable assumptions. Policy design and analysis that substitutes short-run estimates for long-run impacts risks mischaracterizing economic costs. In this paper, we exploit a price shift incurred by a subset of firms that persists over several years to empirically evaluate how the magnitude of firm response to prices evolves over time.

We study this in the context of agricultural groundwater in California, a setting characterized by incomplete markets and dwindling supplies. This common-pool resource traditionally has been mismanaged, with the absence of well-defined property rights leading to too much groundwater extraction at too quick a pace (Provencher and Burt, 1993; Brozović, Sunding and Zilberman, 2010; Pfeiffer and Lin, 2012; Edwards, 2016; Merrill and Guilfoos, 2017). This inefficiency is only exacerbated during times of drought, when the state's reliance on groundwater doubles to provide between 40% and 80% of water supplies. Groundwater has long provided a critical buffer to mitigate the costs of drought and may also substantially dampen the costs of climate change. However, the open-access nature of the resource, makes uncertain its long-run availability.

Prices have long been suggested as a means to correct this market failure and manage agricultural water demand, which accounts for 80% of consumptive use in the West (Brown, 1974). Yet in practice agricultural groundwater is rarely priced. Recent work has advanced our understanding of the short-run effects of prices on agricultural water use (Gonzalez-Alvarez, Keeler and Mullen, 2006; Hendricks and Peterson, 2012; Smith et al., 2017; Burlig, Preonas and Woerman, 2019; Bruno and Jessoe, 2021a). However, many agricultural decisions are longer run, with planting choices occurring on intervals that range from six months to decades. Own-price dynamics may factor critically into the design of prices as a policy to correct externalities and manage water resources. Ex-ante it remains uncertain if the demand elasticity would grow over time.[1]

To evaluate the dynamic impacts of a groundwater tax, our research design exploits a legal ruling that exposed some farms to a large and enduring water price increase. This policy change occurred in the Pajaro Valley, a productive agricultural area in California, and involved a shift from a single price for all farmers to two geographically distinct volumetric prices. The permanence of the price split for a five-year period lends itself to an event study framework to evaluate the water use response in each of the five years following the split. It also affords the opportunity to gauge the importance of dynamics for policy design under California's Sustainable Groundwater Management Act. This regulation requires that all groundwater agencies find ways to achieve sustainable groundwater levels, and over half are currently proposing price-based instruments (Bruno, Hagerty and Wardle, 2022).

Quarterly water meter readings spanning 10 years from over 750 farms allow us to capture how farmers respond to prices over time. It is the quarterly data following the five year price split that enables the estimation of longer-run responses using a panel data approach that controls for fixed farm unobservables, annual county shocks, and time-varying regional observables such as recycled water deliveries that might confound estimation. This approach overcomes omitted variables bias that may be present in cross-sectional examinations, but allows agents time to respond to the price change along longer-run margins.

In the short and longer run, groundwater demand reduces in response to the price

[1] In the context of overdrafted groundwater basins, dynamics might operate in the opposite direction with demand exhibiting a larger elasticity in the short as compared to the long run. This would occur if in the longer run, groundwater stocks were exhausted and/or extraction costs were higher.

increase, with the price elasticity of demand increasing over time. Our results indicate that the 21% price increase led to a 28 acre-foot (AF) or 22% reduction in average annual groundwater extraction. This response is robust to time-varying differences across regions including recycled water supplies that were provided exclusively to treatment households over the duration of our sample. However, this average treatment effect masks dynamics in the response to water pricing. The reduction in annual water use doubles between the first year and the fifth year after the tax, with the implied price elasticity of demand ranging from -0.86 to -1.97.

Our results stand in contrast to the convention in the literature that water demand is inelastic. Studies converging on this qualitative takeaway report elasticity estimates between -0.10 and -0.77 (Bruno and Jessoe, 2021b; Scheierling, Loomis and Young, 2006). Our estimates offer a new interpretation on this literature: over longer time intervals, agricultural groundwater demand is relatively price elastic as farmers adjust through margins that may simply be unavailable in the short run. The sensitivity of elasticity estimates to the time-step of evaluation may also extend to the residential water and energy sectors, two settings characterized by highly inelastic short-run demand (Deryugina, MacKay and Reif, 2020; Reiss and White, 2005; Ito, 2014; Allcott, 2011; Olmstead, Hanemann and Stavins, 2007; Wichman, Taylor and von Haefen, 2016; Browne, Gazze and Greenstone, 2021).

This central result is also timely given the global reach and severity of drought, and the expectation that droughts are to become more frequent and severe with climate change (Diffenbaugh, Swain and Touma, 2015). Currently, the Western U.S., Europe, China and Africa are experiencing historic droughts. Traditionally, water authorities have relied on non-pecuniary approaches for conservation (Olmstead and Stavins, 2009; Olmstead, 2010). We find that in the medium-run, prices may be an effective tool to curtail demand.

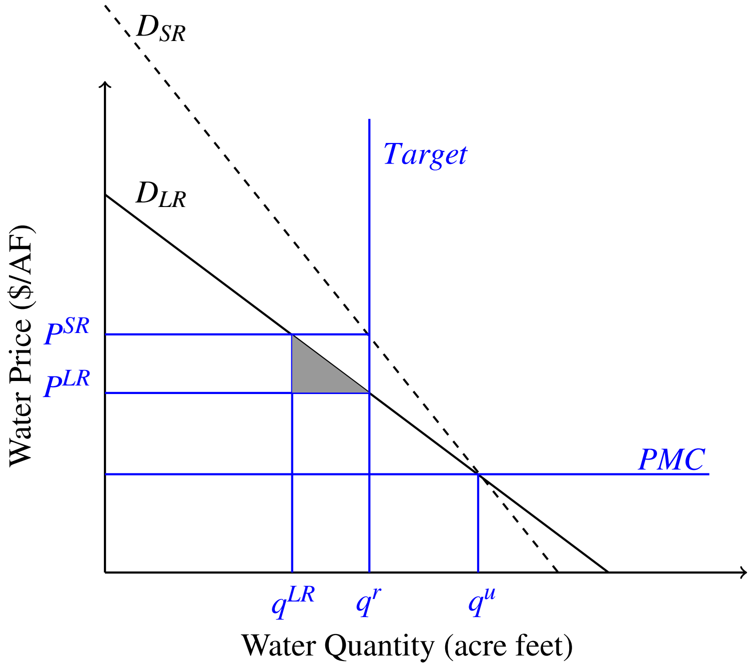
Our study demonstrates that the optimal design of environmental taxes must account for dynamics in the price response. A back-of-the-envelope calculation reveals that if we extrapolate into the longer run using year one estimates, the imposed tax just meets the irrigation district's 10% groundwater conservation target proposed under the Sustainable Groundwater Management Act. However, this tax would be far too high if we instead leaned on the five year estimate, with the irrigation district exceeding the target three-fold. If the 10% target was set efficiently, then the tax actually introduces a new deadweight loss due to underextraction. Setting prices right requires not only a proper accounting of spatial and temporal heterogeneity, but also longer-run dynamics (Muller and Mendelsohn, 2009; Novan, 2015; Borenstein and Bushnell, 2018).

2 The Conceptual Importance of Dynamics

To motivate the empirical importance of distinguishing farmer response to groundwater pricing in the short and longer run, consider a regulator that sets a cap on aggregate groundwater extraction and implements a groundwater price to meet this cap.[2] Figure 1 depicts short-run, D_{SR}, and long-run, D_{LR}, demand for groundwater. In the absence of intervention, the quantity of demand for groundwater is given by q^u, and occurs where the marginal benefit of an additional unit of extraction equals the price of extraction. The regulator now introduces a price instrument to reduce total groundwater extraction to q^r and chooses a price, P^{SR}, based on the short-run demand curve. In the long-run, demand is more elastic and aggregate groundwater will reduce to q^{LR}, leading to excess groundwater conservation. This will introduce an efficiency cost, denoted by the shaded area, since the marginal benefit of groundwater extraction exceeds the marginal cost of extraction. A policy designed using the long-run demand would introduce a lower price, P^{LR}, that would have yielded the quantity objective. This proof-of-concept makes explicit that employing short-run price elasticity estimates to set water quantity restrictions may lead to inefficient and costly policies if long-run responses differ from short-run estimates.

[2]Under SGMA, almost half of the submitted groundwater sustainability plans propose setting a cap on groundwater extraction (Bruno, Hagerty and Wardle, 2022). This includes the Pajaro Valley.

Figure 1: Efficiency Losses from Missing Policy Target



Note: The shaded triangle depicts the deadweight loss associated with setting a price based on SR demand to achieve target when really the LR demand is more elastic.

The on-the-ground implications of using the short-run elasticity as a substitute for the long-run elasticity hinge on an empirical understanding of the magnitudes of each parameter. Recent work has sought to bring credible empirical estimation to the short-run price elasticity of agricultural water demand. In general, this suite of work proxies for water prices using the energy costs of extraction and relies on panel data on energy consumption or groundwater extraction (Gonzalez-Alvarez, Keeler and Mullen, 2006; Hendricks and Peterson, 2012; Pfeiffer and Lin, 2012; Burlig, Preonas and Woerman, 2019). A first shared feature of this work is its reliance on short-run, defined as quarterly or monthly, variation in existing prices to pin down the short-run price elasticity of demand for agricultural water. A second shared feature is the use of panel data that allows the researcher to control for a number of cross-sectional and time-varying factors that may have confounded earlier estimates. Reported short-run elasticities range from -0.1 to -1.21, and offer some of the first credible empirical evidence on how farmers will respond to short-run changes in prices such as those induced by fluctuations in groundwater recharge, energy prices, groundwater levels, temperature, and surface water supplies. While these short-run elasticity estimates are particularly relevant for understanding customer response to the energy costs to extract groundwater, two factors limit their applicability to the design and evaluation of volumetric groundwater pricing programs.

