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ABSTRACT

Property rights are widely prescribed for addressing overextraction of common pool resources, yet causal evidence of their effectiveness remains elusive. We develop a model of dynamic groundwater extraction to demonstrate how a spatial regression discontinuity design exploiting a spatially-incomplete property rights regime recovers a lower bound on the value of property rights. We apply this estimator to a major aquifer in water-scarce southern California and find that the introduction of ground- water property rights generated substantial net benefits, as capitalized in land values. Heterogeneity analyses suggest gains arise in part from tradeability of these rights, which enables more efficient water use.

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1 Introduction

For almost two centuries, scholars have recognized that common-pool resources, if left unmanaged, tend to be inefficiently overextracted (Lloyd, 1833; Coman, 1911; Gordon, 1954; Hardin, 1968; Ostrom, 1990). This "problem of the commons" remains pervasive today as many natural resources around the world deplete at unprecedented rates (Stavins, 2011).

In 1960, Ronald Coase proposed a solution: the introduction of tradeable property rights. In theory, property rights can counter overextraction and improve welfare by providing incentives for more efficient resource use. These appealing predictions have led to the recommendation of property rights for nearly every common-pool resource - from fisheries, forests, water, to the global climate - and provide an intellectual foundation for the use of environmental markets more broadly (Anderson and Libecap, 2014).

The effectiveness of property rights, however, is predicated on a number of stylized theoretical assumptions. Coase (1960) was the first to acknowledge that one key assumption, sufficiently low transaction costs, may be unrealistic in some settings. In the ensuing six decades, a large theoretical literature has systematically explored what happens when other crucial assumptions - such as complete property rights and complete information - are violated.[1] Given the pervasiveness of these violations in practice, it becomes an empirical question whether property rights are effective under real-world conditions, and if so, why. Indeed, Coase advocated for careful empirical analysis in his original article:

> "Satisfactory views on policy can only come from a patient study of . . . the problem of harmful effects . . . This . . . has to come from a detailed investigation of the actual results of handling the problem in different ways." Coase (1960, p.18-19)

This paper provides the first quasi-experimental estimate of the net benefit of using property rights to manage a common-pool resource. We focus on groundwater for two reasons. First, it is a critical and increasingly scarce natural resource. Groundwater provides 50% of potable and 40% of irrigation water globally (Giordano, 2009; Aeschbach-Hertig and Gleeson, 2012). It is also widely overextracted, with one-third of the world's largest aquifers facing declining water levels today (Richey et al., 2015), and signs of inefficient groundwater allocation present in many areas of the world (Bierkens et al., 2019). Second, an opportunity for causal inference arises when property rights do not cover the entire spatial extent of a groundwater resource. We combine a model of dynamic groundwater extraction with a potential outcomes framework to show that under such spatially-incomplete property rights,

[1]See, for example, implications for the Coase theorem in the presence of imperfect competition (Hahn, 1984), incomplete information (Farrell, 1987), transaction costs (Stavins, 1995), endogenous contracting (Jackson and Wilkie, 2005), and voluntary participation (Ellingsen and Paltseva, 2016).

a spatial regression discontinuity (RD) design applied across the property rights boundary recovers a lower bound on the net benefit of property rights. We find substantial net benefits from tradeable groundwater property rights when applying this estimator to a major aquifer in southern California, one of the most water-scarce regions of the United States.[2]

To date, efforts to produce causal evidence on the effectiveness of property rights have been hindered by two main empirical obstacles. First, property rights for common-pool resources remain rare. For example, only 8% of aquifers in California are managed by property rights, despite groundwater providing one-half of the State's water supply. Additionally, property rights are often adopted only when the resource is in a critical state of overextraction (Shertzer and Prager, 2006; Mangin et al., 2018). As a result, simple comparisons between resources governed by property rights and open access may be confounded by differences in unobserved resource characteristics.

To make progress on causal inference, we build an identification strategy that leans heavily on theory. Our estimand of interest is the average difference in land parcel prices between property rights and open access regimes. As in any potential outcomes framework, this difference cannot be directly estimated as one does not jointly observe land prices under both regimes. Instead, we turn to a setting in which groundwater property rights are assigned to a spatial subset of land parcels overlying an aquifer. Spatially-incomplete property rights allow us to compare parcels under property rights and open access within the same observed regime.

We develop a model of dynamic groundwater extraction to first demonstrate that our estimand of interest is ambiguously signed when property rights are spatially incomplete. We then show how a spatial RD design comparing land values on either side of the property rights boundary addresses endogeneity concerns as groundwater characteristics are likely to vary continuously across the boundary. However, that same identifying assumption also removes changes in the water table, a key result of property rights, such that an RD estimate deviates from our estimand. We turn to our model to sign this bias. Theory shows that a RD estimate serves as a lower bound on the local average net benefit of a spatially-incomplete property right regime, and also as a lower bound for the population average net benefit under certain conditions.

We apply our spatial RD estimator to a major aquifer in southern California. The Mojave Desert is the driest in North America, and yet produces water-intensive crops. Its verdant irrigated farms surrounded by a barren desert have long been a poster child for inefficient water use. This stark contrast occurs because underneath the Mojave Desert lies one of Cal-

[2]Interest in the use of water in California has a long history in economics, dating at least back to the inaugural article of the *American Economic Review* by Katharine Coman in 1911.

ifornia's largest aquifers, which has historically been extracted under open access conditions. Agricultural irrigation has resulted in severe groundwater depletion: by the 1980s, estimates suggest two-fifths of the aquifer's total storage had been exhausted (Donohew, 2012; Mojave Water Agency, 2004). To prevent further drawdown of water levels, a court process in the mid-1990s known as "adjudication" introduced groundwater property rights with two key features: (i) individual limits on groundwater pumping to stabilize the groundwater level, and (ii) individual tradeable water rights within those limits. Importantly, the spatial extent of the property rights regime—which is jointly determined by the boundaries of a preexisting regulatory institution and a surface topographical feature—did not include all overlying users of the hydraulically-connected aquifer. We exploit this spatial feature in our analysis.

Using parcel-level data, we estimate that land values on the property rights side of the boundary are, on average, 280% higher than on the open access side. We confirm that relevant covariates vary continuously across the boundary. We also demonstrate that our RD estimate is robust to alternative statistical modeling assumptions, bandwidth choices, noise from land value assessments, how the property rights boundary is defined, and other potential empirical concerns. Reassuringly, we do not detect RD effects across multiple placebo tests. Specifically, there are no discontinuities in modern-day land values when using placebo boundaries falsely set within the property rights and open access areas, nor is there a discontinuity in past land values at the true boundary prior to the introduction of property rights.

Since our RD estimate omits the benefit of a higher water table, it is striking that land values differ so much across the boundary. One explanation is that Mojave's groundwater rights are tradeable, a frequent, though not universal, feature of groundwater rights regimes.[3] Rights trading provides landowners an additional potential benefit of being able to capitalize on water's market value. For the Mojave aquifer, higher water values likely come from municipalities, particularly in the southern, more urban, areas overlying the aquifer. Indeed, heterogeneity analysis reveals that parcels in the southern areas of the aquifer exhibit substantially higher RD estimates than northern parcels. This suggests that the ability to trade groundwater rights in the Mojave enhances land values by reallocating water away from water-intensive agriculture and towards meeting growing urban demand.[4]

Accounting for these heterogeneous effects and further assuming that unobserved characteristics are not systematically correlated with distance to the boundary, we calculate that tradeable groundwater property rights led to a lower-bound total net benefit of $477 million

[3] 18 of the 20 California groundwater basins with individual pumping rights allow for rights trading.

[4] While our RD design prohibits us from exactly decomposing the net benefit of tradeable property rights into gains due to the assignment of rights and to their tradeability, a back-of-the-envelope calculation suggests that at most two-thirds of the net benefit can be attributed to rights trading.

(in 2015 dollars) across all adjudicated parcels, or a 53% increase in total land value. This net benefit is more than an order of magnitude larger than the initial administrative cost of setting up the property rights system.

This paper goes beyond a recent literature using quasi-experimental techniques to understand how the use of common pool resources is affected by the introduction of property rights. These papers focus on resource extraction effort as their primary outcome, finding reduced effort following adoption of property rights (Hsueh, 2017; Costello and Grainger, 2018; Isaksen and Richter, 2018; Drysdale and Hendricks, 2018). Reduced effort (and increased resource levels), however, need not imply higher net benefits as they do not reflect the cost of restricted extraction. We follow the Ricardian tradition by examining land prices, which in California include the value of accessing water underlying a land parcel, and thus should capitalize both costs and benefits of groundwater property rights.

Another related literature in development economics and economic history employs quasi-experimental approaches to study the consequences of stronger property rights for land, through, for example, more secure land title (Banerjee, Gertler and Ghatak, 2002; Field, 2007; Galiani and Schargrodsky, 2010), lower enforcement costs (Hornbeck, 2010; Libecap and Lueck, 2011), and enhanced access rights (Iwanowsky, 2019). However, in these settings, land - the resource of interest - was already privatized to a large degree prior to treatment. A test of whether the *introduction* of property rights can address the problem of the commons requires a resource that was initially held in common. Our groundwater setting satisfies this requirement.[5]

We find that, despite failing to satisfy various theoretical requirements for an optimal property rights regime, groundwater rights in the Mojave resulted in net benefits for resource users. While our setting prevents us from analyzing an optimal regime, causal evidence on the effectiveness of property rights in practice can inform other groundwater settings. Demographic shifts together with changing environmental conditions from anthropogenic climate change portend increased water scarcity in many parts of the world (Vörösmarty et al., 2000; Covich, 2009; McDonald et al., 2011; Prudhomme et al., 2014; Elliott et al., 2014; Ferguson et al., 2018). For California in particular, a recent prolonged drought has led groundwater tables to fall dramatically across the State, raising concerns about long-term water availability (California Dept. of Water Res., 2015). To address this, California recently passed the Sustainable Groundwater Management Act (SGMA), an unprecedented law requiring users of overextracted aquifers to collectively formulate and adopt stringent management plans. Property rights are widely considered a key policy instrument under

[5]Note that in our setting, landowners have rights to land, but groundwater use is still initially under open access because of the absence of groundwater property rights and hydraulic connectivity of the aquifer.

SGMA (Aladjem and Sunding, 2015; Babbitt and Brozovic, 2017; Green Nylen and Doremus, 2017). This paper demonstrates that net benefits from groundwater property rights can be substantial, particularly if such rights are also tradeable.[6]

The remainder of the paper is structured as follows: Section 2 provides background on the Mojave aquifer and its system of spatially-incomplete property rights. Section 3 introduces a dynamic model of groundwater extraction under open access and incomplete property right regimes. This theory informs our empirical strategy in Section 4. Section 5 details data sources. Section 6 presents our main results, robustness checks, heterogeneity analyses, and quantifies the total net benefit of groundwater rights in the Mojave. Section 7 concludes.

