The Dynamic Impacts of Pricing Groundwater Externalities*

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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 understate the price elasticity of demand and introduce efficiency costs.

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

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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 extreme drought. 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.

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 and annual county shocks 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 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. However, this average treatment effect masks dynamics in the response to water pricing. The reduction in annual water use doubles over a five year
period, with the implied price elasticity of demand growing 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 (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 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 Monterrey Bay and spans parts of Santa Cruz and Monterrey counties, is unusual in that the water district meters groundwater pumping, takes quarterly meter readings, and charges volumetric rates for agricultural groundwater use.

2.1 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.
2.2 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.\footnote{Salinity is also a concern for inland agricultural regions because irrigation leads to a build up of salts in the soil and water over time.}

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.\footnote{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.} Recycled water deliveries began in 2002 and grew over time with increases in treatment capacity as shown in Appendix Figure 6. 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.
Figure 1: 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.

2.3 Assignment Mechanism: Delivered Water Zone

Recycled water supplies provide an alternative source to groundwater, but are 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 1 depicts a map of PV Water’s service area and the boundaries that delineate the two regions: inside the DWZ and outside the DWZ.

The recycled water deliveries that are made available to users within the Delivered Water Zone 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

\[^3^\]One primary delineation between zones was Highway 1. As shown in Figure 1, the land bounded between the coast on the west and Highway 1 on the east was designated as inside the DWZ.
costs to extract an acre-foot of groundwater, recycled water is cheaper than pumping groundwater in the Delivered Water Zone.

2.4 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 2 illustrates the annual per AF price charged in each region between 2005 and 2016. 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 across 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 longer-run effects restricts its attention to the five years following the 21% price increase.

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4 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 = Mar, Apr, May; Q3 = June, Jul, Aug; Q4 = Sept, Oct, Nov. Details can be found in Appendix A.
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 only wells located inside the Delivered Water Zone benefited from recycled water deliveries. The courts sided with Griffith, and the district began charging two different prices based on the DWZ bound-

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

\[\text{[Figure 2: Volumetric Groundwater Prices by Zone]}\]

\[\text{[Diagram showing price changes over time for Inside and Outside DWZ zones]}\]

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

3 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

<table>
<thead>
<tr>
<th></th>
<th>Outside DWZ</th>
<th>Inside DWZ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Count</td>
<td>Mean</td>
</tr>
<tr>
<td><strong>Annual</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extraction (AF)</td>
<td>4,981</td>
<td>61.56</td>
</tr>
<tr>
<td>Pumping price ($/AF)</td>
<td>4,981</td>
<td>146.48</td>
</tr>
<tr>
<td>Recycled deliveries (AF)</td>
<td>4,981</td>
<td>0.00</td>
</tr>
<tr>
<td>Delivered rate ($/AF)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Chloride (mg/L)</td>
<td>4,981</td>
<td>57.47</td>
</tr>
<tr>
<td>Depth to water table (ft)</td>
<td>3,797</td>
<td>134.10</td>
</tr>
<tr>
<td><strong>Quarterly</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extraction (AF)</td>
<td>19,080</td>
<td>17.10</td>
</tr>
<tr>
<td>Pumping price ($/AF)</td>
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<td>146.55</td>
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<td>Recycled deliveries (AF)</td>
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<tr>
<td>Delivered rate ($/AF)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Chloride (mg/L)</td>
<td>15,741</td>
<td>74.10</td>
</tr>
<tr>
<td>Depth to water table (ft)</td>
<td>13,020</td>
<td>126.77</td>
</tr>
</tbody>
</table>

Notes: This table reports observations, means, and standard deviations (SD) for the balanced panel by zone at the parcel level. 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 4 in Appendix B 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 4 reveals that water use declined disproportionately for users inside the zone after the price split.

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. Details on recycled water, including a figure of deliveries over time, can be found in Appendix C. Information on other secondary data sources and the construction of these variables is provided in Appendix A.