The volumetric pricing programs under consideration in California will use a well-established rate-setting process to introduce volumetric prices that farmers will respond to in both the short run and long run. Policy design must incorporate dynamics in the response to a previously unpriced good. Recent work takes advantage of the introduction of volumetric pricing programs in agricultural districts and a difference-in-differences research design to overcome the first challenge (Smith et al., 2017; Bruno and Jessoe, 2021a). These studies also make empirical headway on farmer response over longer time horizons by estimating the average price elasticity over a three to ten year window.[3] While these estimates reflect a combination of short- and medium-run responses, these studies were not designed to isolate dynamics in response to the price change. This is because though only some areas are exposed to volumetric prices, the price faced by farmers changes throughout the post-treatment period.

Despite its policy importance, little empirical evidence exists on the long-run response and how this compares to the short-run response. The difference in price sensitivity over time may be particularly acute in the agricultural water setting given that the available margins of response to farmers within a year - less irrigation all else equal - differs substantially from the margins available over a multi-year horizon - land use decisions. The primary empirical contribution of this paper is to assess the dynamic response to volumetric pricing, and provide an empirical case study of the costs from using short-run estimates to set long-term policy.

[3] Smith et al. (2017) further decomposes the intensive and extensive margins of response, where the latter proxies for medium-term effects.

3 Water Pricing and Land Use in the Pajaro Valley

We examine the dynamic effects of volumetric water pricing on water use in the Pajaro Valley, a productive agricultural region situated along California's central coast. This region, which resides east of Monterey Bay and spans parts of Santa Cruz and Monterey counties, is unusual in that the water district meters groundwater pumping, takes quarterly meter readings, and charges volumetric rates for agricultural groundwater use.

3.1 Agriculture and Water Use

The area is home to a large and diverse agricultural sector, with more than 30,000 acres in crop production and annual agricultural revenues totaling almost $1 billion. The region primarily produces high-valued commodities including berries, apples, grapes, artichokes, lettuces, and other vegetable row crops. These crops comprise a mix of annuals and perennials, and differ in fixed planting costs, lifespan, and the lag between when the crop is planted and harvested. These differences imply that the time-step for water use decisions may range substantially, with farmers making cropping choices seasonally or annually for vegetables and longer for fruit trees. A diverse, high-value crop mix characterizes agricultural production throughout much of California. The relevant geographic market for produce grown in the Pajaro Valley is global, with crops traded in world markets, and both exported and imported by the United States.

Almost all agriculture in the Pajaro Valley is irrigated, with water coming almost exclusively from groundwater sources. It is a semi-arid region, like much of the agricultural land in California, with precipitation amounting to on average 20 inches annually but falling mainly in the surrounding hills. In contrast to most water districts which rely heavily on surface water imports for irrigation, in the Pajaro Valley, over 95% of irrigated water supplies are from groundwater sources. This has motivated the water district to implement novel tools to manage existing and develop new water supplies.

3.2 Volumetric Water Pricing and Recycled Water

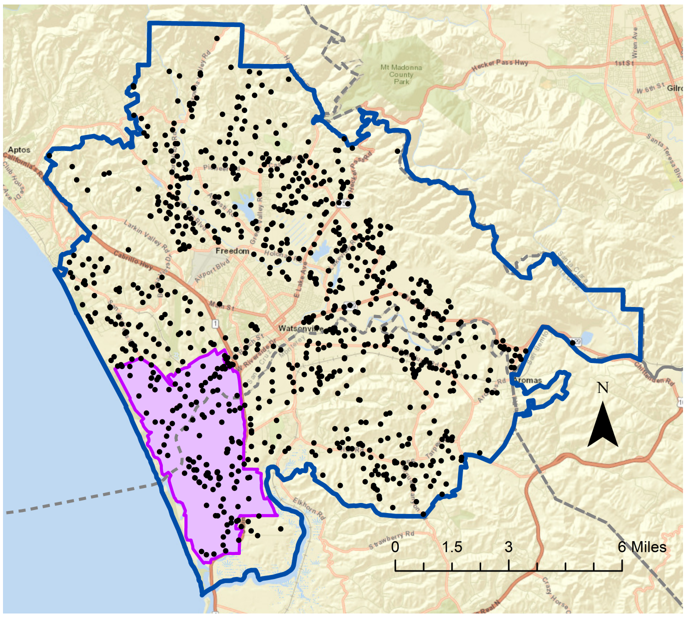
A distinguishing feature of the Pajaro Valley Water Management Agency (PV Water or PVWMA), the water district responsible for managing the water supply, is that it charges volumetric prices for groundwater extraction. This differs sharply from the pricing structure used in most water districts throughout the state. The norm is for the groundwater itself to be unpriced, with the price users face equal to the energy costs required to lift an acre foot of groundwater from the aquifer to the surface.

PV Water introduced volumetric groundwater pricing to address groundwater quality concerns arising from saltwater intrusion. Groundwater extraction led to severe overdraft and a decreasing water table that in some places fell below sea level. Pajaro Valley's location adjacent to the Pacific Ocean made it susceptible to seawater intrusion of the groundwater supplies. The water quality concern posed from seawater intrusion is increased groundwater salinity, measured by chloride concentrations, which makes the water less suitable for irrigating crops.

Revenues raised from groundwater pricing were and are used to fund the development of alternative water supplies. Specifically, volumetric pumping fees cover the capital and operating costs of generating and delivering recycled water supplies.[4] Recycled water deliveries began in 2002 and grew over time with increases in treatment capacity. Details on recycled water deliveries are provided in Appendix C. The idea behind these alternative supplies is that they would reduce groundwater use in the areas most prone to saltwater intrusion. In effect, the volumetric pumping fees act as a tax on the negative externalities caused by groundwater pumping.

[4] A recycled water facility treats wastewater from the City of Watsonville. Recycled water is delivered from the treatment plant to parcels of farmland via an underground pipeline system. The use of recycled water does not restrict the sale or consumption of crops.

Figure 2: Irrigation District Service Area, Rate Zones, and Wells



Note: The service area of the Pajaro Valley Water Management Agency is divided into two different rate zones. The shaded area delineates the Delivered Water Zone, where users began facing a higher water price in 2011. Each dot represents a groundwater well. The dotted line marks county boundaries; the service area is split between Santa Cruz County in the north and Monterey County in the south.

3.3 Assignment Mechanism: Delivered Water Zone

Recycled water provides an alternative source to groundwater, but is only available in limited quantities. To allocate these scarce supplies, the district created two geographic zones, and only made recycled supplies available to users within the designated "Delivered Water Zone" (DWZ). Figure 2 depicts a map of PV Water's service area and the boundaries that delineate the two regions: inside the DWZ and outside the DWZ. As shown in Figure 2, the land bounded between the coast on the west and Highway 1 on the east was designated as inside the DWZ.

The recycled water deliveries that are made available to users within the DWZ differ in price from groundwater. Volumetric recycled water rates are higher than the pumping fees charged by PV Water. However, after accounting for the energy costs to extract an acre-foot of groundwater, recycled water is cheaper than pumping groundwater in the DWZ.

3.4 Prices and Proposition 218

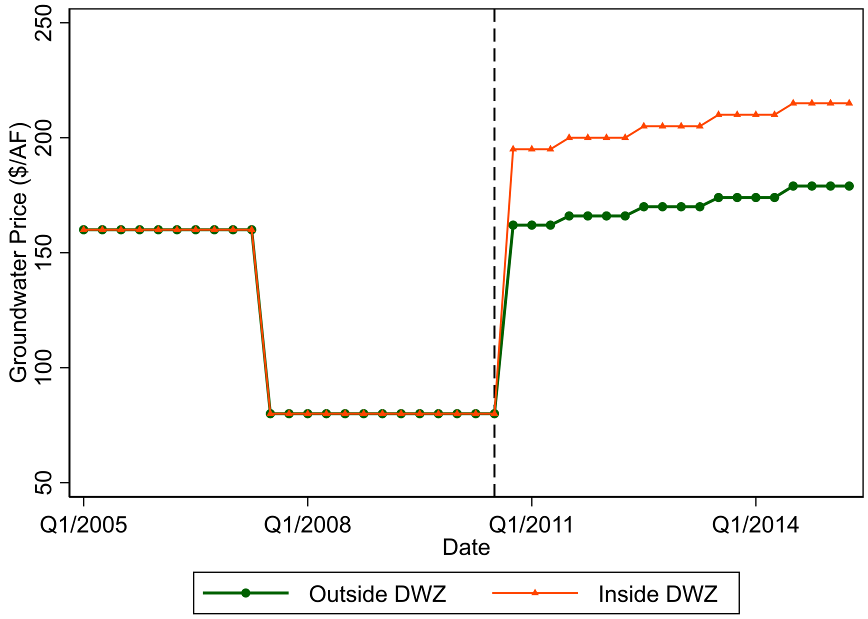
The first pumping charges were administered in 1994, with all customers incurring a uniform price per acre-foot (AF) of groundwater extracted. Figure 3 illustrates the annual per AF price charged in each region between 2005 and 2016.[5] Between 2005 and 2010, all users faced the same volumetric price. Starting in October of 2010, PV Water began charging different prices inside and outside of the DWZ.

After the price split, the percentage difference in price between zones remained constant for five years, with users inside the DWZ facing a price that was 21% higher through June 30, 2015. To provide perspective for the magnitude of the price increase, we place it within the total cost farmers face to extract an acre-foot of groundwater. The cost of groundwater extraction is comprised of the volumetric fee and the energy cost of extraction. We calculate the energy cost per AF of groundwater to be \$47.27. This implies that the total cost per AF of groundwater extraction increased by 17% for users inside the zone relative to users outside the zone following the price split.

The announcement of the price split also contained information on allowable price changes for a 5-year period. Between October 2010 and June 2015, prices inside and outside the DWZ were tagged to the consumer price index in San Francisco, and would increase according to this index. In May 2015, PV Water notified customers that volumetric rates for agricultural water would change beginning in July 2015, and published the rate schedule for July 2015 through 2020 inclusive. As such, our empirical evaluation of

[5] Price changes take place at the start of the fiscal year (July). This coincides with the second month of the third quarter. PV Water defines quarters for meter reading and billing in the following way: Q1 = Dec, Jan, Feb; Q2 = March, April, May; Q3 = June, July, Aug; Q4 = Sept, Oct, Nov. Details can be found in Appendix A.