2 Background

The Mojave Desert, located northeast of Los Angeles in southern California, is the driest desert in North America, receiving on average less than two inches of rainfall annually. Yet, farmers in the Mojave Desert have historically produced alfalfa, pistachios, and stone fruits, all highly water-intensive crops. This production is possible, in part, because beneath this desert lies one of California's ten largest groundwater resources, which has historically been extracted under de facto open access conditions.[7]

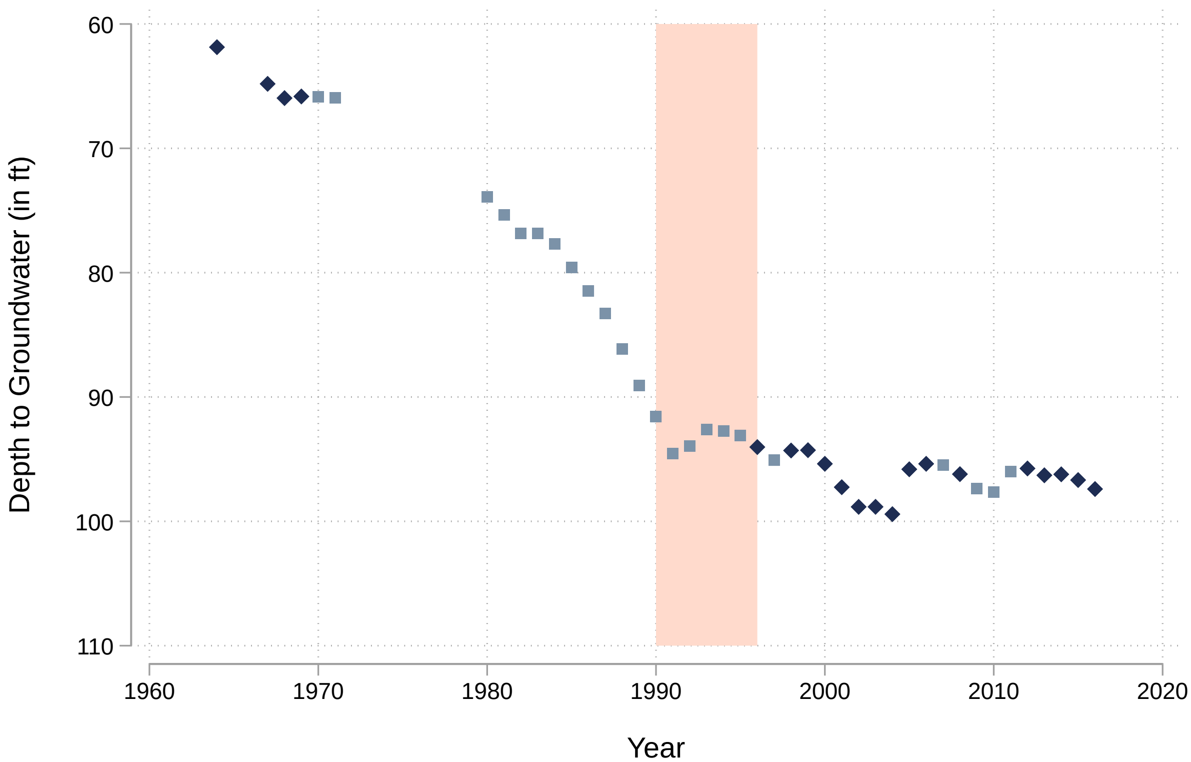
In recent decades, open access pumping has led to a dramatic drop in the aquifer's water table. Figure 1 plots the average depth from surface to the water table across monitoring wells in the Mojave Desert: between 1964 and 1990, the water table fell by 30 feet. After a failed attempt in the 1960s, a lawsuit in 1990 prompted negotiations to address the overextraction of groundwater. By 1997, an agreement was reached between most users and sanctioned by the court to implement a new property rights-based system that would stabilize water table levels. This system is commonly referred to as "adjudication."

Adjudication had two components. First, landowners receive individual annual groundwater pumping rights defined as a proportion of the annual total allowable pumping across the aquifer. Each landowner's proportion is based on her average share of total pumping during 1986-1990, the period prior to adjudication. To stabilize water table levels, total annual pumping across the aquifer ramps down over time. Second, landowners can buy or sell "paper" groundwater rights, either via annual leases or permanent transfers. These are paper rights in the sense that landowners cannot transfer physical water. Instead, they are permitted to transact pumping rights to any other user, agricultural or urban, who also

[6]Hagerty (2019) demonstrates there are also potentially large gains from surface water trading in California.

[7]California law requires groundwater use to be "reasonable and beneficial." However, these criteria have historically allowed unrestricted irrigation in arid regions and, thus, have not limited groundwater extraction.

Figure 1: Depth to groundwater before and after property rights



NOTES: Vertical axis shows average distance (in feet) to water table across monitoring wells in the Mojave Desert. Horizontal axis indicates years. Dark blue diamonds indicate years where there is data for all monitoring wells. Light blue squares indicate years where missing data from one or more monitoring wells is linearly interpolated. Orange-shaded area marks the period from 1990 when the initial adjudication lawsuit was filed to 1996 when the final adjudication court ruling was issued. Data from the U.S. Geological Survey (USGS).

overlies the groundwater resource. Transfer of rights to users not overlying the resource would require physically transporting pumped water and is thus prohibited. The resulting water market enables landowners to reap any allocative efficiency gains arising from the sale of rights to other overlying users. This is an important change from open access, where landowners do not own pumping rights and, thus, can only pump water for use on their own land.[8]

Despite these advantages, several features of the Mojave adjudication system deviate from a textbook optimal policy. First, it is unclear whether simply stabilizing the water level at its pre-adjudication level corresponds to an optimal water table height. Second, in addition to the prohibition on physical water transfers, limits are also placed on water right trading across space and time. Landowners can only trade groundwater rights with overlying landowners

[8]Additionally, landowners have to pay a small fee to cover costs of administering the property rights regime, at around $5 per acre-foot. Section 4 discusses implications of this fee for our empirical results.

or municipalities within the same subarea of the groundwater resource. This implies that each subarea essentially operates its own water rights market involving landowners and municipalities within that subarea. Likewise, water rights can only be banked one year ahead and cannot be borrowed from the future, which limits intertemporal smoothing of water consumption.

The most notable feature of the Mojave adjudication that deviates from an ideal property rights system is that rights were not assigned over the entire spatial extent of the groundwater resource. Figure 2 illustrates the spatial boundary of the property rights regime (shown by purple and red lines) and the subsurface extent of the entire hydraulically-connected Mojave groundwater system (in blue shading), which we henceforth refer to simply as the Mojave aquifer.[9] Observe that the spatial footprint of the property rights and Mojave aquifer areas do not perfectly overlap, so that some areas overlying the aquifer are managed by property rights (i.e., blue areas within the purple and red box) while others remain under open access (i.e., blue areas outside the purple and red box).

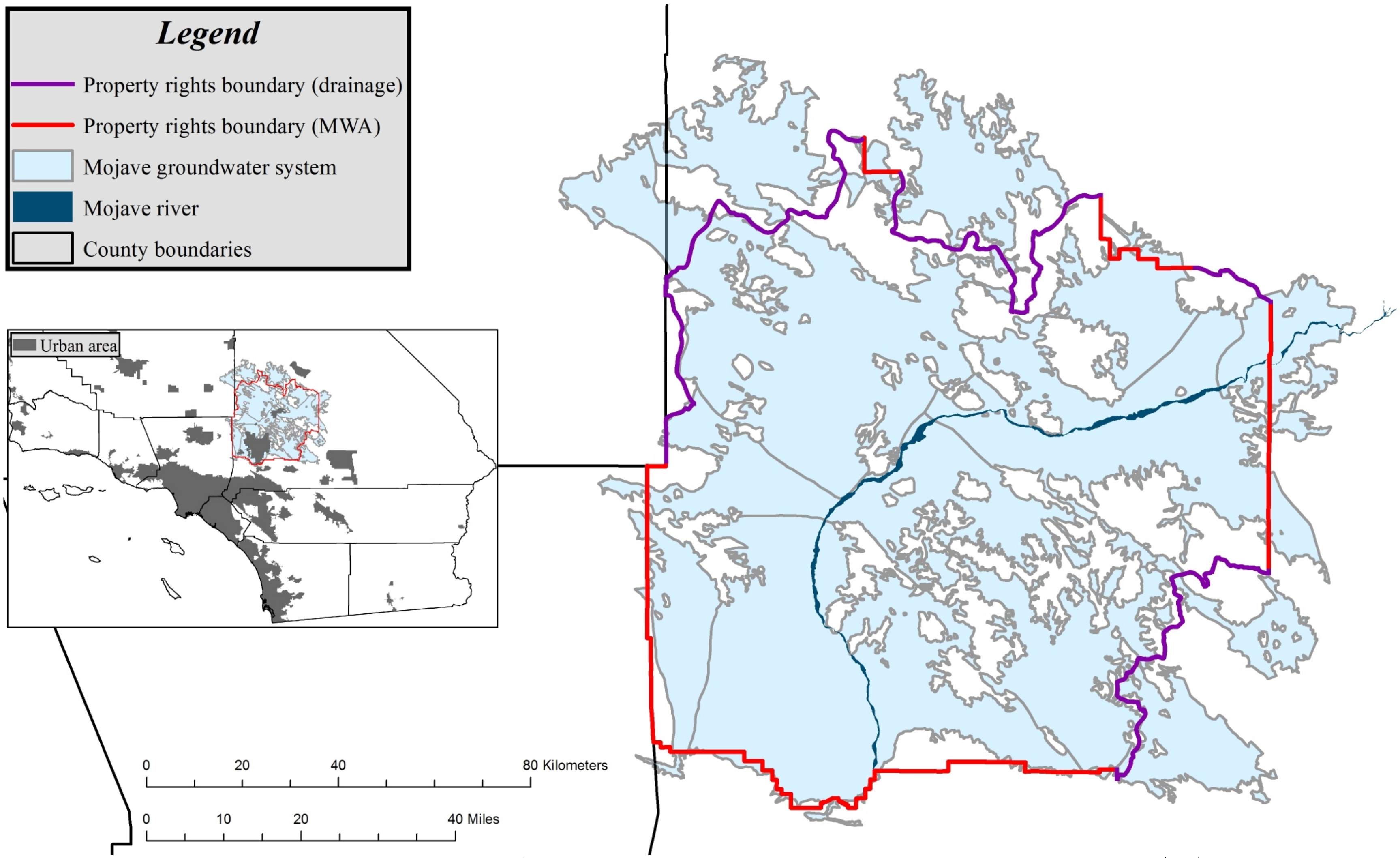
It is important to clarify how the property rights boundary was drawn. Specifically, it is the spatial intersection of two regions: the jurisdictional area of the pre-existing Mojave Water Agency (shown by red line segments) and the physical surface drainage area of the Mojave River (shown by purple line segments). The straight-line boundaries of the Mojave Water Agency (MWA), formed in 1960, are largely based on the regular grid lines imposed by the Public Land Survey System and thus likely unrelated to subsurface groundwater characteristics. Likewise, the drainage extent of the Mojave River which is determined by surface topographical features is also plausibly exogenous to groundwater characteristics.[10]

Spatially-incomplete property rights, together with how the property rights boundary was drawn, suggests an opportunity to apply a spatial RD design. Before we do so, it is instructive to explore what existing data indicates regarding the net benefit of tradeable groundwater property rights in the Mojave. Figure 1 shows that groundwater levels indeed stabilizes after adjudication is introduced. However, stabilized water levels alone do not imply positive net benefits for landowners receiving property rights since pumping restriction and transaction costs may be large. Trends in agricultural activity are also inconclusive. Figure B.1 shows

[9]The key to defining the spatial extent of the relevant groundwater resource is hydraulic connectivity such that extraction in one location can affect the water table in other locations. The blue area in Figure 2 shows the hydraulically connected groundwater resources in the study area, as confirmed by hydrologists at the Mojave Water Agency. State and federal agencies may define multiple administrative "basins" in the region that need not be hydraulically independent. For example, the blue area in Figure 2 consists of several basins defined by California's Department of Water Resources that are largely hydraulically connected.

[10]As robustness checks, we test whether potentially relevant surface topographical features vary smoothly across the boundary. We also examine whether parcels near these two boundary definitions exhibit different RD estimates.

Figure 2: Property rights and groundwater in the Mojave Desert



NOTES: Blue shaded area shows the spatial extent of the hydraulically-connected Mojave groundwater system. Purple (red) line segments track the property rights area as defined by the spatial extent of the Mojave River drainage basin (Mojave Water Agency). Map inset shows the Mojave aquifer relative to urban areas, as defined by the Federal Highway Administration, in the broader southern California region.

that agricultural revenue in the Mojave Desert declines after adjudication begins. However, agricultural revenue does not capture possible gains from the reallocation of water to other sectors (e.g., urban water use), and thus is also inconclusive on whether property rights benefited landowners.

Alternatively, one can follow the Ricardian tradition and examine land prices. This is possible in our data setting because the value of groundwater access in San Bernardino County is bundled together with the value of a land parcel. As such, land prices reflect the present discounted value of rental streams from both land and water assets.[11] For open-access parcels, land prices capture the value of unrestricted groundwater pumping for own use. For parcels under adjudication, land prices reflect the cost of restricted groundwater pumping, as well as the benefits of a higher water table level and the potential gains from trading pumping rights. We now turn to a theoretical model of dynamic groundwater extraction to formalize what drives these land prices and how they relate to our empirical strategy.