4 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. In this set-up we have two farm types ($r \in O,I$) and two time period types ($p \in 0,1$). In time period type 0, all farms face the same volumetric price for water, and in period type 1, different volumetric rates are
introduced based on farm type. Farms of type $I$ are placed on a higher volumetric price relative to farms of type $O$. We write water use for farm $i$ in period $t$ ($Y_{it}$) as,

$$Y_{it} = \alpha_r + \phi_p + \beta T_{rp} + \epsilon_{it}$$  \hfill (1)

where the variable $T_{rp}$ is an indicator variable that takes on a value of 1 for farms inside the DWZ after the price split. Farm type and time period indicators are represented by $\alpha_r$ and $\phi_p$, respectively. We characterize the difference-in-difference estimate of the change water use attributable to a discrete increase in water prices as,

$$\hat{\beta} = \left[ E(Y_{it}|r = I, p = 1) - E(Y_{it}|r = I, p = 0) \right] - \left[ E(Y_{it}|r = O, p = 1) - E(Y_{it}|r = O, p = 0) \right].$$

### 4.1 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 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.

4.2 Average Treatment Effect

We estimate our difference-in-differences model using OLS

\[ Y_{irt} = \alpha_i + \phi_{ct} + \beta T_{rt} + \epsilon_{irt}. \] (2)

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, \( \alpha_i \) and \( \phi_{ct} \), denote whether a farm is inside or outside the delivered water zone, and the time period is pre or post October 2010, respectively. We augment these specifications to control for fixed farm unobservables, \( \alpha_i \), and county-year unobservables, \( \phi_{ct} \). The inclusion of farm fixed effects, \( \alpha_i \), 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 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 Monterrey counties.\(^6\)

Standard errors are clustered at the farm to account for serial correlation within a farm.

\(^6\)Land values are likely to trend differently across counties, with potential implications for land use adjustments that drive water use.
over time.

4.3 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,

$$Y_{it} = \alpha_i + \sum_{\tau=a}^{b} \beta_{\tau} 1\{D_{it} = \tau\} + \phi_{tc} + \epsilon_{it}. \quad (3)$$

All variables are defined as in equation (2), 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 $\tau$ 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, $\beta_{\tau}$, 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 $\tau$ 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.

4.4 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 7, treatment effects retrieved under this framework also rest on the assumption that water use decisions depend additively on the region and time fixed effects.
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 respond differentially to the same price change.

Figure 3 plots estimates of the interaction terms from the estimation of equation 3 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 which are reported 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 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
Figure 3: 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 Zone serves as an assignment mechanism for recycled water deliveries, with only farms located inside the zone eligible to purchase these supplies. Changes in 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 (2) and estimate,

\[ Y_{irt} = \alpha_i + \phi_{ct} + \beta T_{rt} + \omega' X_{rt} + \epsilon_{irt}. \]  

(4)

where \( X_{rt} \) represents region-quarter recycled water deliveries, 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.

5 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

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8In 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.
Table 2: Impact of Regional Pricing on Groundwater Extraction

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<td></td>
</tr>
<tr>
<td></td>
<td>(11.47) (11.47) (11.47) (10.97)</td>
<td>(2.99) (3.51) (3.22) (2.98) (3.55)</td>
</tr>
<tr>
<td>Post-2010</td>
<td>-2.19 -2.06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1.34) (1.36)</td>
<td></td>
</tr>
<tr>
<td>Inside</td>
<td>66.48***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(17.78)</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>62.78*** 70.35*** 64.73*** 65.75***</td>
<td>15.66*** 15.04*** 20.20*** 11.78*** 11.37***</td>
</tr>
<tr>
<td></td>
<td>(3.86) (0.98) (1.42) (1.70)</td>
<td>(0.61) (0.65) (2.36) (4.08) (4.04)</td>
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<td>Mean</td>
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<td>Parcel FE</td>
<td>✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>Year FE</td>
<td>✓ ✓ ✓ ✓</td>
<td>✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>County-Year FE</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td></td>
</tr>
<tr>
<td>Quarter-Year FE</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td></td>
</tr>
<tr>
<td>Recycled Deliveries</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td></td>
</tr>
<tr>
<td>Groundwater Salinity</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td></td>
</tr>
<tr>
<td>Depth to Groundwater</td>
<td>✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓</td>
<td></td>
</tr>
</tbody>
</table>

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.
provides insight on the applicability of short-run estimates as a proxy for the long-run response.