Figure 3: Volumetric Groundwater Prices by Zone



Notes: The figure shows water extraction prices by zone over time. Prices for the two zones diverge in the 4th quarter of 2010.

longer-run effects restricts it attention to the five years following the 21% price increase faced by users inside the zone.[6]

State laws governing water pricing were responsible for the split from a single volumetric pricing regime to zonal pricing. California Proposition 218, the "Right to Vote on Taxes Act" which was passed in November of 1996, requires local governments to get taxpayer approval for property-related fees, and that the taxes charged to different parcels reflect the proportionate service that those land parcels receive in return. The lawsuit, *Griffith v. PVWMA*, made the case that the water district was in violation of Prop 218 by charging everyone the same price. The reason for the lawsuit was that all users were charged the same volumetric price for groundwater, though since 2002 only wells located inside the DWZ benefited from recycled water deliveries. The courts sided with Grif-

[6]One complication is the misalignment between when the price changes and the meter readings occur. Quarter 3 meter readings in 2015 reflect water use under the pre-July 2015 and post-July 2015 price regimes. To account for this we demonstrate the robustness of results to the exclusion of quarter 3. See Appendix B Figure 7.

fith, and the district began charging two different prices based on the DWZ boundaries in October 2010. These prices were established via a rate-setting process that was compliant with Prop 218. The agency justifies charging all users a non-zero price on the basis that everyone benefits from the in-lieu groundwater recharge and improvements in water quality that result from recycled water deliveries.

The price change experienced prior to the price split can also be explained by California's Proposition 218 and associated legal battles. In 2002-03, PV Water increased rates from $80/acre-foot to $160/acre-foot with a rate-setting process based on the premise that these prices were not related to property. This explains the high prices observed in Figure 3 at the start of our sample period. In 2007, *PVWMA v. Amrhein* determined that the pumping fees were in fact property related, and thus subject to Prop 218. This lawsuit drove the drop in prices at the end of 2007, as the courts required PV Water to return to prices that were established prior to 2003.

The rate-making process followed by PV water is shared by most public water utilities in the state, and provides a preview into the regulatory process through which agricultural groundwater fees will be introduced under the Sustainable Groundwater Management Act. While the energy costs of extraction may exhibit short-run price swings due to hydrological and weather conditions or time-variant electricity pricing, direct groundwater fees do not. Rate schedules will be discussed, published, and approved in five-year intervals. The fixed nature of groundwater fees points to the importance of understanding customer response to prices in the short run and longer run.

4 Data and Descriptive Statistics

We combine three distinct datasets on water use, water prices, and land ownership to generate the primary data used to estimate the impact of water prices on water use. These are supplemented with data on groundwater depth, water quality, and recycled water deliveries. Table 1 provides descriptive statistics by zone, including the unit and number of observations for each variable.

Table 1: Descriptive Statistics

	Outside DWZ 554 parcels			Inside DWZ 70 parcels		
	Count	Mean	SD	Count	Mean	SD
Annual						
Extraction (AF)	4,981	61.56	93.82	635	112.99	139.39
Pumping price ($/AF)	4,981	146.48	37.22	635	165.83	51.99
Recycled deliveries (AF)	4,981	0.00	0.00	635	2,846	1,376
Delivered rate ($/AF)	-	-	-	635	295.97	31.77
Chloride (mg/L)	4,981	57.47	7.26	635	130.74	27.46
Depth to water table (ft)	3,797	134.10	99.81	493	84.79	60.69
Quarterly						
Extraction (AF)	19,000	16.48	29.36	2,480	26.45	38.65
Pumping price ($/AF)	19,000	146.55	39.20	2,480	164.50	53.28
Recycled deliveries (AF)	19,000	0.00	0.00	2,480	677.93	524.06
Delivered rate ($/AF)	-	-	-	2,480	293.80	33.02
Chloride (mg/L)	15,675	74.10	88.59	2,108	145.68	81.92
Depth to water table (ft)	12,964	126.84	76.55	1,736	83.49	60.03

Notes: This table reports observations, means, and standard deviations (SD) for the balanced panel by zone at the parcel level. A total of 624 parcels remain in the balanced panel. Water is measured in acre-feet (AF). Groundwater salinity is measured by chloride levels. Extraction data span 2005-2015 (2010 is removed). Depth to water table data are available for 2008 onward. Quarterly variables are aggregated to the annual level by summing or averaging data over the 12 month period from Q4 to Q3 to align with the price change.

PV Water provided quarterly data on groundwater extraction for all of its roughly 800 metered wells spanning the period 2005 to 2015. Figure 6 in Appendix A plots quarterly average well-level groundwater use by zone. Groundwater extraction exhibits strong seasonal patterns with extraction peaking in the hot and dry summer months that coincide with the third quarter, and ebbing in the relatively dormant and wet first quarter that spans December through February. We also observe regional differences, with average well-level extraction greater inside the DWZ. A visual inspection of Figure 6 reveals that water use declined disproportionately for users inside the zone after the price split.[7]

[7] We also observe a price reduction from $160 to $80 per AF of groundwater in late 2007 for all agricultural groundwater users. This is correlated with a 3% increase in parcel level groundwater use for all

Land ownership data collected from the County Assessor offices are used to define our unit of observation. Tax assessor data delineate property boundaries and enable us to assign wells to each property and calculate property size. Since our goal is to measure a farm-level response and a single land owner may operate multiple wells, we aggregate wells to the tax parcel level and treat each parcel as a farm.

Micro-level panel data on water quality, depth, and, importantly, zonal recycled water supplies allow us to directly account for observables that may be correlated with prices, and likely influence groundwater extraction. A figure of recycled water deliveries over time can be found in Appendix C. Information on other secondary data sources and the construction of variables is provided in Appendix A.

5 Empirical Framework

Our empirical setting lends itself to a difference-in-differences framework in which we look at the water use effects of a shift from a single water price for all users to zone-specific prices. Beginning in October 2010, users within the Delivered Water Zone faced a price 21% greater than users outside of the zone.

5.1 Timing of Price Change

One complication in our setting is the timing of the price split. Legal documents and conversations with the utility confirm that the price split occurred in October 2010, but when farmers learned of this price change is more circumspect. The rate-setting process followed by PV Water – a public hearing, followed by a vote on the price change, and then implementation of the price change one month after the vote – describes the process for all public water utilities throughout California. In March 2010, the Board of Directors announced a date for a May 2010 public hearing on the proposed price changes for the two

users.

regions. After the hearing, a election was held on August 10 to vote on the price change. This price increase was approved by a majority of property owners, adopted by the Board at the September 2010 board meeting, and took effect on October 1, 2010. Notification of board meetings, ballots on the price measure, and the approved price change occurred through the mail.

These communications raise the possibility that farmers anticipated the October 2010 price change as early as January 2010, and responded in anticipation of it. Anticipation will overstate treatment effects if farms respond by extracting and storing groundwater supplies, and understate treatment effects if farmers respond by fallowing land or switching out of water-intensive crops. To account for the possibility that anticipation confounds estimation of the price split, we remove the 12 months preceding the price change, a period when farmers might have been aware of but not subject to the price change.

5.2 Average Treatment Effect

To compare the change in water use in the DWZ before and after the price change, to the change in water use for farms outside the zone, we estimate a difference-in-differences model using OLS:

$$Y_{irt} = \alpha_i + \phi_{ct} + \beta T_{rt} + \varepsilon_{irt}. \tag{1}$$

The dependent variable, Y_{irt}, measures the quantity of groundwater extraction for farm i in zone r during year t. The indicator variable T_{rt} is the interaction between $Post_t$, which is set equal to 1 after October 2010, when the water district implemented zone-specific pricing, and the variable $Inside_i$ which takes a value of 1 if farm i is located inside the DWZ, and a value of 0 if it is located outside of the DWZ. Our regressor of interest is the interaction of these indicator variables, and captures the effect of this price change on water use. In base specifications, α_i and ϕ_{ct}, denote whether a farm is inside or outside the DWZ, and the time period is pre or post October 2010, respectively. We augment these specifications to control for fixed farm unobservables and county-year unobservables. The inclusion of farm fixed effects, α_i, accounts for farm unobservables such as soil type that may be systematically correlated with water use and water prices in a zone. County-year fixed effects, ϕ_{ct}, control for aggregate annual time shocks, such as precipitation that may correlate with water prices and water use, and county-specific shocks such as property values that differ between Santa Cruz and Monterey counties. Standard errors are clustered at the farm to account for serial correlation within a farm over time.

5.3 Dynamic Treatment Effects

To evaluate the dynamic impacts of the price change, we deploy an event study framework and estimate the effects of the price split on water use in each of the years following the price split,

$$Y_{it} = \alpha_i + \sum_{\tau=a}^{b} \beta_\tau 1\{D_{it} = \tau_{it}\} + \phi_{tc} + \varepsilon_{it}. \tag{2}$$

All variables are defined as in equation (1), except our regressors of interest are now given by the vector D_{it}. The indicator variables take on a value of 1 for a farm inside the delivered zone in year τ following the price split. Years are defined over the event period $\tau = [a,b]$, and relative to 2009, the year preceding the price split. We normalize $\beta_0 = 0$ such that all coefficients, β_τ, are measured relative to the final baseline year. Lastly, we restrict our sample to the balanced panel of farms in the event time window $\tau = [-3,5]$.

Our coefficients of interest $\sum_{\tau=a}^{b} \beta_\tau$ measure the difference in water use across the two farm types in each of the τ years following the price change. This allows us to evaluate the effect of the permanent price increase on water use in each of the 5 years following the price split, and compare short run to longer run responses.