3 Theory

This section develops a model of dynamic groundwater extraction for the Mojave aquifer. Recognizing that the Mojave adjudication regime deviates in practice along several dimensions from an optimal policy, we explicitly avoid characterizing optimality and instead consider a model that closely mirrors the policy's objective to stabilize water levels using spatially-incomplete property rights.[12] In particular, to replicate observed falling groundwater water levels prior to adjudication, as shown in Figure 1, we begin with all land parcels over the aquifer extracting groundwater under open access but without having yet reached a steady state. We then model land prices dynamics under counterfactual and factual regimes for the period after adjudication is introduced. In the first (counterfactual) regime, we model land price dynamics had open access conditions continued for all parcels over the aquifer. In the second (factual) regime, we model land price dynamics following the introduction of a spatially-incomplete property rights system.[13]

Our theory generates several predictions that are used for interpreting our spatial RD estimator, presented in Section 4. First, we show that the difference in land prices between the two regimes, our estimand of interest, is of ambiguous sign. Intuitively, this is because

[11] Land prices, however, do not capture the one-time sunk costs of setting up the property rights regime.

[12] An optimal policy will always do at least as well as open access. To be useful for empirical testing, our model must leave open the question of whether spatially-incomplete property rights increases net benefits.

[13] A comparison of land prices under the two regimes is valid only if the initial groundwater level is the same in both cases, implying that our theory must necessarily be dynamic in order to characterize adjustments to the steady states under open access and incomplete rights.

relative to open access, property rights impose the cost of restricted pumping but also lead to benefits from a higher water table and the ability to trade water rights. Next, we demonstrate that in an incomplete property rights regime, a spatial RD estimator comparing parcels under property rights and open access at the property rights boundary produces a lower bound for the estimand at the boundary. This is because a spatial RD estimator, by design, omits differences in water table height, thus excluding the benefit of a higher water table due to property rights. Finally, because water table levels are lower at the boundary than in the interior of the property rights area, the RD estimator is also a lower bound on the estimand in the interior.

3.1 Setup

There are N identical landowners, each of whom occupies $1/N$ of the area overlying the aquifer. Instantaneous profits are given by $\pi(w, h)$ where w is the pumping rate and h is the water table height, measured as the vertical distance from the bottom of the aquifer to the water level. $\pi(w, h)$ is assumed to be concave and singled-peaked in w, increasing in h, and $\pi_{wh} > 0$ since raising the water table height reduces the cost of pumping, making the marginal unit of water more profitable. The initial height of the water table is h_0 and the instantaneous rate of change in the water table height is $\dot{h}(t)$, where t is time. After the initial period, dynamics of h differ depending on whether the aquifer is under full open access or incomplete property rights, as we discuss below.

3.2 Full open access

Under full open access, profit-maximizing landowners ignore any effects of their pumping on the water table,[14] solving at each instant in time:

$$\max_{w} \pi(w, h) \tag{1}$$

The first-order condition $\frac{\partial \pi}{\partial w} = 0$ defines $w^a(h)$, the pumping rate as a function of the height of the water table (the 'a' indicates full open access). Using Cramer's rule, $\frac{dw^a}{dh} = -\frac{\pi_{wh}}{\pi_{ww}} > 0$, by the concavity of the profit identity, $\pi_{ww} < 0$, and $\pi_{wh} > 0$. Pumping rates under open access increase with the height of the water table.

Transition and steady state. Under open access, all users pump at the same rate and

[14] Our open access model is a limiting case of uncoordinated spatial ownership (Kaffine and Costello, 2011), where each user has exclusive access to the water beneath their property, but pumping by other landowners gives rise to a stock externality.

so the water table height is the same for all landowners. It evolves according to:

$$\dot{h}^a(t) = R - Nw^a(h(t)) \tag{2}$$

where R is natural recharge and $Nw^a(h(t))$ is aggregate pumping.[15] Consistent with Figure 1, we assume that the aquifer is out of steady state initially and that aggregate pumping $Nw^a(h_0)$ exceeds recharge. By equation (2), this results in a declining water table. However, the drop in the water table height causes the open-access pumping rate to fall, by Cramer's rule. Assuming that exhaustion of the resource is unprofitable[16], a steady-state will be reached where pumping is equal to recharge. The steady-state is defined as $\bar{h}^a$ such that $\dot{h}^a = R - N\bar{w}^a = 0$, where $\bar{w}^a = w^a(\bar{h}^a) = R/N$.

The dynamics of the full open access system are illustrated in panel (a) of Figure 3. For a given value of h, the pumping rate is $w^a(h)$. Thus, any $w \neq w^a(h)$ moves immediately to the $\dot{w} = 0$ locus defined by $w^a(h)$. From there, the dynamics of the system are governed by equation 2. The blue line in Figure 3 shows the transition to the steady state from the initial height of $h_0 > \bar{h}^a$. When $h < \bar{h}^a$, the pumping rate and the water table height increase until the steady state is reached. In summary, under the full open access regime, we have $h_0 \geq h^a(t) \geq \bar{h}^a$ and $w^a(h_0) \geq w^a(h^a(t)) \geq \bar{w}^a$ for $t \geq 0$.

Land price. Under perfect competition, the price of a land parcel is equal to the present discounted value of the infinite stream of profits generated from the land. Thus, the full open access land price is given by:

$$V^a = \int_0^\infty \pi(w^a(s), h^a(s))e^{-\delta s} ds \tag{3}$$

where δ is the discount rate and the time interval covers both the transition period and the steady state.

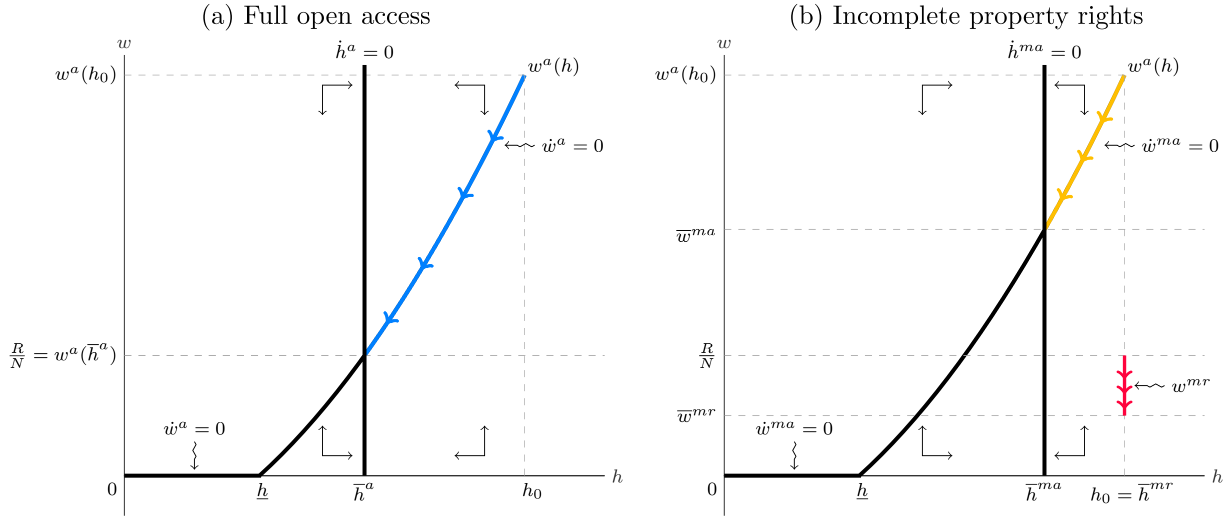
3.3 Spatially-incomplete property rights

Property rights are introduced to stabilize the water table at h_0, preventing the draw down of the aquifer that occurs under open access. If all N landowners were under the property rights regime, the regulator would simply assign individual pumping rights equal to R/N. If users pump their full allocation, then by equation (2), the water table remains at its initial level h_0. In the steady state, the same volume of water is pumped as under the open access regime, but because $h_0 > \bar{h}^a$, profits are higher than under open access (Gisser and Sanchez,

[15] The volume of the aquifer is normalized to one so that volumetric variables, R and w, are conformable with h.

[16] Formally, there exists an $\underline{\mathrm{h}} > 0$ such that $w^a(\underline{\mathrm{h}}) = 0$.

Figure 3: Phase plane diagrams of full open access and incomplete rights regimes



Notes: Figure illustrate the transition to the steady state for the full open access and incomplete rights regimes starting from an initial water table height h_0. The directionals in each isosector apply to the open access users and are described in the text. The blue line in panel (a) is the transition path to the steady state at $\bar{h}^a$ and $w^a(\bar{h}^a)$ for open access users under the full open access regime. Under the incomplete property rights regime shown in panel (b), a representative open access parcel follows the orange line to the steady state at $h = \bar{h}^{ma}$ and $w = \bar{w}^{ma}$. A representative parcel with property rights follows the red line with a constant stabilization target of $\bar{h}^{mr}$ and an exogenous pumping rate (determined by the regulator) that reaches a steady state at $w = \bar{w}^{mr}$.

1980). The steady state is more complicated when property rights are incompletely assigned over the aquifer because users can pump at different rates.[17]

We examine this incomplete property rights setting by modeling the two components of the Mojave adjudication regime: a restriction on pumping to stabilize water levels and tradeable property rights to pump groundwater. First, we characterize how pumping restrictions allow for stabilization of the water table. We then show how the market value of tradeable pumping rights is capitalized into land prices.

Under incomplete rights, only a share of the N landowners hold property rights, with the rest of the landowners remaining under open access. Define $\alpha \in [0, 1]$ as the share of open access landowners. We assume that all landowners under the property rights regime (indicated by 'mr' where 'm' denotes the incomplete, or mixed, regime and 'r' indicates users with rights) face the same pumping restriction w^{mr}, whereas open access users (indicated by 'ma') are unconstrained. To simplify the analysis, we focus on two representative users, one within the property rights area with water table h^{mr} and the other in the open access

[17]See Costello, Quérou and Tomini (2015) for a comparison of open access, incomplete property rights, and complete property rights regimes.

area with water table h^{ma}. The dynamics of the water table are described by a variant of equation (2):[18]

$$\dot{h}^{ma} = \alpha R + \theta(h^{mr} - h^{ma}) - \alpha N w^a(h^{ma}) \tag{4}$$

$$\dot{h}^{mr} = (1-\alpha)R + \theta(h^{ma} - h^{mr}) - (1-\alpha)N w^{mr} \tag{5}$$

where it is assumed that recharge occurs uniformly throughout the aquifer and that the maximum allowable pumping occurs in the property rights area. Due to gravity, differences in the water table height produce a flow of water, dictated by $\theta \in [0, 1]$, from one area to another.

Stabilization and transition. We assume that the goal of property rights is to stabilize the aquifer within the rights area at $\bar{h}^{mr} = h_0$ by imposing the pumping limit $w^{mr}(t)$. That is, the pumping limit is set in each period to achieve:

$$\dot{h}^{mr} = (1-\alpha)R + \theta(h^{ma}(t) - \bar{h}^{mr}) - (1-\alpha)N w^{mr}(t) = 0 \tag{6}$$

Although the water table is stabilized in the rights area, it continues to be drawn down in the open access area. Consider $\dot{h}^{ma}$ at $t = 0$:

$$\dot{h}^{ma} = \alpha R + \theta(\bar{h}^{mr} - h^{ma}) - \alpha N w^a(h^{ma}) = \alpha R - \alpha N w^a(h_0) \tag{7}$$

where $\bar{h}^{mr} = h^{ma} = h_0$. As under full open access, open access users under incomplete rights pump more than recharge at h_0 and $\dot{h}^{ma} < 0$. The pumping rate by open access users depends only on the water table height according to $w^{ma} = w^a(h^{ma})$, as in the full open access case. The dynamics of the incomplete rights system is illustrated in panel (b) of Figure 3, where the orange line depicts the transition to the steady state for open access users.[19] Although the same trajectory is followed as under full open access, there is a positive flow of water to the open access area ($\bar{h}^{mr} - h^{ma} > 0$ for $t > 0$), which slows the decline in h^{ma} relative to the full open access case (we prove this result in this next section).

In order to keep $\bar{h}^{mr}$ at h_0, $w^{mr}(t)$ must fall over time by equation 6. Solving for $w^{mr}(t)$ in equation 6 and taking the time derivative yields $\dot{w}^{mr} = \frac{\theta}{(1-\alpha)N}\dot{h}^{ma} < 0$. The transition path for the pumping rate in the rights area is depicted by the red line in panel (b) of Figure 3. At $t = 0$, $w^{mr} = R/N$, which is established from equation 6 and the fact that $\bar{h}^{mr} = h^{ma}$ at $t = 0$. The pumping limit $w^{mr}(t)$ declines until steady states are reach in both areas, which we solve for next.

[18] We suppress time arguments except when it is necessary to clarify a variable's dependence on time.