5.1 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 (2); 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), which conditions on farm and county-year fixed effects, reveals that this price change induced on average a 28.17 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.

We explore the robustness of our results to potential time-varying zonal confounding factors in the latter portion of Table 2. 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 9.5 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. The magnitude of the price response is also insensitive to the inclusion of recycled water deliveries (col. 6), groundwater quality as measured by chloride (col. 7), depth to the water table (col. 8) and the combination of all three (col. 9). Conditioning on recycled water deliveries allows us to directly account for the possibility that recycled water, which motivated the existence of PV Water’s regional pricing scheme, is correlated with both pricing zones and groundwater extraction. Appendix C further demonstrates the robustness to
inclusion of recycled water at the annual time step. Collectively, our results highlight that the price-induced reduction in water use is robust to a number of region-specific, time-varying observables.

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. 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.

5.2 Dynamic Effects on Water Use

The annual and summertime effects of the price split on agricultural water use in each of the first 5 years spanning the price split are presented in Figure 3. Coefficient estimates correspond to the \( \beta_\tau \) set forth in equation (3), are inclusive of parcel and county-year fixed effects, and are measured relative to the year preceding the price split.

These figures make 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 -18 AF in 2011 to -36 AF by 2015. A similar trend is observed when comparing summertime water use, with the -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.

These results suggest that the margins of response available to farmers in the 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.

6 Policy Implications of the Dynamic Response

To understand the policy importance of the time-step chosen for estimation, we compute the extent to which the price increase yields the groundwater conservation targets set forth under the Sustainable Groundwater Management Act using our one-year and five-year estimates. This 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 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 (GSA) 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 (3) 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 (3) by parcel area. Coefficient estimates, which are reported in Appendix Table 6, 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: 24,418 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.

7 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 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 long-run is crucial to the design and deployment of prices to regulate water use. In this paper, we quantify the dynamic impacts of pricing a groundwater externality. 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.

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.
References


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 4: 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.

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 4 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 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 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 and quarterly water use, respectively. 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

<table>
<thead>
<tr>
<th></th>
<th>Annual Extraction</th>
<th>Quarterly Extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>Time</td>
<td>-1.59</td>
<td>-5.85***</td>
</tr>
<tr>
<td></td>
<td>(1.37)</td>
<td>(1.99)</td>
</tr>
<tr>
<td>Inside × Time</td>
<td>-4.46</td>
<td>-4.28</td>
</tr>
<tr>
<td></td>
<td>(3.36)</td>
<td>(3.39)</td>
</tr>
<tr>
<td>Inside</td>
<td>49.86***</td>
<td>44.86***</td>
</tr>
<tr>
<td></td>
<td>(11.17)</td>
<td>(11.24)</td>
</tr>
<tr>
<td>Observations</td>
<td>3,509</td>
<td>3,509</td>
</tr>
<tr>
<td>Time FE</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>County-Year FE</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

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.
Figure 5: 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 6. 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.

⁹Ordinance 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 6: 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.
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 inside DWZ pumpers. 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. In addition to the robustness test in Table 2 of the main text, we provide further evidence here that suggests this is not the case, first by visual inspection and then by reproducing our main results while conditioning on recycled water deliveries.

Figure 7 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 7 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 4.

Our motivation for testing the sensitivity of treatment effects to recycled water deliveries stems from the fact that regional pricing exists to fund PV Water’s recycled water program, and thus deliveries may be correlated with both the price change and groundwater use. Table 4 reproduces the first four columns of Table 2 from the main text except now with the inclusion of recycled water deliveries as a control in each specification. Across all specifications, we continue to see that pricing groundwater extraction meaningfully impacted groundwater extraction. We find that the inclusion of year and county-year fixed effects reduces the magnitude of the treatment effect, and attribute the attenuated and noisier estimates in the county-year fixed effects model partly to collinearity. This table decreased. Historical ordinances regarding rate changes over time can be accessed on the agency’s website here: https://www.pvwater.org/director-agendas
Figure 7: 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 4. The vertical line denotes the introduction of the price treatment in October 2010.
underscores the robustness of our results to the inclusion of recycled water deliveries.