5.4 Identification

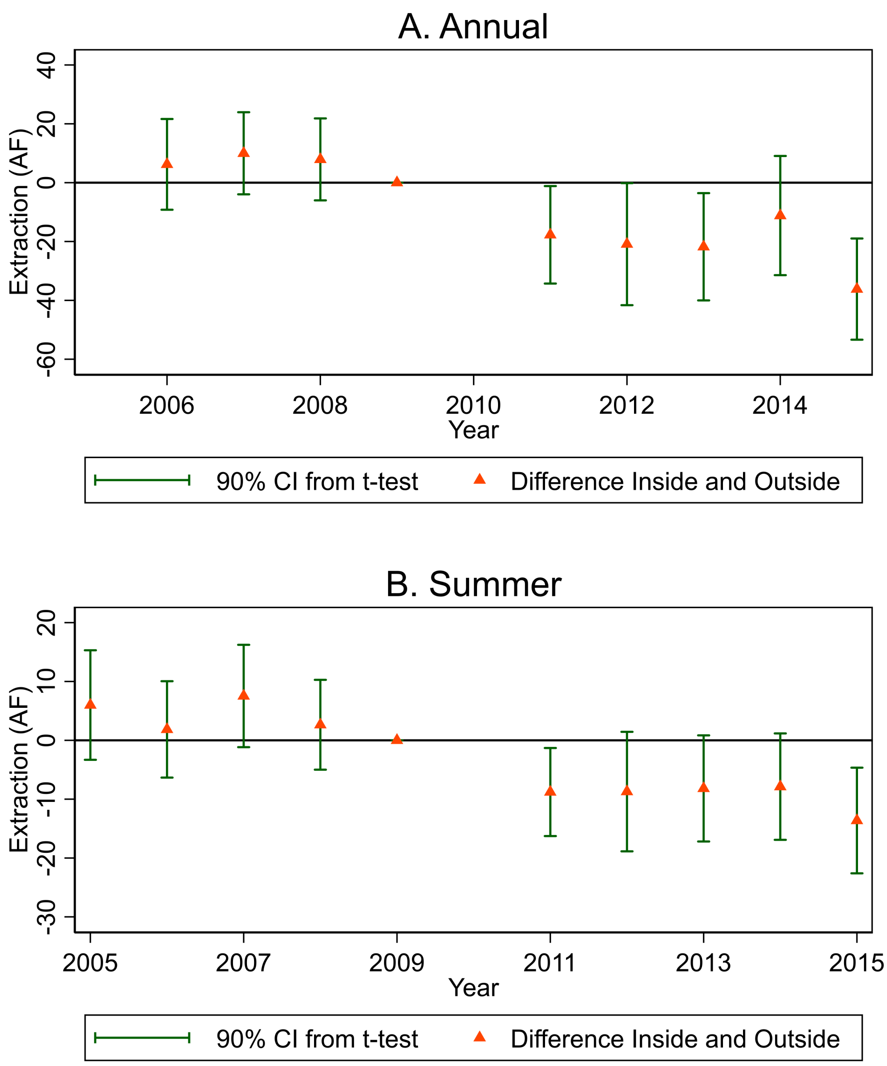
Identification of the price effect requires that in the absence of a switch from a single to region-specific prices, differences in water use across regions would be fixed over time. While we cannot directly test this assumption, we can lean on the long panel of water use to test for differences in annual and summer groundwater extraction between farms inside and outside the Delivered Water Zone prior to the price split. As shown in Figure 3, one unique feature in our panel is that prior to the price split all users simultaneously experienced an identical and large price decrease. This provides an opportunity to test if users in each zone responded differentially to the same price change.

Figure 4 plots estimates of the interaction terms from the estimation of equation (2), as well as the 90% confidence intervals where period 0 is defined as 2009, or two years preceding the price split. In the years preceding the price split, we fail to reject that the difference in average annual water use between farms located inside and outside the zone is statistically different than the 2009 difference in water use. Summertime differences in water use across the two zones in each of the four years spanning 2005 to 2008 are also not statistically different from the 2009 difference in summertime use.

In a second test for pre-treatment trends, we regress water use on a linear time trend, an indicator variable denoting whether or not the farm is located within the DWZ, and the interaction of the two. The sample in this indirect test for parallel trends is restricted to pre-treatment years and is no longer balanced. Results in Appendix Table 3 indicate no differential trend in pre-treatment water use across farms located inside and outside the DWZ. While we cannot directly show that the parallel trends assumption holds, these two tests provide indirect evidence in support of it.

Identification also hinges on the stable unit treatment value assumption. In our setting, this requires that water use for farms located outside of the DWZ remain unaffected by the price increase experienced by users inside the zone. A violation of this assumption would occur if, for example, pumping decisions taken by farmers inside the zone affected the

Figure 4: Groundwater Extraction Event Study



Note: The figure plots differences in groundwater extraction across pricing regions relative to 2009, or two years prior to the price split, conditional on parcel and county-year fixed effects. The sample is comprised of wells with extraction data observed in all years spanning 2005 to 2015. Data from 2010 have been removed. The vertical lines denote 90% confidence intervals. The top panel shows annual aggregate groundwater use and the bottom panel focuses on summertime use only.

water quality or depth to the water table for users outside of the zone. While we cannot demonstrate that this assumption holds, we empirically test for two spillover effects: water quality and depth to the water table.

Despite the absence of differential baseline trends in water use across zones, features of our institutional setting raise the possibility that water use could have trended differently in the two regions even without the price change. One issue is that the Delivered Water Zone serves as an assignment mechanism for recycled water deliveries, with only farms located inside the zone eligible to purchase these supplies.[8] Changes in contemporaneous or past recycled water deliveries may lead to differential trends in groundwater use across the zones even in the absence of the price split. Differential trends in water use may also arise because of region-specific changes in pumping costs and groundwater quality. Saltwater intrusion and the resulting changes in groundwater salinity served as the motivation for volumetric pricing in the Pajaro Valley, and vary across zones and over time. The depth to the water table, and hence the energy cost required to pump a unit of groundwater, may also trend differently across the two regions.

To examine the robustness of our results to each of these potential region-time varying confounding observables, we augment equation (1) and estimate,

$$Y_{irt} = \alpha_i + \phi_{ct} + \beta T_{rt} + \omega' X_{rt} + \varepsilon_{irt}. \tag{3}$$

where X_{rt} represents region-quarter recycled water deliveries (current and previous), groundwater salinity, and/or groundwater depth. While data are available for each of these observables, the time coverage is limited. For this reason, we construct a balanced panel comprised of time periods where all region-quarter variables are observed, and measure water use quarterly as opposed to annually.

[8] In the Pajaro Valley, available recycled water deliveries are exhausted each quarter because recycled water rates are always less than the full cost to pump groundwater. Since prices do not operate to allocate this scarce supply, we include instead aggregate and binding water deliveries as a control in a robustness check.

6 Results

We begin by presenting results on the average impact of the introduction of regional water pricing on water use, and show the robustness of our results to confounding factors and potential spillovers. We then map out the dynamics of the response over 5 years, which provides insight on the applicability of short-run estimates as a proxy for the longer-run response.

6.1 Average Impact on Water Use

Table 2 reports the average effect of the price split on annual groundwater extraction. Column (1) presents results from the estimation of the simple difference-in-differences model set forth in equation (1); column (2) conditions on parcel fixed effects; column (3) further adds year fixed effects; and column (4) includes county-year fixed effects.

Our results highlight that the discrete increase in water prices for farms inside the DWZ led to a substantial reduction in annual groundwater use. Our preferred specification in column (4) reveals that this price change induced on average a 28.15 AF or 21.8% reduction groundwater use in the 5 years following the price split. This result implies that on average over a five year period groundwater demand is price elastic with a calculated elasticity of -1.0. Our finding that agricultural groundwater is perfectly price elastic aligns with existing work that reports an average price elasticity of -0.77 over a three-year period (Smith et al., 2017).

We explore the robustness of our results to potential time-varying zonal confounding factors in the latter portion of Table 2, and to the choice of sample, unit of observation, and alternative spatial error clusterings. We begin by reporting in column (5) results from our preferred difference-in-differences specification, except that groundwater is now measured at the quarterly time step. We find that conditional on county-year fixed effects, the price split reduced quarterly groundwater extraction by 9.02 AF per quarter. Controlling for county-year shocks in our setting is crucial since water savings are often achieved via land use changes, and land values are likely to vary over time across the counties. We also find that the price response remains stable conditional on the inclusion of contemporaneous recycled water deliveries (col. 6), contemporaneous and past recycled water deliveries (col. 7), groundwater quality as measured by chloride (col. 8), depth to the water table (col. 9), and the combination of all three (col. 10). In Appendix Tables 8, 9, and 10, we demonstrate the insensitivity of our results to the (i) use of the balanced or unbalanced panel of parcels, (ii) measurement of extraction at the well or parcel level, and (iii) clustering of standard errors at higher spatial resolutions.

Conditioning on recycled water deliveries allows us to directly account for the possibility that current and past recycled water deliveries are correlated with both pricing zones and groundwater extraction. As shown in columns (6) and (7), after controlling for contemporaneous and lagged quarterly recycled water deliveries, the price increase reduces quarterly groundwater extraction by 9.7 to 10.5 AF. Appendix C provides visual evidence to further demonstrate the robustness of the price response. Collectively, our results highlight that the price-induced reduction in water use is not driven by an increase in recycled deliveries for farms located inside the DWZ.

The stability of our results to the inclusion and exclusion of water quality and depth to the water table also provides indirect evidence to support the stable unit treatment value assumption, which requires that outcomes for control farms be unaffected by groundwater pricing for treated farms. The concern is that reductions in groundwater extraction for users inside the DWZ could increase groundwater extraction for control farms via the channels of groundwater quality and/or depth to the water table.[9] The insensitivity of our estimates to the inclusion of these variables suggests that groundwater demand for farms outside the zone is unaffected by changes in groundwater depth or groundwater quality.

[9]For example, given groundwater-surface water interconnections, extraction-induced changes in upstream return flows could contribute to downstream aquifer levels via rivers and canals. Our results suggest that this spillover effect is minimal.