[19] An additional assumption is needed to guarantee that a unique value of h^{ma} solves $\dot{h}^{ma} = \alpha R + \theta(\bar{h}^{mr} - h^{ma}) - \alpha N w^a(h^{ma}) = 0$, as shown in panel (b): $\frac{d^2 w^a(h)}{dh^2} \geq 0$, which holds if $\pi_{www}\pi_{wh} - \pi_{whh}\pi_{ww} \geq 0$.

Steady states. Setting $\dot{h}^{ma} = 0$ in equation 4 and substituting $\bar{h}^{mr}$, we define the following relationship between steady-state water table heights:

$$\bar{h}^{mr} = \bar{h}^{ma} + \frac{\alpha}{\theta}(Nw^a(\bar{h}^{ma}) - R) \tag{8}$$

The assumption in footnote 19 implies that for any stabilization target for the property rights area $\bar{h}^{mr}$, there is a unique steady-state water table $\bar{h}^{ma}$ and pumping rate $\bar{w}^{ma} = w^a(\bar{h}^{ma})$ in the open access area. We denote this mapping $q : \bar{h}^{mr} \to \bar{h}^{ma}$.

The steady state for the property rights area is found by substituting $\bar{h}^{mr}$ in equation (8) into equation (5) and setting $\dot{h}^{mr} = 0$, yielding:

$$R - \alpha N w^a(\bar{h}^{ma}) - (1-\alpha)N\bar{w}^{mr} = 0 \tag{9}$$

Substituting $\bar{h}^{ma} = q(\bar{h}^{mr})$ and rearranging equation (9), we obtain:

$$\bar{w}^{mr}(\bar{h}^{mr}) = \frac{R - \alpha N w^a(q(\bar{h}^{mr}))}{(1-\alpha)N} \tag{10}$$

For a given stabilization target $\bar{h}^{mr}$, equation (10) gives the steady-state pumping limit $\bar{w}^{mr} = \bar{w}^{mr}(\bar{h}^{mr})$ that needs to be imposed on landowners within the property rights area. The steady states are depicted in panel (b) of Figure 3.[20] In summary, under the incomplete property rights regime, we have $h_0 \geq h^{ma}(t)$, $w^a(h_0) \geq w^a(h^{ma}(t))$, and $w^{mr}(0) \geq w^{mr}(t)$ for $t \geq 0$.

Land price. Tradeable property rights allow right holders to exchange water with other agricultural users or to meet non-agricultural demand such as that coming from nearby expanding urban areas. We assume the trade in rights occurs at a single time t^* and represent the outside option with a salvage value $F(t)$, where it is assume $F_t > 0$.[21] The profit-maximizing landowner will solve:

$$\max_{t^*} \int_0^{t^*} \pi(w^{mr}(s), \bar{h}^{mr})e^{-\delta s} ds + F(t^*)e^{-\delta t^*} \tag{11}$$

where t^* may occur before or after the steady state $w^{mr}(t) = \bar{w}^{mr}$ is reached. In equation 11, landowners pump up to the limit $w^{mr}(t)$ in every period because $\frac{\partial \pi}{\partial w} > 0$ at every $w^{mr}(t)$.[22] Assuming an interior solution, the first-order condition for the optimal time to buy or sell

[20] It can be shown that $\bar{w}^{ma} \geq \bar{w}^{a} \geq \bar{w}^{mr}$ and $\bar{h}^{mr} \geq \bar{h}^{ma} \geq \bar{h}^{a}$.

[21] If all rights are transferred to another party, $F(t)$ includes the residual value of land without water. If the landowner buys additional rights for agricultural production or sells only a portion of her rights, $F(t)$ is the present discounted value of net gain from this transaction.

[22] This follows from $\frac{\partial \pi(w^a(h_0), h_0)}{\partial w} = 0$, $w^a(h_0) > w^{mr}(t)$ for all t, $\bar{h}^{mr} = h_0$, and the properties of π.

water rights is:

$$\pi(w^{mr}(t^*), \bar{h}^{mr}) + F_t(t^*) - \delta F(t^*) = 0 \tag{12}$$

Water rights are optimally transacted when the annual return to using the full allocation of water in agriculture equals the annualized salvage value net of the instantaneous rate of increase in this value (i.e., $\delta F(t^*) - F_t(t^*)$). Under incomplete property rights, the land price is:

$$V^{mr} = \int_0^{t^*} \pi(w^{mr}(s), \bar{h}^{mr}) e^{-\delta s} ds + F(t^*) e^{-\delta t^*} \tag{13}$$

The land price for landowners in the open access area is:

$$V^{ma} = \int_0^{\infty} \pi(w^{ma}(s), h^{ma}(s)) e^{-\delta s} ds \tag{14}$$

We made the simplifying assumption that there are single water table heights in the two areas. In reality, there is a declining gradient in the water table as one moves from the property rights to the open access area. At the boundary of the two areas, the water table height is the same for parcels under the rights and open access regimes. That is, denoting water table height at the boundary as $h^b(t)$, $\bar{h}^{mr} \geq h^b(t) \geq h^{ma}(t)$ for $t \geq 0$. This property has important implications for our RD estimator, as discussed below.

3.4 Comparing across regimes

We now compare land values between the full open access and incomplete property right regimes that will facilitate interpretation of an RD estimate in Section 4.

Proposition 1 *If (i)* $\bar{h}^{mr} \geq h^a(t)$*, (ii)* $\bar{h}^{mr} \geq h^{ma}(t)$*, (iii)* $h^{ma}(t) \geq h^a(t)$*, and (iv)* $w^a(h_0) \geq w^{ma}(t) \geq w^a(t) \geq w^{mr}(t)$ *for* $t \geq 0$*, then*

(a) $V^{mr} - V^a \gtreqless 0$ *(treatment effect has ambiguous sign)*

(b) $V^{mr} - V^{ma} \gtreqless 0$ *(estimated effect has ambiguous sign)*

(c) $(V^{mr}(h^b) - V^a) - (V^{mr}(h^b) - V^{ma}(h^b)) \geq 0$ *(estimated effect at the boundary is a lower bound for treatment effect at the boundary)*

(d) $(V^{mr} - V^a) - (V^{mr}(h^b) - V^a) \geq 0$ *(treatment effect at the boundary is a lower bound for treatment effect in the interior)*

(e) $\frac{d}{dt}(V^{mr}(h^b) - V^{ma}(h^b)) \gtreqless 0$ *(the change over time in the estimated effect at the boundary has ambiguous sign)*

Proof. We establish conditions (i)-(iv) here and prove Proposition 1(a) -1(e) in Appendix A. It was shown in Sections 3.2 and 3.3 that $h_0 \geq h^a(t)$ and $h_0 \geq h^{ma}(t)$ for $t \geq 0$, respectively. Conditions (i) and (ii) follow from the definition $\bar{h}^{mr} = h_0$. To prove condition (iii), we show that $\dot{h}^a \leq \dot{h}^{ma}$ at any $h_0 \geq h \geq \bar{h}^a$. Condition (iii) then follows from $h^a(0) = h^{ma}(0) = h_0$. As shown in Section 3.2, $w^a(\bar{h}^a) = R/N$. For any $h \geq \bar{h}^a$, $w^a(h) \geq R/N$ by $\frac{dw^a}{dh} > 0$. Using equations 2 and 4, we write:

$$\dot{h}^{ma} - \dot{h}^a = \theta(\bar{h}^{mr} - h) + (1-\alpha)(Nw^a(h) - R) \tag{15}$$

This difference is positive from $\bar{h}^{mr} = h_0$ and $w^a(h) \geq R/N$, which establishes condition (iii). It follows immediately from conditions (i)-(iii) and $\frac{dw^a}{dh} > 0$ that $w^a(h_0) \geq w^{ma}(t) \geq w^a(t)$ for $t \geq 0$. It remains to show that $w^a(t) \geq w^{mr}(t)$ for $t \geq 0$. In Section 3.3, we showed that $w^{mr}(0) = R/N$ and $\dot{w}^{mr} \leq 0$, which implies $w^{mr}(t) \leq R/N$ for $t \geq 0$. We showed earlier that $w^a(t) \geq R/N$ for $t \geq 0$ and so condition (iv) is established.

4 Empirical strategy

This section draws on the theoretical results from Section 3 to inform our empirical strategy. We first introduce our estimand of interest. We then propose a spatial RD estimator that exploits the incomplete nature of property rights over the Mojave aquifer. Theoretical predictions from Section 3 inform the relationship between the spatial RD estimate and the estimand, what drives the RD estimate, and how the RD estimate varies over time.

4.1 Causal estimand

We are interested in whether the Mojave aquifer's incomplete property rights regime led to net benefits for landowners under property rights relative to a full open access counterfactual. For the population of parcels under the property rights regime, indexed by $i = 1, ..., N$, this is the difference in potential outcomes V_i^{mr} (see equation (13)) and V_i^a (see equation (3)). Our estimand of interest is the population average treatment effect:

$$\beta = \underbrace{\mathbb{E}_i[V_i^{mr} - V_i^a]}_{\lesseqgtr 0} \tag{16}$$

β is the average net benefit of property rights to adjudicated landowners relative to the full open access counterfactual. By Proposition 1(a), β is of unknown sign. This is because relative to a full open access regime, parcels with property rights benefit from a higher water table and the ability to transact rights, but also bear the cost of restricted pumping. Unfortunately, β cannot be directly estimated since V_i^{mr} and V_i^o are potential outcomes under counterfactual states and thus are not simultaneously observed (Holland, 1986).

4.2 Spatial regression discontinuity estimator

Instead, we consider a spatial RD estimator that exploits the incomplete property rights boundary of the Mojave adjudication regime. Define d_i as parcel i's distance to the property right boundary of the property rights regime. d_i is normalized so that a parcel is under property rights when $d_i \geq 0$ (i.e., blue area inside the red and purple-lined box in Figure 2) and under open access when $d_i < 0$ (i.e., blue area outside the red and purple-lined box in Figure 2). Our spatial RD estimator is:

$$\begin{aligned} \hat{\beta}^{RD} &= \underset{d_i \downarrow 0}{\mathbb{E}}\left[V_i^{mr}\right] - \underset{d_i \uparrow 0}{\mathbb{E}}\left[V_i^{ma}\right] \\ &= \underbrace{\underset{i:d_i=0}{\mathbb{E}}\left[V_i^{mr} - V_i^{ma}\right]}_{\lesseqgtr 0} \end{aligned} \tag{17}$$

where the first equality defines our spatial RD estimator at the property rights boundary. The second equality uses the RD identifying assumption that expected land price under open access is continuous at the boundary, $d_i = 0$.[23] In particular, it implies that the water table height $h_i(d_i)$ and other unobserved characteristics are continuous at $d_i = 0$. While $\hat{\beta}^{RD}$ removes the benefit of a water table, the remaining opposing influences of gains from rights trading and losses from pumping restrictions imply that $\hat{\beta}^{RD}$ remains of unknown sign, as indicated by Proposition 1(b).

How does $\hat{\beta}^{RD}$ relate to β? There are both internal and external validity considerations. Turning first to internal validity, let us denote the local β for parcels at the boundary as $\beta_{i:d_i=0}$. The difference between $\beta_{i:d_i=0}$ and $\hat{\beta}^{RD}$ is:

$$\beta_{i:d_i=0} - \hat{\beta}^{RD} = \underbrace{\underset{i:d_i=0}{\mathbb{E}}\left[(V_i^{mr} - V_i^{a}) - (V_i^{mr} - V_i^{ma})\right]}_{\geq 0}$$

which is weakly positive by Proposition 1(c). The RD estimator serves as a lower bound for the treatment effect at the boundary because it omits the benefit of a higher water table. This lower bound can also be interpreted from the perspective of spillover effects. As our

[23] Specifically, following Hahn, Todd and Van der Klaauw (2001), the identifying assumption states that $\mathbb{E}\left[V_i^{ma}\right]$ is continuous in d_i at $d_i = 0$.

theory shows, in an incomplete property rights regime, water from the property rights area spills into the open access area, raising land prices for remaining open access parcels. Because this spillover benefit would not occur under full open access, the RD estimator produces a lower value than our estimand.

The external validity of our RD estimate depends on the spatial structure of other land parcel characteristics. Water levels increase as one moves into the property rights area away from the boundary. If other land parcel characteristics are uncorrelated with distance to the property rights boundary, then by Proposition 1(d), the treatment effect at the boundary serves as a further lower bound for the treatment effect in the interior of the property rights area. Thus, this orthogonality assumption, together with Propositions 1(c) and 1(d) jointly imply that the spatial RD estimate is a lower bound for the population average net benefit, $\hat{\beta}^{RD} < \beta$.