Table 4: Impact of Regional Pricing on Annual Groundwater Extraction

<table>
<thead>
<tr>
<th>Groundwater Extraction (AF)</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside × Post</td>
<td>-37.26***</td>
<td>-33.32***</td>
<td>-22.05*</td>
<td>-18.93</td>
</tr>
<tr>
<td></td>
<td>(13.34)</td>
<td>(12.67)</td>
<td>(12.76)</td>
<td>(12.28)</td>
</tr>
<tr>
<td>Post-2010</td>
<td>-2.19</td>
<td>-2.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1.34)</td>
<td>(1.36)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inside</td>
<td>60.17***</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(17.37)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>62.78***</td>
<td>70.05***</td>
<td>65.05***</td>
<td>66.37***</td>
</tr>
<tr>
<td></td>
<td>(3.86)</td>
<td>(1.17)</td>
<td>(1.53)</td>
<td>(1.85)</td>
</tr>
</tbody>
</table>

Observations 5,616 5,616 5,616 5,616
Parcel FE ✓ ✓ ✓
Year FE ✓
County-Year FE ✓
Recycled Deliveries ✓ ✓ ✓ ✓

Notes: This table reports results from a 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 extraction (AF) inside the DWZ prior to treatment. *, **, *** denote significance at the 10%, 5%, and 1% levels.

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 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:

\[
\% \Delta P = \left( \frac{P_{\text{inside}=1, \text{post}=1}}{P_{\text{inside}=0, \text{post}=1}} \right) - \left( \frac{P_{\text{inside}=0, \text{post}=1}}{P_{\text{inside}=0, \text{post}=1}} \right). \tag{5}
\]

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 2. We then use this to impute elasticities using the treatment effect on water use:

$$\eta = \frac{\% \Delta Q}{\% \Delta P}.$$  \hspace{1cm} (6)

First using our average treatment effect from column (4) of Table 2, we calculate an average price elasticity of groundwater demand of -1.02. We follow a similar exercise using the estimated equation from the event study framework presented in equation 3 to calculate elasticities over time. 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>
<thead>
<tr>
<th>Year</th>
<th>Elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>-0.86</td>
</tr>
<tr>
<td>2012</td>
<td>-0.95</td>
</tr>
<tr>
<td>2013</td>
<td>-0.97</td>
</tr>
<tr>
<td>2014</td>
<td>-0.37</td>
</tr>
<tr>
<td>2015</td>
<td>-1.97</td>
</tr>
</tbody>
</table>

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.
### E Appendix: Weighted Event Study Results

Table 6: Impact of Regional Pricing on Annual Per-Acre Extraction

<table>
<thead>
<tr>
<th></th>
<th>(1) Per-acre Extraction</th>
<th>(2) Aggregate Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside × 1(2011)</td>
<td>-0.207 (0.181)</td>
<td>-5,054.7</td>
</tr>
<tr>
<td>Inside × 1(2012)</td>
<td>-0.344 (0.224)</td>
<td>-8,400.1</td>
</tr>
<tr>
<td>Inside × 1(2013)</td>
<td>-0.384* (0.199)</td>
<td>-9,376.9</td>
</tr>
<tr>
<td>Inside × 1(2014)</td>
<td>-0.237 (0.220)</td>
<td>-5,787.3</td>
</tr>
<tr>
<td>Inside × 1(2015)</td>
<td>-0.608*** (0.192)</td>
<td>-14,846.7</td>
</tr>
<tr>
<td>Observations</td>
<td>5,589</td>
<td></td>
</tr>
<tr>
<td>Total Acreage</td>
<td>24,419</td>
<td></td>
</tr>
</tbody>
</table>

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.