Table 2: Impact of Regional Pricing on Groundwater Extraction

	Annual Extraction (AF)				Quarterly Extraction (AF)					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Inside × Post	-27.24**	-29.18**	-29.12**	-28.15**	-9.02***	-10.48***	-9.70***	-9.97***	-8.95***	-10.64***
	(11.47)	(11.47)	(11.47)	(10.97)	(3.12)	(3.50)	(3.41)	(3.31)	(3.11)	(3.53)
Post-2010	-2.20	-2.06								
	(1.35)	(1.36)								
Inside	66.28***									
	(17.78)									
Constant	62.98***	70.55***	64.92***	65.93***	15.66***	15.04***	14.77***	20.20***	11.78***	11.37***
	(3.87)	(0.98)	(1.43)	(1.70)	(0.61)	(0.65)	(0.63)	(2.36)	(4.08)	(4.04)
Mean	129.3	129.3	129.3	129.3	29.7	29.7	30.1	29.7	29.7	29.7
Observations	5,598	5,598	5,598	5,598	12,640	12,640	12,469	12,640	12,640	12,640
Parcel FE		✓	✓	✓	✓	✓	✓	✓	✓	✓
Year FE			✓							
County-Year FE				✓	✓	✓	✓	✓	✓	✓
Quarter-Year FE					✓	✓	✓	✓	✓	✓
Recycled Deliveries						✓	✓			✓
Lagged Deliveries							✓			
Groundwater Salinity								✓		✓
Depth to Groundwater									✓	✓

Notes: This table reports results from the estimation of an OLS regression. Standard errors (reported in parentheses) are clustered at the parcel level. Extraction is measured in acre-feet (AF). Means reported are average annual or quarterly extraction (AF) inside the DWZ prior to treatment. *, **, *** denote significance at the 10%, 5%, and 1% levels.

6.2 Dynamic Effects on Water Use

The annual and summertime effects of the price split on agricultural water use in each of the first five years spanning the price split are presented in Figure 4. Coefficient estimates correspond to the β_τ set forth in equation (2), are inclusive of parcel and county-year fixed effects, and are measured relative to the year preceding the price split.

This figure makes clear that the response to the price increase grows over time, and highlights that short-run estimates meaningfully differ from those estimated in the longer-run. Between the first and fifth year following the price increase, the annual reduction in water use doubled from -17.7 AF in 2011 to -36.2 AF by 2015, and a Wald test rejects that the two coefficients are equal with over 95% confidence (t-stat 2.57).[10] A similar trend is observed when comparing summertime water use, with the -8.8 AF first year response growing to -14 AF by year five. Appendix D which translates these reductions into elasticities highlights a doubling of the elasticity from -0.86 to -1.97 over the five year window.

When compared to the existing literature, our estimates find farmers to be more price elastic in the short-run. The general consensus in the literature is that in the short-run agricultural groundwater demand is price insensitive, with elasticity estimates ranging from -0.10 to -0.48 (Bruno and Jessoe, 2021b; Schoengold, Sunding and Moreno, 2006).[11] The more elastic response detected in our setting may arise because of the magnitude of the price increase, salient and improved information about prices, or features of the hydrological and agricultural setting. With the exception of Bruno and Jessoe (2021a), the existing literature leans on variation in the energy cost of extraction to identify the short-run elasticity of demand. In these settings, groundwater extraction costs may not be salient since they are bundled into electricity expenditures, and imperfect informa-

[10] We also reject that estimated response in three of the first four years of treatment are equal to the reduction in 2015. For a full set of Wald t-tests for pairwise comparisons between coefficient estimates over time, see Table 5 in Appendix D.

[11] An exception is Burlig, Preonas and Woerman (2019). Using short-run variation in the energy cost of extraction, this study estimates a price elasticity of -1.12

tion about the mapping between energy expenditures and water consumption may hinder customer responsiveness. Contrast this with our setting, where farmers face and are responding to a direct, salient (due to the voting process) and uniform fee for groundwater consumption. Differences in the elasticity of demand may also arise due to the magnitude of the price change. The $33 AF price increase experienced in our setting amounts to a 71% increase in the energy cost to extract an AF of groundwater, and far exceeds the energy price differentials that are the focus of existing work. Lastly, agricultural and hydrological differences may explain the larger elasticity. Our study occurs in an area that relies exclusively on groundwater and grows a diverse array of high-value crops.

Shocks that differentially impact users inside and outside the zone in 2015 may explain the increased price responsiveness in the fifth year after the price change. While we cannot rule out this possibility, we provide evidence that energy price shocks and anticipation about upcoming rate changes are unlikely to drive the differential response. In our setting, PG&E provides electricity to all users. Though all consumers face the same rate schedule, an equivalent price increase will result in a differential percentage change in the cost of groundwater extraction for users inside and outside the zone. For this reason, electricity price shocks may have a different impact on users inside and outside the zone. Appendix Figure 5, which plots electricity rates over the study period, indicates that energy price shocks are unlikely to explain the 2015 response. Energy prices are relatively stable over the study period, and do not exhibit any swings in 2015.

A new rate schedule for groundwater extraction took effect in July 2015, and a concern is that anticipation about this upcoming rate change and the rate change itself may drive the 2015 response. We test for this two ways. First, regulatory documents point to a fundamental change in the rate-setting process in 2015. Specifically, water fees fell under Proposition 26, and as a result the water district could shorten the timeline for the rate-setting process and did not require voter approval for the rate change.[12] The proposed

[12]Historically, water fees were subject to Proposition 218 and as a result proposed rate changes followed

rate schedule was made public and adopted on May 20, 2015, not voted upon by property owners, and went into effect on July 1, 2015. Given that there was a short window between the adoption and implementation of the rate change and it was not subject to a vote, we hypothesize that anticipation plays a limited role. We empirically test for this by excluding June, July and August water consumption data from our sample, and estimating equation (2). This sample is comprised of data from September to May of each year, and excludes (with the exception of 11 days) the window after the announcement of the 2015 price change but before its implementation. Appendix Figure 7 reports our results. We continue to find that farmers are more responsive to the price change five years post-treatment. The rules governing water fees in 2015 and empirical evidence collectively suggest that anticipation does not explain the differential response estimated in 2015.

Figure 4 also raises the possibility that the estimated 2015 response is simply an anomaly. To examine if the large reduction estimated in year 5 is an aberration or a longer-run response to water prices, we extend our panel to include data from the fiscal year 2015 to 2016. This additional year allows us to test the persistence of the effects beyond 2015 but is subject to the one major caveat that in 2016 the water agency introduced a new five-year rate schedule that included a price increase for all users. This makes it impossible to disentangle the short-run effect of the price increase from the longer-run differential. The reason we choose to test the robustness of our results to the inclusion of 2016 is because, while there is a new rate schedule for all users, in 2016 there is no change in the price differential between zones. We estimate equation (2) on the extended panel to test if the treatment effects estimated in year 5 extend into year 6. The estimated effects in 2016, shown in Table 6 in Appendix E, in both the annual and summer event studies provide some supporting evidence that longer-run effects estimated in 2015 may persist.

Our annual results suggest that the margins of response available to farmers in the

a lengthy process that required voter approval. A court ruling during the 2015 rate process concluded that water fees were subject to Proposition 26 (though more recent decisions have ruled otherwise).

short term may differ from the suite available in the longer run. In the short term, farmers may respond to a price increase on the intensive margin, reducing the amount of water applied per acre of a given crop. However, land use decisions such as fallowing, crop switching or converting land out of agriculture may require a longer time horizon, and not manifest as a short-run response. Our findings underscore that the time step for water use decisions is long and estimates of water use change using short-run variation in prices may fail to characterize the true response.

7 Policy Implications of the Dynamic Response

To understand the policy importance of the time-step chosen for estimation, we use our one-year and five-year econometric estimates to simulate basin-wide water conservation from the price increase, ceteris paribus. Our back-of-the-envelope exercise reveals that substituting short-run estimates in for longer-run estimates would yield fundamentally different policy conclusions.

In 2014, California passed the Sustainable Groundwater Management Act (SGMA), a historic statewide regulation that requires the more than 140 groundwater (sub)basins in the state to reach and maintain sustainable groundwater levels by 2040. Implementation of the regulation is occurring at the local level, with over 250 Groundwater Sustainability Agencies (GSAs) responsible for submitting and implementing Groundwater Sustainability Plans. These plans define sustainability and set forth the policy instruments that will be used to meet sustainable groundwater levels. The Groundwater Sustainability Plan for Pajaro Valley seeks to reduce overdraft by 80% and achieve reductions of 5,000 AF per year by 2023. This plan specifies that the conservation target will be measured on a basin-wide scale, and that pricing should be investigated as a conservation tool.

To examine if groundwater pricing could achieve the 5,000 AF per year conservation target, we calculate the basin-wide water use changes five years after the price split using short-run and five-year estimates. Aggregation from the parcel to the service territory in this back-of-the-envelope exercise poses a challenge since the outcome variable used for estimation in equation (2) measures water use on a parcel, and parcels differ in size. To scale our results to the service territory, we standardize our outcome variable by parcel size and weight the event study regression in equation (2) by parcel area. Coefficient estimates, which are reported in Appendix Table 7, should be interpreted as the effect of the price split on water use per acre of land. We then predict the basin-wide change in water use had all parcels been exposed to the 21% price increase by multiplying these effects by the total agricultural acreage in the Valley: 24,419 acres.

We find that dynamics in the price response alter the policy conclusions drawn from the price split. In the first year following the price split, the expected water savings amount to 5,055 AF and just meet the 2023 water conservation goal. If one were to use this short-run estimate as a proxy for the longer-run response, the policy implication is that the price split would have achieved the 5,000 AF or 10% conservation target without causing an undue tax burden to farmers. However, our weighted regression results reveal that the water response per acre increases three fold over time, and that the price split would induce water savings of 14,846 AF five years later. Accounting for dynamics indicates that the 21% price increase generates water conservation savings that exceed by three-fold those set forth in the Water Management Plan. If the 5,000 AF target was set efficiently, then PV Water's price increase, and more generally the failure to account for longer-run time steps in the decision making process, would introduce a new deadweight loss since agricultural water would be underconsumed.

Our estimates are specific to a time period that precedes the Sustainable Groundwater Management Act; the short-run and long-run elasticities may change depending on the suite of policies that are used by a groundwater agency to comply with SGMA. If a number of prescriptive policies accompany SGMA, then differences between short-run and long-run elasticities might shrink because farmers can no longer avail themselves of the full suite of responses. Alternatively, these differences may grow if new policies under SGMA provide farmers with both groundwater fees and subsidies or incentives, e.g., for on-farm groundwater recharge or land repurposing. Farmer response to groundwater pricing in the short and long run will also evolve with the water regulatory landscape in the state. Changes in the allocation of water rights and the rules regulating water transfers will likely alter price elasticites in the short and long run. As such our results should not be viewed as predictions but instead interpreted as the impact of water prices conditional on the current regulatory environment.