Our theory also elucidates the determinants of the RD estimate. Specifically, we can write $\hat{\beta}^{RD}$ as the difference between equations (13) and (14) at the boundary:

$$\hat{\beta}^{RD} = \mathop{\mathbb{E}}_{i:d_i=0}\left[\underbrace{\int_0^{t^*}[\pi(w^{mr}(s), h(s, d_i=0)) - \pi(w^{ma}(s), h(s, d_i=0))]e^{-\delta s}ds}_{\leq 0 \text{ restriction cost}}\right.$$
$$\left. + \underbrace{F(t^*)e^{-\delta t^*} - \int_{t^*}^{\infty} \pi(w^{ma}(s), h(s, d_i=0))e^{-\delta s}ds}_{\lesseqgtr 0 \text{ potential trading benefit}}\right]$$

$\hat{\beta}^{RD}$ is positive when the potential gains from transacting pumping rights offset the cost of restricted pumping, and depends on the value of water for own use relative to its market value across the aquifer. When the value of own water use is high, so too is the cost of pumping restrictions under property rights relative to open access, resulting in a lower $\hat{\beta}^{RD}$. Alternatively, when the value of own water use is low, the gains from transacting water rights to other users increase, which drives up $\hat{\beta}^{RD}$.[24]

Finally, Section 3 defines land prices at the start of the program, when $t = 0$ or in 1997. In this case, $\hat{\beta}^{RD}$ indicates whether landowners received a positive stream of discounted net benefits when property rights were first introduced. One may also be interested in whether continuation of the policy since 1997 has been economically justified. Our theory is agnostic on this matter: Proposition 1(e) shows that the time derivative of the estimate effect at the

[24]For simplicity, our theory in Section 3 ignores fees paid by landowners to administer the property rights regime, as described in footnote 8. Such fees provide another reason for why $\hat{\beta}^{RD}$ is a lower bound for β.

boundary is of ambiguous sign. To test this, we use land prices for later periods to estimate an average RD effect over time, as well as separate RD effects for different periods since 1997.

5 Data

Our ideal outcome of interest from Section 3 is parcel price, which bundles together the present discounted value of a parcel's land and water assets. Two measures for parcel price are available in San Bernardino County: sales value and assessed value. Unfortunately, sales records in San Bernardino are not required to include adjudicated water rights when such rights are jointly transferred with a land parcel, nor are they required to indicate whether or not a sale includes water rights. This limitation rules out the use of sales data for our analysis. By contrast, land assessments in San Bernardino include the value of adjudicated water rights held on a parcel.[25] For our primary dataset, we collect 2015 data on assessed land value, parcel size, location, and most recent transaction year (known also as base year) from the San Bernardino County Assessor.

In years when a parcel is not transacted, land assessors determine the value of water rights using market information from comparable sales. While this determination does not follow a prescribed, mechanistic formula,[26] it is potentially subject to errors that arise in determining which sales are comparable. Two features of our assessed land values help to address this issue. First, since 1978, Proposition 13 in California has limited property tax increases across the State by capping the annual appreciation rate of assessed land value at 2% following a property sale. This implies that, for any given year, the assessed land value of a previously transacted parcel likely captures its value at the time of last sale, with a 2% annual adjustment.[27] As a consequence of Proposition 13, assessors play a smaller role in determining land values in California, reducing potential assessment error. Second, for parcels whose most recent transaction year equals the year of assessment, assessed land value is sales value. As a robustness check, we limit our estimating sample of 2015 assessed values to parcels transacted in 2015.

We impose three sample restrictions on our primary dataset. First, we restrict our

[25]Specifically, San Bernardino County requires the land assessor to be in contact with the Mojave Water Agency regarding water rights ownership and transfers. The assessor, however, does not separately report the value of water rights, only the total value of water and land assets.

[26]See Sections 501 and 542 of the California Assessor's Handbook. Available here: http://www.boe.ca.gov/proptaxes/ahcont.htm

[27]Strong housing demand in southern California over recent decades means that this 2% limit has regularly constrained increases in assessed value. We calculate that between 2000 and 2015, Proposition 13's 2% annual cap was binding for 80% of land parcels in our sample that were last sold before 2000.

sample to land parcels that were most recently transacted from 1997 onwards, the period after property rights were introduced. Second, we remove all land parcels that do not overlie the aquifer. Third, we remove urban land parcels as they are not eligible for water rights.

Additional covariates include a parcel's average slope and aspect (compass direction), constructed from a USGS digital elevation map,[28] and whether a parcel is within one mile of a groundwater well, constructed using well completion reports from California's Department of Water Resources.[29] Table C.1 shows summary statistics for variables in our primary dataset, which includes both land parcels close to the property rights boundary used in RD estimation and those further away. Finally, for a placebo test, we also obtain assessed land values in 1976, well before property rights were introduced.

6 Results

This section presents our main result, robustness checks, heterogeneity analyses, and quantifies the total net benefit of groundwater rights.

6.1 Specification

To estimate our RD coefficient, $\hat{\beta}^{RD}$, from Section 4.2, we follow Hahn, Todd and Van der Klaauw (2001) and model log land value for parcel i using a local polynomial regression

$$lnV_i = \beta^{RD} R_i + f(d_i) + \theta' \mathbb{X}_i + \epsilon_i, \tag{18}$$

where, as in Section 4.2, d_i is normalized distance to the boundary of the property rights regime. $R_i = \mathbf{1}\{d_i \geq 0\}$ is an indicator variable equaling 1 when parcel i is in the property rights regime and 0 otherwise. $f(d_i)$ is a flexible local polynomial function that is fully interacted with R_i, allowing for different parameters on either side of the boundary. For example, under a linear specification $f(d_i) = \alpha_1 + \alpha_2 d_i + \alpha_3 d_i R_i$.

In some models, we include a vector of covariates, $\mathbb{X}_i$, which contains a land parcel's average slope, average aspect, size, most recent transaction year, and a dummy for whether the parcel is within one mile of a groundwater well. For our baseline specification, standard errors are clustered at the zip code level to allow for arbitrary forms of heteroscedasticity and spatial autocorrelation among land parcels within the same zip code. To address the bias-precision trade-off inherent in RD designs, our baseline model uses a mean squared error (MSE) optimal RD bandwidth that is common across both sides of the threshold

[28] Available here: https://viewer.nationalmap.gov/basic/

[29] Available here: https://data.ca.gov/dataset/well-completion-reports.

following Calonico, Cattaneo and Titiunik (2014) and Calonico et al. (2019). Observations within the bandwidth are uniformly weighted in our baseline model. Robustness checks consider alternative bandwidths, error structures (including a zip code-level wild bootstrap procedure), and other estimation choices.

6.2 Covariate smoothness

To assess the validity of our RD estimator, we begin by examining whether relevant covariates exhibit discontinuities at the property rights boundary. Specifically, we estimate separate versions of equation (18), where each covariate in $\mathbb{X}_i$ serves as the dependent variable. Each model uses a local linear function for $f(d_i)$ and excludes other covariates as regressors. Table 1 shows $\hat{\beta}^{RD}$ for each covariate, displayed across columns.

Table 1: Examining covariate smoothness

	(1) slope	(2) aspect	(3) near well?	(4) size	(5) transaction year
$\hat{\beta}^{RD}$	1.575	11.291	-0.048	9.660	-1.117
	(1.271)	(36.255)	(0.104)	(7.340)	(0.872)
Observations	3288	3288	3288	3288	3288
Zip codes	27	27	27	27	27

NOTES: Estimates of β^{RD} from equation (18) with each covariate as outcome. Specification includes a local linear model for $f(d_i)$ and excludes $\mathbb{X}_i$. Estimating bandwidth from benchmark log land value model in column 1 of Table 2. Observations uniformly weighted within the bandwidth. Covariates indicated across columns rows. Average slope in column 1 is measured in degrees relative to level surface. Average aspect in column 2 is measured in compass direction between 0 and 360. Column 3 examines a dummy variable equaling one if a parcel is within 1 mile of a well. Column 4 examines parcel size in acres. Column 5 examines the most recent year in which the parcel was transacted. Standard errors clustered at the zip code level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

In some places, the property rights boundary is defined according to the surface water drainage area of the Mojave River. Because this typically corresponds to a local elevation peak, surface topological features may vary systematically across the boundary. For example, the slope of the land may change at the boundary, which could affect the marginal value of water for agriculture. The aspect of the land, or its compass direction, may also vary systematically at the boundary, affecting sunlight exposure and thus the marginal value of water.[30] Columns 1 and 2 do not detect a discontinuity in parcel slope or aspect at the

[30]We thank Jeff Vincent for this insight.

boundary. Using another proxy measure for the agricultural value of water, column 3 shows that the presence of a groundwater well within one mile of a parcel also does not differ across the boundary.

We examine two additional covariates. If groundwater property rights led to consolidation or division of land parcels, there may be a discontinuity in land parcel size across the boundary. Column 4 reports that parcel size, measured in acres, does not jump at the boundary. Parcels with property rights may also be sold more or less recently, perhaps due to baseline differences in uncertainty over future land values with and without water rights. If so, we may be unable to detect time-varying treatment effects, discussed below. Column 5 does not detect a boundary discontinuity in a parcel's most recent transaction year.[31]

6.3 Main RD estimate and robustness checks

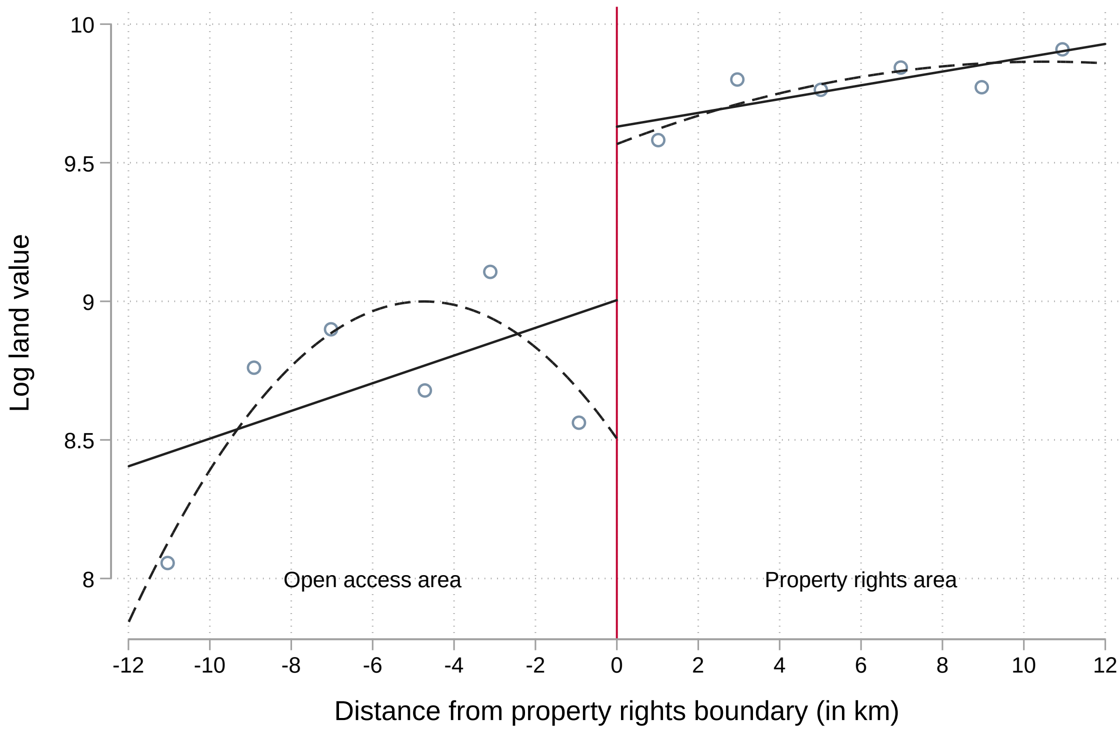
We first present our main RD result graphically. Figure 4 plots log land value, our main outcome of interest, against distance to the property rights boundary, d_i. Log land value is shown as local averages within 2 km-wide bins (circles) as well as separate linear (solid line) and quadratic (dashed line) fits over the unbinned data on each side of the discontinuity. Two features of Figure 4 are worth noting. First, there is a clear jump in land values at the discontinuity. Second, we find that land values are generally increasing from left to right in Figure 4. This is consistent with our theoretical prediction that water table levels rise as one moves from the open access area into the interior of the property rights area. We conduct a continuity test provided by Cattaneo, Jansson and Ma (forthcoming), an alternative to the McCrary (2008) procedure that avoids prebinning data, and do not detect a discontinuity in the density of the distance variable at the threshold.[32]

We now turn to estimates of β^{RD} from equation (18), shown in Table 2. Columns 1

[31] We would also like to test whether the groundwater level varies smoothly across the boundary but, unfortunately, cannot credibly do so. Monitoring wells, which are specifically designed to measure groundwater levels, are spatially sparse in this part of California. For example, the calculation for average groundwater level in 2015 shown in Figure 1 was based on only nine monitoring wells. Spatial interpolations with such a small number of point measurements would generate maps of groundwater levels that likely vary more smoothly than the actual groundwater table, and thus would be uninformative of groundwater levels at the boundary. Alternatively, California's Department of Water Resources well completion reports document privately-drilled wells, which are far more spatially dense than monitoring wells. However, the depth to well water available for privately-drilled wells may not correspond to the true groundwater level and are only available for the time when the well was initially drilled, which may not correspond to when we observe land values.

[32] We further note that traditional RD sorting concerns are lessened in our context. First, land parcels are fixed in space. Second, although there could be unobserved preference heterogeneity among landowners (e.g., some landowners may strongly prefer parcels with secure rights to water), competition in the land market implies that the value of an individual parcel's attributes is determined by the aggregate distribution of preferences across the market and not by individual preferences of that parcel's buyer and seller (Rosen, 1974).

Figure 4: Graphical RD effect



NOTES: Vertical axes shows log land value. Horizontal axes shows normalized distance in kilometers, d_i, to property rights boundary with $d_i \geq 0$ indicating property rights area and $d_i < 0$ indicating open access area. Circles indicate average log land values within a 2 km-wide bin. Solid (dashed) line shows linear (quadratic) fit over unbinned data separately on each side of the boundary.

and 3 model $f(d_i)$ as a local linear function, while columns 2 and 4 use a local quadratic model. Models in columns 1 and 2 exclude covariates while models in columns 3 and 4 include covariates. We detect a positive and statistically significant RD effect across all specifications. Translating these coefficients on binary treatment into percentage effects, we estimate a 190% to 280% increase in land value due to groundwater property rights at the boundary, relative to a mean value of $14,700 for open access parcels within 2 km of the boundary.

We next consider several additional robustness checks to the baseline model in column 1 of Table 2. Table 3 presents RD estimates using bandwidths smaller than one-half and larger than twice that of the baseline MSE-optimal bandwidth. Our RD result is not sensitive to these different bandwidth sizes.

Table C.2 considers alternative variance estimators. Our main RD sample uses zip code clustered standard errors with 29 zip codes. To address potential issues with fewer than 30 clusters (Cameron, Gelbach and Miller, 2008), column 2 conducts a zip code-level wild

Table 2: Main RD results

	(1)	(2)	(3)	(4)
	Outcome is log land value			
$\hat{\beta}^{RD}$	1.327**	1.328**	1.256***	1.071**
	(0.519)	(0.583)	(0.452)	(0.447)
Percentage effect (%)	277	277	251	192
Polynomial order	1	2	1	2
Covariates	No	No	Yes	Yes
Bandwidth	2.894	4.971	3.060	4.872
Observations	3288	5664	3513	5564
Zip codes	29	30	29	30

NOTES: Estimates of β^{RD} from equation (18) with log land value as outcome. Columns 1 and 2 exclude covariates; columns 3 and 4 include covariates. Columns 1 and 3 use a local linear model for $f(d_i)$; columns 2 and 4 use a local quadratic model for $f(d_i)$. Estimating sample based on a common MSE-optimal bandwidth across both sides of the threshold (Calonico, Cattaneo and Titiunik, 2014). Observations uniformly weighted within the bandwidth. Percentage effects are $100(e^{\hat{\beta}^{RD}} - 1)$. Standard errors clustered at the zip code level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 3: Robustness: alternative bandwidths

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Outcome is log land value						
$\hat{\beta}^{RD}$	1.327**	1.237***	0.943***	0.801**	1.176**	1.291***	1.066***
	(0.519)	(0.289)	(0.292)	(0.346)	(0.559)	(0.480)	(0.400)
Bandwidth	2.894	1.000	1.500	2.000	4.000	5.000	6.000
Observations	3288	1079	1601	2151	4609	5684	6653
Zip codes	29	23	25	26	27	27	29

NOTES: Estimates of β^{RD} from equation (18) with log land value as outcome. All models use a local linear model for $f(d_i)$, exclude covariates, and uniformly weights observations. Column 1 replicates baseline model in column 1 of Table 2 with sample restriction based on a common MSE-optimal bandwidth across both sides of the threshold (Calonico, Cattaneo and Titiunik, 2014). Column 2-7 use narrower and wider bandwidths, imposing the same value for both the main and bias bandwidths. Standard errors clustered at the zip code level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

bootstrap procedure specific for RD designs following He and Bartalotti (2020). This has little influence on the precision of our RD estimate. We further show in columns 3-5 that our RD result is insensitive to whether variance estimation is undertaken using zip code-level clustering, nearest neighbor matching, or both. Column 7 shows that our RD result also holds when a local randomization method is applied which allows for exact inference in finite samples, but requires the additional assumption that potential outcomes are non-random (Cattaneo, Frandsen and Titiunik, 2015; Cattaneo, Titiunik and Vazquez-Bare, 2016).

Finally, in Table C.3, we re-estimate the RD coefficient allowing the MSE-optimal bandwidth to differ on both sides of the discontinuity and consider bandwidths that are coverage error-rate (CER) optimal (Calonico, Cattaneo and Farrell, 2019). We also alternatively weight observations using a triangular, rather than a uniform, kernel. Our RD estimate is relatively stable across these estimation choices.

6.4 Placebo tests

We conduct two placebo tests that apply our RD estimator at different spatial locations and at a point in time before property rights were introduced. Because there is no spatial discontinuity between property rights and open access regimes in these settings, one should not detect any RD effects.

Table 4: Placebo tests

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
				Outcome is log land value			
$\hat{\beta}^{RD}$	-0.274	0.043	0.014	-0.252	0.066	-0.117	0.505
	(0.646)	(0.752)	(0.817)	(0.329)	(0.232)	(0.293)	(0.338)
Dist. to true boundary (km)	-9	-6	-3	3	6	9	0
Land value year	2015	2015	2015	2015	2015	2015	1976
Bandwidth	2.009	2.221	6.318	4.092	3.210	3.673	1.395
Observations	197	387	4382	7077	6388	6851	1152
Zip codes	10	18	23	33	31	31	24

NOTES: Estimates of β^{RD} from equation (18) with log land value as outcome. All models use a local linear model for $f(d_i)$, exclude covariates, restrict sample based on a common MSE-optimal bandwidth across both sides of the threshold (Calonico, Cattaneo and Titiunik, 2014), and uniformly weight observations. Columns 1-6 use placebo property right boundaries set 9, 6, and 3 kilometers within the open access (i.e., $d_i < 0$) and property rights areas (i.e., $d_i > 0$) with land values at 2015. Column 7 use the true property rights boundary but with land values in 1976. Standard errors clustered at the zip code level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Columns 1-6 of Table 4 show RD estimates for equation (18) using 2015 land values, but estimated at placebo boundary thresholds. For models in columns 1-3, we create false boundaries that are 9, 6, and 3 kilometers, respectively, within the open access area relative to the actual property rights boundary. In columns 4-6, we create similarly spaced false boundaries within the property rights area. We do not detect an RD effect with any of these false boundaries.

Despite the covariate balance demonstrated in Table 1, the discontinuity in land values at the true boundary could still reflect a jump in some unobserved, time-invariant factor that is correlated with groundwater property rights. We conduct a second placebo test examining whether there is a discontinuity in historical land values well before the implementation of groundwater property rights. In column 7 of Table 4, we provide estimates for equation (18) at the true boundary but using land values from 1976.[33] Land values from this earlier period do not exhibit a discontinuity.

6.5 Heterogeneity

We now turn to heterogeneity analyses, across time and space.

Our main RD estimate pools land parcels that were most recently transacted within the 1997-2015 period. Recall that under Proposition 13, the 2015 assessed land value for a previously transacted parcel would not reflect its 2015 market value but rather its price at the time of last sale, with a 2% annual adjustment. This implication of Proposition 13, together with column 5 of Table 1 showing no boundary discontinuity in the most recent sales year, suggests that our main RD estimate reflects the average treatment effect of groundwater property rights over the 1997-2015 period, rather than the treatment effect for only 2015. A natural question, then, is whether the net benefit of groundwater property rights has changed since adjudication was introduced. Since Proposition 1(e) shows that the time derivative of discounted net benefits is ambiguously signed, we turn to estimates of the RD effect over time.

Column 1 of Table 5 reproduces our benchmark RD estimate, pooling 1997-2015 transaction years. In columns 2-4, we report estimates of our baseline model using the same bandwidth as in column 1, but for separate subsamples of parcels that were most recently transacted during the 1997-2013, 2004-2009, and 2010-2015 periods, respectively. Remarkably, the discounted net benefit of groundwater property rights has changed very little since its introduction. That our estimates remain positive across time suggests that the continuation of this policy has been economically justified.

Despite Proposition 13, it may still be the case that the assessed value of a parcel transacted in an earlier year is noisy due to errors made by the land assessor. To isolate parcels whose assessed value equal sales value, columns 5 and 6 of Table 5 provide estimates of our baseline model for the subsample of parcels that were transacted in 2015, the same year as

[33] We choose 1976 for three reasons. First, 1976 is the earliest year for which digitized land values are available for our study area. Second, 1976 is early enough such that land markets are unlikely to be expecting future groundwater rights imposed in the mid-1990s. Third, 1976 is two years before the enactment of Proposition 13.

Table 5: Heterogeneity across time

	(1)	(2)	(3)	(4)	(5)	(6)
	Outcome is log land value					
$\hat{\beta}^{RD}$	1.327**	1.440**	1.449***	1.233*	1.489	1.517**
	(0.519)	(0.668)	(0.498)	(0.748)	(0.977)	(0.597)
Transaction year	1997-2015	1997-2003	2004-2009	2010-2015	2015	2015
Bandwidth	2.894	2.894	2.894	2.894	2.894	3.176
Observations	3288	722	1441	1125	192	220
Zip codes	29	22	25	27	21	24

NOTES: Estimates of β^{RD} from equation (18) with log land value as outcome. All models use a local linear model for $f(d_i)$, exclude covariates, restrict sample based on a common MSE-optimal bandwidth across both sides of the threshold (Calonico, Cattaneo and Titiunik, 2014), and uniformly weight observations. Column 1 replicates baseline model in column 1 of Table 2. Columns 2-4 estimate baseline model using the baseline bandwidth for the subsample of parcels most recently transacted in 1997-2013, 2004-2009, and 2010-2015, respectively. Column 5 estimates the baseline model using the baseline bandwidth for the subsample of parcels most recently transacted in 2015. Column 6 estimates the baseline model for the subsample of parcels most recently transacted in 2015, but uses a MSE-optimal bandwidth for that subsample. Standard errors clustered at the zip code level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

our assessed land value data. For consistency with other results, the model in column 5 uses the distance bandwidth from our baseline sample, while the model in column 6 employs a distance bandwidth that is MSE-optimal for the subsample of 2015-transacted parcels. We find that these subsamples produce RD effects that are similar to our baseline result, mitigating concerns regarding noise in assessed land values.

Section 4.2 discusses how the net benefit of tradeable groundwater rights depends on the market value of water (i.e., "salvage value"). When this outside value is higher than one's own value of water, tradeable property rights allow landowners to gain from sales of water rights to other users in the aquifer. For groundwater in the Mojave, this higher-value use is likely strongest in the more urban southern part of the aquifer (see inset map in Figure 2).