8 Conclusion

The Western U.S., Europe, China and parts of Africa are currently experiencing severe drought, and with climate change many of the world's most productive agricultural regions will suffer from increased water scarcity and water variability. Agricultural water pricing may be a critical instrument to cost-effectively curtail demand during drought and manage increasingly scarce resources. Understanding agricultural firm response to pricing both in the short and longer-run is crucial to the design and deployment of prices to regulate water use. In this paper, we quantify the dynamic impacts of pricing groundwater extraction. We do so by leveraging a large and permanent shift from a single price for groundwater pumping to two geographically distinct prices, and estimating how farmers respond in each year following the price increase.

We find that average treatment effects obscure important dynamics in firm response to prices. On average, the 21% price increase reduced groundwater extraction by 22% following the price split. Over time, however, firms become increasingly responsive to prices with the implied price elasticity doubling between the first and fifth year after the price change. The margins of response available to farmers – both in the short run and in the long run – are likely to change across geographies, with implications for the external validity our results. Differences in the available margins of adjustment will grow as we move further from the Pajaro Valley, though agriculture in our study region shares several important features with agriculture in the rest of California: farming depends almost exclusively on irrigation; available crops consist of a mix of annuals and perennials; and the available set of crops are numerous, diverse, and relatively high value. What is less certain is dynamics in the response to groundwater pricing outside of California, where agriculture is often rainfed and a different portfolio of crops are grown.

Our work underscores the limitations of leaning on short-run estimates in the design and evaluation of long-run policies. Many decisions ranging from driving behavior to electricity consumption are longer run, with purchasing decisions occurring over a multi-year window. A back-of-the-envelope calculation highlights the cost of using short-run estimates for longer-run policy in the context of California's recent groundwater regulation. Short-run estimates indicate that under the price increase the groundwater basin would just comply with the conservation target, but year five estimates imply the basin would exceed it by three fold. If the target was set efficiently, then the failure to incorporate dynamics in policy design would introduce efficiency costs.

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A Appendix: Supplementary Data

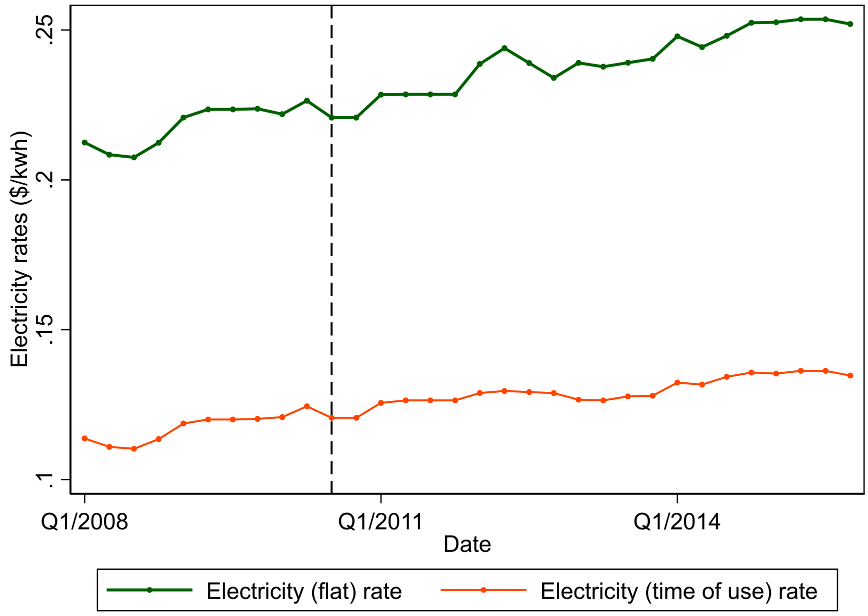
In this section, we detail sources, collection, and construction details for supplementary data. Quarters are defined by PV Water's meter reading schedule, which is one month off a typical calendar year. The first quarter encompasses December, January, and February pumping, the second quarter includes March, April, May, and so on. Recycled water deliveries are also reported by PV Water quarters. Careful attention was given to other variables to appropriately align changes.

Groundwater prices: Water prices were recorded manually from agency documents (historical ordinances). The 2010 bifurcation in prices between zones occurs in October, the middle of quarter 4. Similarly, subsequent price changes occur in July, the middle of quarter 3. We make the assumption that October price changes occur at the start of Q4 and July price changes occur at the start of Q3. The same assumption holds for delivered (recycled) water rates.

Groundwater quality: Quarterly information on groundwater quality including chloride levels, our proxy for salinity, comes from a rich network of 200 monitoring wells maintained by the water agency. We used a natural neighbor spatial interpolation tool to estimate quarterly zone-level chloride levels from extensive sampling of the monitoring wells. Data on groundwater quality were aggregated in time at the quarter-level with quarters determined by PV Water's meter reading schedule. Groundwater quality data feature gaps in collection, leading to an unbalanced panel of observations. Several time periods within our sample window had an insufficient number of observations to complete the nearest neighbor spatial interpolation.

Groundwater depth: A spatial variable measuring the depth to the groundwater table at each well was constructed from groundwater depth contour maps provided by the water agency. These are recorded once a year in the fall. After accounting for the land elevation, these maps provide an annual snapshot of the depth to the water table which

Figure 5: PG&E Electricity Prices



Note: The dashed line marks the point in 2010 when the price split between zones occurred. While rising slightly over time, electricity rates in this region remained fairly stable over our sample period.

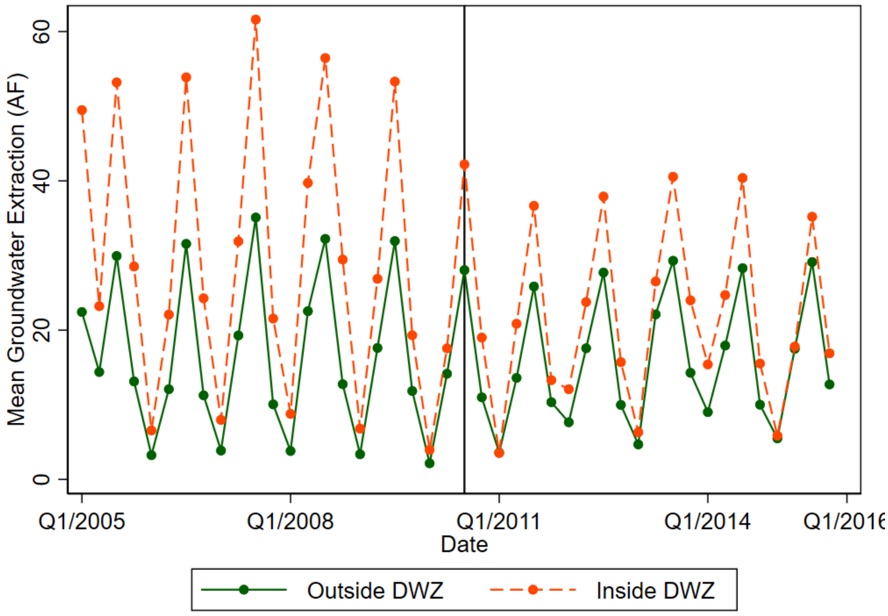
is important for understanding the cost of extracting groundwater from below. Data on annual groundwater depth became available in 2008.

B Appendix: Water Use and Parallel Trends

Figure 6 shows the strong seasonal patterns and trends in average well-level groundwater use by pricing zone over time. On average, users inside the DWZ extract at greater levels. Water use visually declines after the price split for those inside the DWZ.

In a test for pre-treatment trends, we regress water use on a linear time trend, an indicator variable denoting whether or not the farm is located within the DWZ, and the interaction of the two. The sample in this indirect test for parallel trends differs in two dimensions from the one used in the event study: the panel is restricted to pre-treatment years and is no longer balanced. Columns (1) and (2) of Table 3 report results for annual

Figure 6: Average Extraction by Zone



Notes: The figure shows average quarterly groundwater extraction across the two regions. The average was computed at the farm level. The vertical line denotes the introduction of the price treatment in October 2010.

water use and columns (3) and (4) report results for quarterly water use. We find no differential trend in pre-treatment water use across farms located inside and outside the DWZ, and this result is insensitive to an annual or quarterly measure of water use.

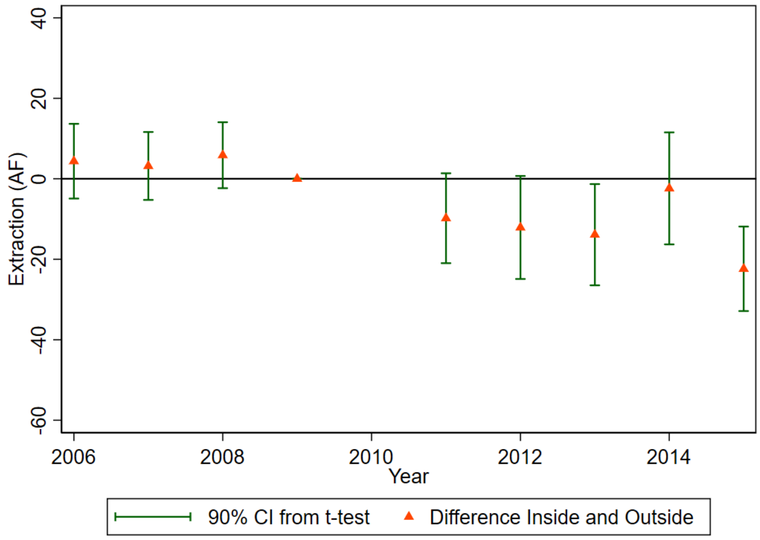
Table 3: Test for Pre-treatment Regional Trends in Extraction

	Annual Extraction		Quarterly Extraction	
	(1)	(2)	(3)	(4)
Time	-1.59	-5.85***	0.51***	0.18
	(1.37)	(1.99)	(0.11)	(0.13)
Inside × Time	-4.46	-4.28	0.21	0.18
	(3.36)	(3.39)	(0.19)	(0.19)
Inside	49.86***	44.86***	5.81	5.19
	(11.17)	(11.24)	(3.88)	(3.91)
Observations	3,509	3,509	10,971	10,971
Time FE	✓		✓	✓
County-Year FE		✓		✓

Note: Table reports results from a regression of regional time trends on extraction. Time FE refer to year FE in columns (1)-(2) and quarter-by-year FE in columns (3)-(4). Standard errors are clustered at the parcel level. *, **, *** denote significance at the 10%, 5%, and 1% levels.