To test whether potential urban water demand creates larger benefits from tradeable property rights, Table 6 examines heterogeneity in the RD coefficient for southern and northern subareas of the aquifer. Because trading of water rights can only occur within a particular subarea of the aquifer, one would expect the RD effect to be larger in the more urbanized southern subareas. Column 1 replicates our baseline results. The model in column 2 restricts the sample to parcels in the southern subareas, while only northern subarea parcels are used to produce estimates in column 3. The RD coefficient in the southern subareas of the aquifer is almost six times larger than in the northern subareas, though statistical inference is complicated by the limited number of zip code clusters. As an alternative approach to modeling

Table 6: Heterogeneity across space

	(1)	(2)	(3)	(4)	(5)
	Outcome is log land value				
$\hat{\beta}^{RD}$	1.327**	1.984**	0.334	1.219***	0.017
	(0.519)	(0.845)	(0.464)	(0.401)	(0.841)
Area	All	South	North	South	North
Boundary definition	All	All	All	River basin	River basin
Bandwidth	2.894	2.894	2.894	2.894	2.894
Observations	3288	2412	876	166	535
Zip codes	29	15	15	4	10

NOTES: Estimates of β^{RD} from equation (18) with log land value as outcome. All models use a local linear model for $f(d_i)$, exclude covariates, restrict sample based on a common MSE-optimal bandwidth across both sides of the threshold (Calonico, Cattaneo and Titiunik, 2014), and uniformly weight observations. Column 1 replicates baseline model in column 1 of Table 2. Columns 2 and 3 restrict the sample to land parcels in southern and northern subareas, respectively. Columns 4 and 5 further restrict the southern and northern subarea sample, respectively, by including only parcels whose nearest property rights boundary is defined by the Mojave River drainage basin. Standard errors clustered at the zip code level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

this heterogeneity, we interact R_i and $f(d_i)$ from our baseline model of equation (18) with a parcel's latitude. Figure B.2 plots how $\hat{\beta}^{RD}$ varies as one moves northward across the aquifer, showing a statistically significant decline. For parcels that are farthest north, the RD effect becomes negative, which is possible when the gain from trading rights is small.

How much does the tradeability of property rights contribute to the net benefit of the Mojave adjudication regime? Columns 1-3 of Table 6 merely show that gains from rights trading contribute to the net benefit, but not by how much. Note also that by controlling for groundwater level differences, our RD approach cannot definitively separate net benefits into components due to the assignment of property rights and to their tradeability. To conduct a back-of-the-envelope calculation, we assume that the benefit of a higher water table can be identified using land value differences farther away from the boundary and that the gains from rights trading in the northern subareas is small. With these assumptions, we calculate that rights trading contributes to at most two-thirds of the net benefit of the Mojave adjudication regime.[34]

[34] To obtain this number, we divide the difference between RD estimates in columns 1 and 3 in Table 6 (i.e., 1.33-.33), which isolates the gains from rights trading, by the difference in average land values at the edge of the support shown in Figure 4 (i.e., 9.9-8.4), which incorporates the water table gradient. This is an upper bound on the contribution of rights trading because gains from rights trading in the northern subarea, while smaller, are still positive (i.e., the true numerator is smaller) and because the true water table difference is likely larger (i.e., the true denominator is larger).

Finally, the RD effect may be heterogeneous depending on how the boundary is defined. The model in column 4 of Table 6 further restricts the sample of southern subarea parcels to those whose nearest property right boundary is defined by the spatial extent of the Mojave River drainage basin (shown by purple line segments in Figure 2) and not the Mojave Water Agency (shown by red line segments in Figure 2). We find a similar RD effect as that shown in column 2. Likewise, column 5 shows that the RD effect for northern subareas is similar across the two boundary definitions. Thus, it does not appear that our RD effect differs systematically by how the property rights boundary is defined.[35]

6.6 Total net benefit of tradeable property rights

We quantify the total net benefit of tradeable groundwater property rights across all adjudicated parcels in the Mojave aquifer.

Section 4.2 notes that our RD estimate is a lower bound on the local average treatment effect for adjudicated parcels at the boundary. If one assumes that unobserved characteristics are uncorrelated with distance to the boundary, our RD estimate further serves as a lower bound for the population average treatment effect of all adjudicated parcels. This orthogonality assumption, together with the south-north heterogeneity in the RD coefficient, enables a lower bound calculation for the total net benefit of property rights across adjudicated parcels.

To that end, we multiply the heterogeneous RD effect separately for parcels in southern (i.e., column 2 of Table 6) and northern (i.e., column 3 of Table 6) subareas with each parcel's land value. We then sum this product across all regulated land parcels in the property rights area. This results in a lower bound total net benefit of groundwater property rights of $477 million (in 2015 dollars), or a 53% increase in total land value.[36] By contrast, the initial administrative cost of setting up the adjudication system is estimated at $40 million (in 2015 dollars) (Figueroa, 2001).

[35] Figure 2 shows that property rights boundary segments defined by the Mojave River drainage basin (shown by purple line segments) are better represented in the northern parts of the property rights area. Thus, an RD estimate using all parcels near the Mojave River drainage basin boundary would have more northern subarea parcels and would not be comparable to an RD estimate using all parcels near the Mojave Water Agency boundary. Table 6 addresses this by examining whether RD estimates differ by boundary definition separately for northern and southern subsamples. Alternatively, we also follow Gerardino, Litschig and Pomeranz (2017) by running an RD subsample test that weights all parcels by their latitude and do not find RD estimates that differ by boundary definition.

[36] Observe that by Proposition 1(c), this value is yet another lower bound for the total net benefit of groundwater property rights for all parcels overlying the aquifer, both those with property rights and under open access.

7 Conclusion

Coase's property rights solution to the tragedy of the commons has become widely advocated despite limited empirical evidence. This paper applies a spatial regression discontinuity design to quantify the net benefit of using tradeable property rights to manage a common-pool resource. We find that the introduction of such rights for a major groundwater aquifer in southern California led to substantial gains, as captured by higher land values. Using a model of dynamic groundwater extraction, we show that our RD estimate corresponds to a lower bound on the net benefit of property rights. Additional analyses suggest that a key component of these benefits derives from the tradeability of these rights, which enable more efficient allocation of water away from water-intensive agriculture toward urban residential and commercial use.

Our findings can inform efforts to address overextraction of other common-pool resources, such as fisheries, forests, and the global climate. For groundwater in particular, California recently passed the Sustainable Groundwater Management Act, an unprecedented policy requiring users of overextracted aquifers to adopt management plans to achieve sustainable use. While it remains contentious which management tools should be employed, this paper's findings suggest that property rights, and particularly those that are tradeable, can help stabilize groundwater levels, increase land value, and induce more efficient water use. Users and regulators alike may reference these benefits in future efforts to establish tradeable property rights for groundwater and common-pool resources more generally.

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Appendix – For Online Publication

A Theory appendix

This section derives Proposition 1.

Proposition 1(a): $V^{mr} - V^{a} \gtreqless 0$

Using equations (3) and (13), define

$$V^{mr} - V^{a} = \int_0^{t^*} \pi(w^{mr}(s), \bar{h}^{mr}) e^{-\delta s} ds + F(t^*)e^{-\delta t^*} - \int_0^{\infty} \pi(w^{a}(s), h^{a}(s)) e^{-\delta s} ds$$

which we now examine separately for each period.

Before rights are sold: $t \in [0, t^*]$ The difference in discounted profit before t^* is

$$\begin{aligned}\int_0^{t^*} \left[\pi(w^{mr}(s), \bar{h}^{mr}) - \pi(w^{a}(s), h^{a}(s))\right] e^{-\delta s} ds = \int_0^{t^*} &\Bigg[\underbrace{\pi(w^{mr}(s), \bar{h}^{mr}) - \pi(w^{a}(s), \bar{h}^{mr})}_{\leq 0} \\ &+ \underbrace{\pi(w^{a}(s), \bar{h}^{mr}) - \pi(w^{a}(s), h^{a}(s))}_{\geq 0}\Bigg] e^{-\delta s} ds \\ &\gtreqless 0\end{aligned} \tag{A.1}$$

where the first bracketed term in equation (A.1) is weakly negative because for $\bar{h}^{mr}$, $\pi(w, \bar{h}^{mr})$ is optimal at $w^{a}(h_0)$ and $w^{a}(h_0) \geq w^{a}(t) \geq w^{mr}(t)$ for $t \geq 0$. The second bracketed term in equation (A.1) is weakly positive because $\bar{h}^{mr} \geq h^{a}(t)$ for $t \geq 0$ and $\pi_h > 0$.

After rights are sold: $t \in [t^*, \infty]$ The difference in discounted profit after t^* is

$$\begin{aligned}F(t^*)e^{-\delta t^*} - \int_{t^*}^{\infty} \pi(w^{a}(s), h^{a}(s)) e^{-\delta s} ds = &\underbrace{F(t^*)e^{-\delta t^*} - \int_{t^*}^{\infty} \pi(w^{mr}(s), \bar{h}^{mr}(s)) e^{-\delta s} ds}_{\geq 0} \\ &+ \int_{t^*}^{\infty} \Bigg[\underbrace{\pi(w^{mr}(s), \bar{h}^{mr}(s)) - \pi(w^{a}(s), h^{a}(s))}_{\gtreqless 0}\Bigg] e^{-\delta s} ds \\ &\gtreqless 0\end{aligned} \tag{A.2}$$

where the first bracketed term in equation (A.2) is weakly positive because t^* solves the optimization problem in equation (11). The second bracketed term in equation (A.2) is ambiguously signed by equation (A.1).

$V^{mr} - V^a \gtreqless 0$ follows from summing the terms in equations (A.1) and (A.2).

Proposition 1(b): $\boldsymbol{V^{mr} - V^{ma} \gtreqless 0}$

Using equations (13) and (14), define

$$V^{mr} - V^{ma} = \int_0^{t^*} \pi(w^{mr}(s), \bar{h}^{mr}) e^{-\delta s} ds + F(t^*)e^{-\delta t^*} - \int_0^{\infty} \pi(w^{ma}(s), h^{ma}(s)) e^{-\delta s} ds$$

which we now examine separately for each period.

Before rights are sold: $\boldsymbol{t \in [0, t^*]}$ The difference in discounted profit before t^* is

$$\begin{aligned}\int_0^{t^*} \left[\pi(w^{mr}(s), \bar{h}^{mr}) - \pi(w^{ma}(s), h^{ma}(s))\right] e^{-\delta s} ds &= \int_0^{t^*} \Bigg[\underbrace{\pi(w^{mr}(s), \bar{h}^{mr}) - \pi(w^{ma}(s), \bar{h}^{mr})}_{\leq 0} \\ &\quad + \underbrace{\pi(w^{ma}(s), \bar{h}^{mr}) - \pi(w^{ma}(s), h^{ma}(s))}_{\geq 0}\Bigg] e^{-\delta s} ds \\ &\gtreqless 0\end{aligned} \tag{A.3}$$

where the first bracketed term in equation (A.3) is weakly negative because for $\bar{h}^{mr}$, $\pi(w, \bar{h}^{mr})$ is optimal at $w^a(h_0)$ and $w^a(h_0) \geq w^{ma}(t) \geq w^{mr}(t)$ $t \geq 0$. The second bracketed term in equation (A.1) is weakly positive because $\bar{h}^{mr} \geq h^{ma}(t)$ for $t \geq 0$ and $\pi_h > 0$.

After rights are sold: $\boldsymbol{t \in [t^*, \infty]}$ The difference in discounted profit after t^* is

$$\begin{aligned}F(t^*)e^{-\delta t^*} - \int_{t^*}^{\infty} \pi(w^{ma}(s), h^{ma}(s)) e^{-\delta s} ds &= \underbrace{F(t^*)e^{-\delta t^*} - \int_{t^*}^{\infty} \pi(w^{mr}(s), \bar{h}^{mr}(s)) e^{-\delta s} ds}_{\geq 0} \\ &\quad + \int_{t^*}^{\infty} \Bigg[\underbrace{\pi(w^{mr}(s), \bar{h}^{mr}(s)) - \pi(w^{ma}(s), h^{ma}(s))}_{\gtreqless 0}\Bigg] e^{-\delta s} ds \\ &\gtreqless 0\end{aligned} \tag{A.4}$$

where the first bracketed term in equation (A.4) is weakly positive because t^* solves the maximization problem in equation (11). The second bracketed term in equation (A.4) is ambiguously signed by equation (A.3).

$V^{mr} - V^{ma} \gtreqless 0$ follows from summing the terms in equations (A.3) and (A.4).