In Figure 7, we test the sensitivity of our results to the exclusion of quarter 3. This is motivated by two concerns. First, quarter 3 meter readings in 2015 reflect water use under the pre-July 2015 and post-July 2015 price regimes, and we want to ensure that this new price increase is not confounding our estimates. Second, users were aware of the a new rate schedule beginning May 20, 2015 and we want to account for the possibility that anticipation of the upcoming price change is driving the 2015 response. Neither the misalignment between when the price changes and when the meter readings occur nor anticipation about the upcoming price changes appear to be driving our results.

Figure 7: Robustness of Annual Groundwater Use Event Study to Exclusion of Q3



Note: The figure plots differences in annual groundwater extraction across regions relative to 2009 conditional on county-year fixed effects where a year is defined as Q4 through Q2. Data from 2010 have been removed. The vertical lines denote 90% confidence intervals.

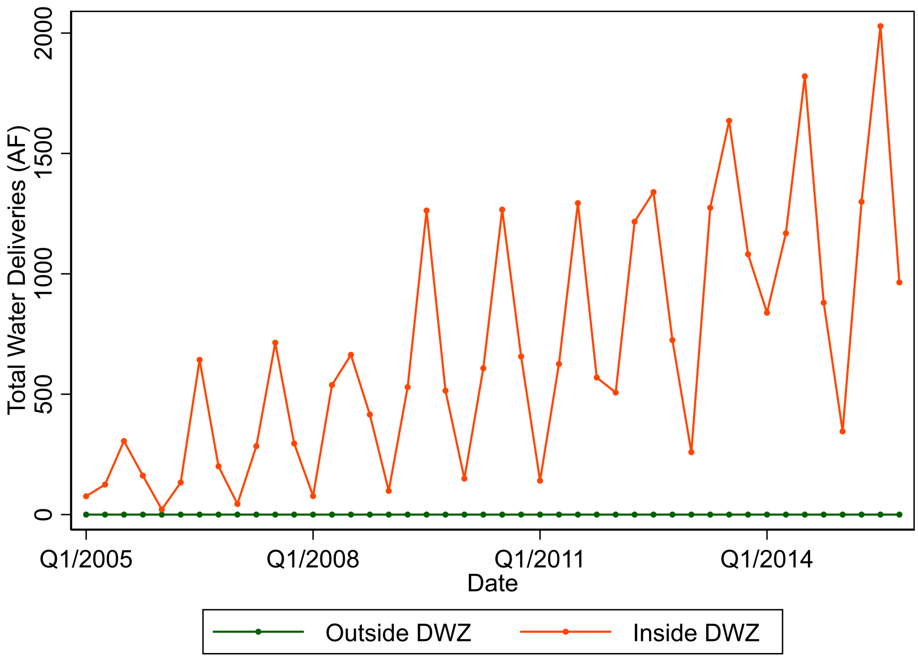
C Appendix: The Influence of Recycled Water

Recycled water deliveries began in 2002 in an effort to reduce seawater intrusion. The idea was to supply coastal groundwater pumpers with an alternative source of irrigation water to reduce groundwater extraction in sensitive coastal regions where overpumping could lead to saltwater intrusion of the underlying aquifer. The agency's capacity to supply recycled water ramped up over time and is reflected in the gradual increase in recycled water deliveries each year shown in Figure 8. Seasonal fluctuations reflect irrigation water demands.

While recycled water is priced by the agency, recycled water prices are intentionally set below that of groundwater, even after accounting for energy extraction costs, because the agency wants to exhaust its recycled water supplies.[13] To the best of our knowledge,

[13]Ordinance 2004-03 establishes a formula for setting recycled water delivery rates and explicitly ties the recycled water rate to the groundwater pumping fee. The delivered water charge is the sum of the amount of the groundwater augmentation charge and the estimated avoided cost of pumping groundwater. The initial delivery charge was set at $262 per AF. The first component of the delivery charge is automatically adjusted if the groundwater augmentation charge is changed at any time, either increased or

Figure 8: Recycled Water Deliveries by Zone



Notes: The figure shows recycled water deliveries (made available to users in the Delivered Water Zone only) over time. These deliveries gradually grew from 1.2% of the supply in 2005 to 19% by 2015. This proportional change over time reflects both the increase in recycled water and the decrease in groundwater extraction observed over time.

the allocation mechanism of recycled water supplies among farms in the DWZ is not detailed in agency documents. One plausible allocation is an equal share among pumpers inside DWZ, which would be consistent with the allocation schemes of other irrigation districts in California. Another reasonable prioritization would be based on water quality, delivering more recycled water to farms with greatest seawater intrusion of their wells.

While recycled water deliveries remain a small portion of the overall water supply throughout our sample, one concern is that the increase in recycled water deliveries over time correlates with the increase in water prices, potentially confounding estimation of treatment effects. Columns (6) and (7) of Table 2, which report results from specifications in which groundwater and recycled water deliveries are measured at the quarterly level, indicate that groundwater response to the price increase is insensitive to the inclusion or exclusion of lagged and contemporaneous recycled water deliveries.

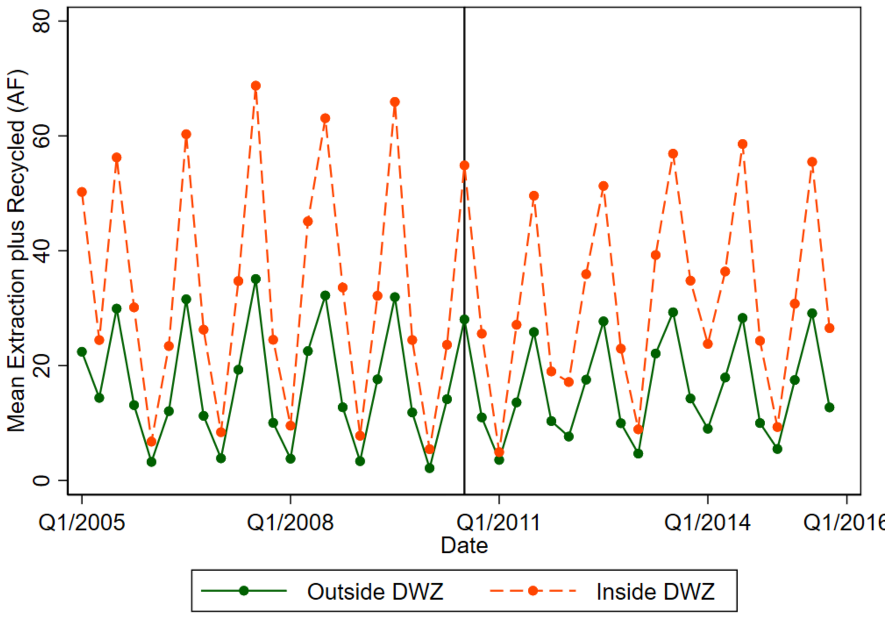
We provide further visual evidence on the stability of our results to this concern. Figure 9 plots average gross water use by zone over time. We add an estimate of well-level recycled water to the average groundwater extraction of wells inside the DWZ and plot this over time against average groundwater extraction outside the DWZ. A look at Figure 9 reveals a reduction in water use following the price increase at the end of 2010 that appears to be disproportionately large for those inside the DWZ, despite the additional recycled water deliveries. Not surprisingly, the disproportionate reduction is not as pronounced as that in Figure 6.

D Appendix: Elasticity Calculations

A price elasticity of groundwater demand characterizes the percentage change in groundwater extraction due to a percentage change in groundwater price. The percentage price change observed in this study is a 21% increase, which is the difference between the price

decreased. Historical ordinances regarding rate changes over time can be accessed on the agency's website here: https://www.pvwater.org/director-agendas

Figure 9: Average Gross Water Use



Note: The figure shows average quarterly gross water use across the two regions (groundwater extraction plus recycled water deliveries). Aggregate recycled water deliveries was divided by 100, the number of wells inside the DWZ then added to average farm-level groundwater extraction. Gross water use outside the DWZ is equivalent to average groundwater extraction in Figure 6. The vertical line denotes the introduction of the price treatment in October 2010.

paid by users inside and outside the zone after the price split, expressed relative to the price for users outside the zone in the post period:

$$\%\triangle P = \frac{(P_{inside=1,post=1}) - (P_{inside=0,post=1})}{P_{inside=0,post=1}}. \quad (4)$$

To calculate the corresponding percentage change in groundwater extraction, we want to express our estimated treatment effects as a function of an unobserved counterfactual: what the inside group would have extracted in the post period had the relative price increase not occurred. We predict the average post period groundwater extraction for the inside zone net of treatment effects using regression results from the estimation of equation (1). We then use this to impute elasticities using the treatment effect on water use:

$$\eta = \frac{\%\triangle Q}{\%\triangle P}. \quad (5)$$

First using our average treatment effect from column (4) of Table 2, we calculate an average price elasticity of groundwater demand of -1.05. We follow a similar exercise using the estimated equation from the event study framework presented in equation (2) to calculate elasticities over time.[14] With one exception, the elasticity grows over time in absolute value, suggesting that firms are more responsive to the price change in subsequent years. The elasticity estimated five years after the price split suggests farmers are quite price responsive.

Table 4: Imputed Elasticities over Time

Year	Elasticity
2011	-0.86
2012	-0.95
2013	-0.97
2014	-0.37
2015	-1.97

[14]We calculate counterfactuals and impute elasticities using an estimating equation that substitutes a zone indicator for parcel fixed effects and uses year fixed effects instead of county-year fixed effects. Treatment effects are similar between specifications.