Proposition 1(c): $(V^{mr}(h^b) - V^a) - (V^{mr}(h^b) - V^{ma}(h^b) \geq 0$

Using equations (3) and (14), define

$$\begin{aligned}(V^{mr}(h^b) - V^a) - (V^{mr}(h^b) - V^{ma}(h^b) &= V^{ma}(h^b) - V^a \\ &= \int_0^\infty \left[\pi(w^{ma}(s), h^b(s)) - \pi(w^a(s), h^a(s))\right] e^{-\delta s} ds \\ &= \int_0^\infty \Bigg[\underbrace{\pi(w^{ma}(s), h^b(s)) - \pi(w^a(s), h^b(s))}_{\geq 0} \\ &+ \underbrace{\pi(w^a(s), h^b(s)) - \pi(w^a(s), h^a(s))}_{\geq 0}\Bigg] e^{-\delta s} ds \qquad \text{(A.5)} \\ &\geq 0\end{aligned}$$

where the first bracketed term in equation (A.5) is weakly positive because for $h^b(t)$, $\pi(w, h^b(t))$ is maximized at $w^{ma}(t)$ for $t \geq 0$. The second bracketed term in equation (A.5) is weakly positive because $h^b(t) \geq h^a(t)$ since $h^{ma}(t) \geq h^a(t)$ and $h^b(t) \geq h^{ma}(t)$for $t \geq 0$ and $\pi_h > 0$.

Proposition 1(d): $(V^{mr} - V^a) - (V^{mr}(h^b) - V^a) \geq 0$

Using equation (13), define

$$\begin{aligned}(V^{mr} - V^a) - (V^{mr}(h^b) - V^a) &= V^{mr} - V^{mr}(h^b) \\ &= \int_0^{t^*} [\underbrace{\pi(w^{mr}(s), \bar{h}^{mr}) - \pi(w^{mr}(s), h^b(s))}_{\geq 0}] e^{-\delta s} ds \qquad \text{(A.6)} \\ &\geq 0\end{aligned}$$

where the bracketed term in equation A.6 is weakly positive because $\bar{h}^{mr} \geq h^b(t)$ for $t \geq 0$ and $\pi_h > 0$.

Proposition 1(e): $\frac{d}{dt}(V^{mr}(h^b) - V^{ma}(h^b)) \gtreqless 0$

Using equations (13) and (14), the estimated effect at the boundary at any time t is

$$V^{mr}(h^b) - V^{ma}(h^b) = \int_t^{t^*} \pi(w^{mr}(s), h^b(s))e^{-\delta(s-t)}ds + F(t^*)e^{-\delta(t^*-t)} - \int_t^{\infty} \pi(w^{ma}(s), h^b(s))e^{-\delta(s-t)}ds$$

Using Liebnitz's Rule, we obtain

$$\frac{d}{dt}(V^{mr}(h^b) - V^{ma}(h^b)) = \delta[V^{mr}(h^b) - V^{ma}(h^b)] + [\underbrace{\pi(w^{ma}(t), h^b(t)) - \pi(w^{mr}(t), h^b(t))}_{\geq 0}]$$

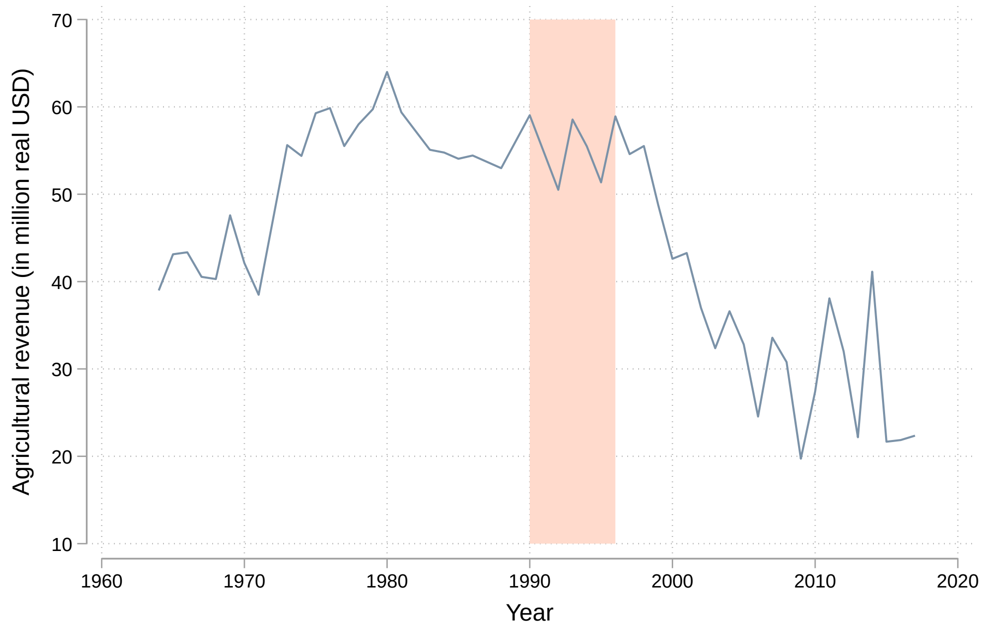
The second bracketed term is weakly positive because for $h^b(t)$, $\pi(w, h^b(t))$ is maximized at $w^{ma}(t)$ for $t \geq 0$. The first bracketed term is

$$V^{mr}(h^b) - V^{ma}(h^b) = \int_t^{t^*} [\underbrace{\pi(w^{mr}(s), h^b(s)) - \pi(w^{ma}(s), h^b(s))}_{\leq 0}]e^{-\delta(s-t)}ds + \underbrace{F(t^*)e^{-\delta(t^*-t)} - \int_{t^*}^{\infty} \pi(w^{ma}(s), h^b(s))e^{-\delta(s-t)}ds}_{\gtreqless 0}$$

The second term is ambiguously signed since our model imposes no constraints on the value of $F(t^*)$. Thus, $\frac{d}{dt}(V^{mr}(h^b) - V^{ma}(h^b)) \gtreqless 0$.

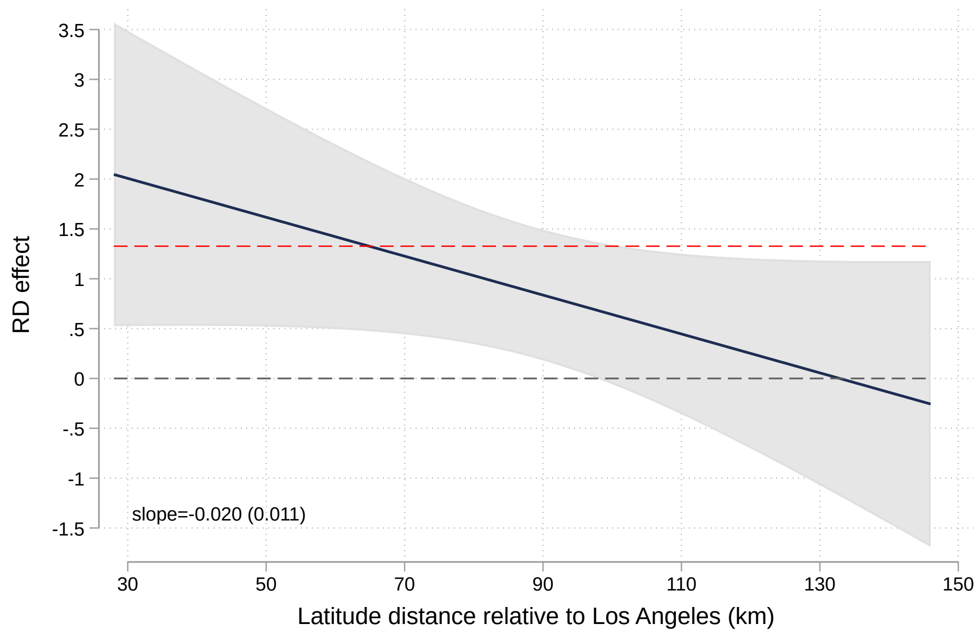
B Appendix Figures

Figure B.1: Agricultural revenue before and after property rights



Notes: Plot shows agricultural revenue (in real million USD) for the Mojave Desert from 1960-2017. Data takes the sum of revenue from the North and South Desert regions of San Bernardino county, obtained from the San Bernardino county Annual Crop Reports. Orange-shaded area marks the period from 1990 when the initial adjudication lawsuit was filed to 1996 when the final adjudication court ruling was issued.

Figure B.2: Heterogeneity: south to north



Notes: Plot shows heterogeneity in $\hat{\beta}^{RD}$ as a function of a parcel's latitude, relative to the centroid of Los Angeles. Point estimate and standard error on slope shown. Horizontal red dashed line shows baseline uninteracted RD effect from column 1 of Table 2. 95% confidence intervals shown.

C Appendix Tables

Table C.1: Summary statistics

	Obs	Mean	Std dev	p(1)	p(99)
Land value (in 2015 USD)	22725	32587.7	66214.6	612.0	287000.0
Dist. from prop. rights boundary (in km)	22725	11.9	11.0	-14.3	37.6
Avg. slope (in degrees)	22725	1.9	2.7	0.1	15.2
Avg. aspect (in compass direction)	22703	166.4	99.2	11.6	347.0
Dummy whether near 1 mile of well	22725	0.9	0.3	0.0	1.0
Parcel size (in acres)	22725	13.5	39.4	0.2	160.0
Most recent transaction year	22725	2007.3	4.6	1997.0	2015.0

NOTES: Number of observations, mean, standard deviation, 1st percentile and 99th percentile of variables in primary dataset (see Section 5). Sample includes land parcels close to the property rights boundary used in RD estimation and those further away.

Table C.2: Robustness: alternative variance estimators

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
			Outcome is log land value				
$\hat{\beta}^{RD}$	1.327**	1.346	1.098***	1.013***	1.017***	1.259***	1.240
	(0.519)		(0.159)	(0.160)	(0.161)	(0.428)	{0.000}
	[0.309, 2.345]	[0.483, 2.210]	[0.787, 1.408]	[0.700, 1.326]	[0.702, 1.332]	[0.421, 2.098]	
Std. error/inference	zipcode cluster	wild bootstrap zipcode cluster	50 NN	100 NN	200 NN	200 NN/ zipcode cluster	random-ization
Bandwidth	2.894	2.894	2.644	2.574	2.568	3.456	2.894
Observations	3288	3288	2902	2822	2815	3978	3288

NOTES: Estimates of β^{RD} from equation (18) with log land value as outcome. All models use a local linear model for $f(d_i)$, exclude covariates, restrict sample based on a common MSE-optimal bandwidth across both sides of the threshold (Calonico, Cattaneo and Titiunik, 2014), and uniformly weights observations. Column 1 replicates column 1 of Table 2 using standard errors clustered at the zip code level. Column 2 uses a block wild bootstrap procedure at the zip code level following He and Bartalotti (2020). Columns 3, 4, and 5 use a nearest neighbor variance estimator with 50, 100 and 200 minimum nearest neighbors (NN). Column 6 uses a zip code cluster-robust, nearest neighbor variance estimator with 200 minimum nearest neighbors. Column 7 uses local randomization inference following Cattaneo, Frandsen and Titiunik (2015) and Cattaneo, Titiunik and Vazquez-Bare (2016). Standard errors in parentheses; p-values in curly brackets; 95% confidence interval in square brackets. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table C.3: Robustness: optimal bandwidth selector

	(1)	(2)	(3)	(4)	(5)
	Outcome is log land value				
$\hat{\beta}^{RD}$	1.327**	1.234**	0.977*	1.176**	1.181**
	(0.519)	(0.537)	(0.542)	(0.501)	(0.495)
Optimal bandwidth selector	MSE-1	MSE-2	CER-1	CER-2	MSE-1
Kernel	uniform	uniform	uniform	uniform	triangular
Bandwidth	2.894	2.559/5.038	2.423	2.142/4.218	3.355
Observations	3288	5153	2611	4317	3864
Zip codes	29	30	29	30	29

NOTES: Estimates of β^{RD} from equation (18) with log land value as outcome. All models use a local linear model for $f(d_i)$ and exclude covariates. Columns 1-4 uniformly weight observations. Column 1 replicates baseline model in column 1 of Table 2 with sample restriction based on a common MSE-optimal bandwidth across both sides of the threshold (Calonico, Cattaneo and Titiunik, 2014) Column 2 allows the MSE-optimal bandwidth to differ on both sides. Column 3 uses a common coverage error-rate (CER) optimal bandwidth (Calonico, Cattaneo and Farrell, 2019). Column 4 allows the CER-optimal bandwidth to differ on both sides. Column 5 uses a common MSE-optimal bandwidth but weights observations using a triangular kernel. Standard errors clustered at the zip code level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.