Table 5: Wald test pairwise comparisons

	$t+1$ 2011	$t+2$ 2012	$t+3$ 2013	$t+4$ 2014	$t+5$ 2015
2011	–	0.44	0.57	-0.70	2.57
2012	-0.02	–	0.11	-0.96	1.61
2013	-0.19	-0.13	–	-1.22	1.84
2014	-0.26	-0.20	-0.09	–	2.99
2015	1.38	1.09	1.55	1.78	–

Note: The table reports t-statistics of a Wald test between each estimated coefficient in the event study regressions. Wald test t-stats for results at the annual level are reported along the top diagonal. Summertime pairwise comparisons are reported in gray along the bottom diagonal.

E Appendix: Event Study Results

To examine if the large reduction estimated in year 5 is an anomaly or a longer-run response to water prices, we extend our panel to include data from the fiscal year 2015 to 2016 by re-estimating equation (2) on the extended panel. The estimated effects in 2016, shown in Table 6 for both the annual and summer event studies, provide some supporting evidence that longer-run effects estimated in 2015 persist.

Table 7 estimates equation (2) with observations weighted by parcel size for use in the back-of-the-envelope policy simulation. Coefficient estimates should be interpreted as the effect of the price split on water use per acre of land.

Table 6: Impact of Regional Pricing on Summer and Annual Extraction

	(1) Annual Extraction	(2) Summer Extraction
Inside × **1**(2011)	-17.72*	-8.79*
	(10.07)	(4.55)
Inside × **1**(2012)	-20.90*	-8.71
	(12.61)	(6.17)
Inside × **1**(2013)	-21.79**	-8.18
	(11.08)	(5.48)
Inside × **1**(2014)	-11.19	-7.87
	(12.31)	(5.50)
Inside × **1**(2015)	-36.18***	-13.63**
	(10.46)	(5.46)
Inside × **1**(2016)	-34.66***	-16.65***
	(11.49)	(5.43)
Inside × **1**(2005)		5.99
		(5.66)
Inside × **1**(2006)	6.22	1.85
	(9.37)	(4.98)
Inside × **1**(2007)	9.98	7.53
	(8.48)	(5.29)
Inside × **1**(2008)	7.91	2.64
	(8.46)	(4.64)
Constant	80.14***	31.85***
	(1.54)	(0.93)
Observations	6,240	6,424
Parcel FE	✓	✓
County-Year FE	✓	✓

Notes: This table reports results from the event study regression with annual data. Standard errors (reported in parentheses) are clustered at the parcel level. Extraction is measured in acre-feet (AF). *, **, *** denote significance at the 10%, 5%, and 1% levels.

Table 7: Impact of Regional Pricing on Annual Per-Acre Extraction

	(1) Per-acre Extraction	(2) Aggregate Counterfactual
Inside × $\mathbf{1}$(2011)	-0.207	-5,054.7
	(0.181)	
Inside × $\mathbf{1}$(2012)	-0.344	-8,400.1
	(0.224)	
Inside × $\mathbf{1}$(2013)	-0.384*	-9,376.9
	(0.199)	
Inside × $\mathbf{1}$(2014)	-0.237	-5,787.3
	(0.220)	
Inside × $\mathbf{1}$(2015)	-0.608***	-14,846.7
	(0.192)	
Observations	5,589	
Total Acreage		24,419

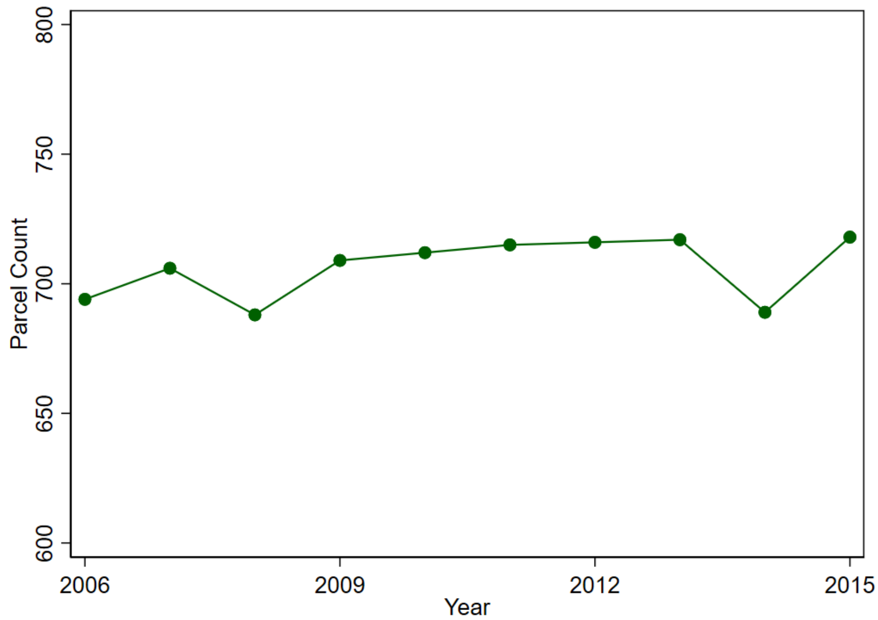
The table reports results from a weighted OLS regression on per-acre extraction. Standard errors are clustered at the parcel level. *, **, *** denote significance at the 10%, 5%, and 1% levels.

F Appendix: Balance of Sample

By focusing on the balanced sample in the main results, we eliminate firm exit as a possible explanation of the dynamic treatment effects that we estimate. A look at the count of unique parcels in each year of our sample in Figure 10 suggests that the number of agricultural parcels over time is relatively stable. To further explore the robustness of our results to our choice of sample, Table 8 reports results from the estimation of equation (1) using quarterly data on the unbalanced panel.[15] Our results using the unbalanced sample mirror those reported using the balanced panel.

[15] Note that variables such as groundwater salinity and depth feature gaps in the data; we limit our sample to parcels that contain observations for each of these explanatory variables for consistency across specifications.

Figure 10: Parcel Count by Year



Note: The figure shows how many parcels come in and out of the sample.

Table 8: Impact of Regional Pricing on Quarterly Groundwater Extraction

	Groundwater Extraction (AF)					
	(1)	(2)	(3)	(4)	(5)	(6)
Inside × Post	-7.31***	-8.84***	-8.37***	-8.50***	-7.26***	-9.18***
	(2.36)	(2.81)	(2.78)	(2.56)	(2.35)	(2.84)
Constant	13.50***	13.09***	12.96***	17.22***	10.70***	11.53***
	(0.50)	(0.53)	(0.56)	(1.98)	(3.36)	(3.43)
Mean	25.83	25.83	26.00	25.83	25.83	25.83
Observations	16,101	16,101	15,869	16,101	16,101	16,101
Parcel FE	✓	✓	✓	✓	✓	✓
Quarter-Year FE	✓	✓	✓	✓	✓	✓
County-Year FE	✓	✓	✓	✓	✓	✓
Recycled Deliveries		✓	✓			✓
Lagged Deliveries			✓			
Groundwater Salinity				✓		✓
Depth to Groundwater					✓	✓

Notes: This table reports results from the estimation of an OLS regression on an unbalanced panel. Standard errors (reported in parentheses) are clustered at the parcel level. Means reported are average quarterly extraction (AF) inside the DWZ prior to treatment. Extraction is measured in acre-feet (AF). *, **, *** denote significance at the 10%, 5%, and 1% levels.

G Appendix: Aggregation and Clustering

In our main specifications, we aggregate wells to the tax-parcel level and treat each parcel as a farm. This is because our goal is to measure a farm-level response and a single land owner may operate multiple wells. To demonstrate the sensitivity of our results to this choice, Table 9 presents a well-level analysis where the data are not aggregated in this way and shows that results are robust to measuring water use at the well. We find that the price split led to a 20.3 to 21.3 AF reduction in water use. Measured in levels, the well effects are slightly attenuated when compared to the parcel-level response. When expressed relative to mean pre-treatment extraction, the well- and parcel-level responses mirror each other. We find a 18-19% decrease in extraction in response to the price increase.

Table 9: Impact of Regional Pricing on Annual Groundwater Extraction (well-level)

	Annual Extraction (AF)			
	(1)	(2)	(3)	(4)
Inside × Post	-21.31**	-21.31**	-21.31**	-20.29**
	(10.24)	(10.24)	(10.24)	(9.92)
Post-2010	-4.33***	-4.33***		
	(1.37)	(1.37)		
Inside	56.75***			
	(14.67)			
Constant	55.94***	62.16***	56.84***	56.09***
	(3.22)	(0.92)	(1.29)	(1.53)
Observations	5,823	5,823	5,823	5,823
Parcel FE		✓	✓	✓
Year FE			✓	
County-Year FE				✓

Table reports results from an annual difference-in-differences regression at the well level. Standard errors are clustered at the parcel level. Average extraction for wells inside the DWZ prior to treatment is 112.68 acre-feet (AF). *, **, *** denote significance at the 10%, 5%, and 1% levels.

We test the robustness of our results to the decision to cluster standard errors at the parcel level. We created arbitrary grid cells of 400m, 500m, 600m, and 1000m lengths to allow for spatial correlation between neighboring parcels. Spatial grids of 500mx500m, for example, contain 4 average-sized parcels or 9 median-sized parcels. We report average treatment effects from the difference-in-differences regression for a range of alternative clustering schemes in Table 10. We find that results are robust to alternative spatial clusters.

Table 10: Impact of Regional Pricing on Annual Groundwater Extraction

	Annual Extraction (AF)				
	(1)	(2)	(3)	(4)	(5)
	parcel	400m	500m	600m	1km
Inside × Post	-28.15**	-28.15**	-28.15***	-28.15***	-28.15***
	(10.97)	(11.10)	(9.96)	(10.16)	(10.54)
Constant	65.93***	65.93***	65.93***	65.93***	65.93***
	(1.70)	(1.70)	(1.62)	(1.64)	(1.70)
Observations	5,598	5,598	5,598	5,598	5,598
Parcel FE	✓	✓	✓	✓	✓
County-Year FE	✓	✓	✓	✓	✓
Clusters	624	531	456	405	222

Table reports results from an annual difference-in-differences regression at the parcel level. Standard errors are clustered at various levels of spatial aggregation. *, **, *** denote significance at the 10%, 5%, and 1% levels.