Groundwater Under Open Access:
A Structural Model of the Dynamic Common Pool Extraction Game*

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Abstract

Groundwater is a critical resource whose common pool and partially nonrenewable nature poses a challenge to sustainable management. We analyze groundwater extraction decisions under an open access regime by estimating a structural econometric model of the dynamic game among agricultural, recreational, and municipal groundwater users in the Beaumont Basin in Southern California during a period of open access. We use our parameter estimates to simulate a counterfactual scenario of continued open access, which we then compare with the actual extraction decisions of players after the institution of quantified property rights. Results show that while imposing property rights on the previously open-access groundwater resource did not deliver significant economic benefits on groundwater users, the joint effect of the property rights system and the introduction of artificial recharge of imported water prevented a significant decline in the basin's stock of groundwater. Furthermore, by preventing a shift in groundwater extraction to wells outside of Beaumont, these policies also had a positive spillover effect on the level of groundwater stocks at neighboring basins. Finally, we find that municipal water districts tend to value the interests of their customers more than water sale profits, resulting in inefficient underpricing of water and significant social welfare loss.

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1 Introduction

Groundwater is a critical natural resource for both irrigated agriculture and the development of population centers in arid regions of California (California Department of Water Resources, 2019), a state which produces almost 70 percent of the nation's top 25 fruit, nut, and vegetable crops (Howitt and Lund, 2014). Groundwater extraction has generally outpaced recharge in California, leading to long-term declines in groundwater table levels (Famiglietti et al., 2011; Famiglietti, 2014). At the height of a recent sustained drought, the state declared 21 groundwater basins to be in critical overdraft (California Department of Water Resources, 2016a).

Two features of groundwater make its sustainable management difficult. First, groundwater users who share the same aquifer face a common pool resource problem: groundwater pumping by one user raises the extraction cost and lowers the total amount available to other nearby users (Provencher and Burt, 1993; Brozović et al., 2002, 2010). Second, if an aquifer receives very little recharge, then groundwater is at least partially a nonrenewable resource and therefore should be managed dynamically and carefully for long-term sustainable use (Lin Lawell, 2016; Sears and Lin Lawell, 2019).

In this paper, we analyze groundwater extraction decisions under an open access regime by developing a structural econometric model of the dynamic common pool extraction game among farmers, other overlying users, and appropriators in the Beaumont Basin area of Southern California prior to the institution of quantified property rights. For much of its history, groundwater was the only source of water in the Beaumont Basin area, and during the 20th century the water table level declined by over 100 feet due to overdraft (Rewis et al., 2006). We estimate our model using a large, detailed, and comprehensive spatial user-level panel data set we have collected and constructed from handwritten hard-copy historical records and remotely sensed data on the actual decisions that have been made by individual farmers, water districts, and other groundwater users in the years prior to the institution of quantified property rights. We take advantage of variation across players over space and over time in key hydrological and economic drivers of groundwater extraction to identify parameters of the payoff functions of agricultural, recreational, and municipal users.

The parameters we estimate are structural parameters under open access, wherein groundwater users are able to extract as much as they desire without being required to obtain or verify that they possess any formal property right. We use our parameter estimates to simulate a counterfactual scenario of continued open access, and compare our open access counterfactual with the actual extraction decisions that were made after the institution of quantified property rights in order to quantify the welfare gains and losses from shifting to a quantified property rights system for the different groundwater users in our empirical setting.

Our results provide several useful findings for policy-makers. First, we find that groundwater was and remains a critical resource for municipal water providers, whose total annual welfare from groundwater extraction was around $47.2 million per year during the period of open access, and around \$29.6 million per year after the institution of quantified property rights. Both before and after the introduction of property rights, municipal water providers received most of their benefits in the form of being able to sell cheaper water to their customers. On average, municipal water districts value consumer surplus twice as much as they do profits from water sales. This socially inefficient overweighting of consumer surplus leads to inefficient underpricing of water and a social welfare loss of approximately \$3.4 million per year after the institution of property rights.

Second, we estimate that, for municipal water districts and farmers inside Beaumont Basin, short-run welfare gains from the imposition of property rights and imported water, relative to a counterfactual of continued open access, were statistically insignificant. Moreover, short-run social welfare gains from the imposition of property rights and imported water, relative to a counterfactual of continued open access, were statistically insignificant as well. Nevertheless, we find that these policy changes helped to prevent a collapse in groundwater use in the Beaumont Basin, as well as a rush to pump from nearby basins, since they enabled appropriators to continue to draw on water from the Beaumont Basin rather than having to exploit other stocks.

The balance of our paper proceeds as follows. We review the previous literature in Section 2. We describe our empirical setting and data in Section 3. We present our model of the open access dynamic game in Section 4. We describe the estimation of our structural econometric model in Section 5. We present our results in Section 6. We simulate our counterfactual open access scenarios in Section 7. We present robustness checks in Section 8. We discuss our results and conclude in Section 9.

2 Literature

We build on the literature on groundwater management and property rights.[1] Groundwater management is often considered a classic example of a "common pool resource" problem (Gardner et al., 1990; Ostrom, 2008; Roumasset and Wada, 2013). Common pool resources are characterized by two main features: (i) they are large enough in size that it is costly, although not necessarily impossible, to exclude potential beneficiaries from using the resource; and (ii) extraction of a unit of the resource by one user prevents access of a unit of the resource from others (Gardner et al., 1990). Historical groundwater management in California clearly fits this definition, due to a relative lack of regulation – historically, groundwater extractors have not been required to seek approval before exercising their right to extract groundwater – and to the hydrology of groundwater in the state which leads to the flow of the resource between properties. With multiple users, cooperation can be difficult to achieve owing to strong free-rider incentives (Ansink and Weikard, 2020).

As a common pool resource, groundwater suffers from spatial pumping externalities whereby one user's groundwater extraction raises the extraction cost and lowers the total amount available to other nearby users, making its sustainable management difficult (Dasgupta and Heal, 1979; Eswaran and

[1] For a more comprehensive review of the literature on groundwater management and property rights, see Sears et al. (2025d).

Lewis, 1984; Negri, 1989; Provencher and Burt, 1993; Brozović et al., 2002; Rubio and Casino, 2003; Koundouri, 2004; Msangi, 2004; Saak and Peterson, 2007; Brozović et al., 2010; Lin and Pfeiffer, 2015; Lin Lawell, 2016; Dinar and Dinar, 2016; Sears et al., 2018b; Merrill and Guilfoos, 2018; Sears and Lin Lawell, 2019; Sears et al., 2019, 2025a). In addition, if an aquifer receives very little recharge, then groundwater is at least partially a nonrenewable resource and therefore should be managed dynamically and carefully for long-term sustainable use (Lin Lawell, 2016; Sears and Lin Lawell, 2019).

The degree to which common pool resources are inefficiently exploited depends on the ability of rights holders to identify, keep track of, and assert property rights (Sweeney et al., 1971). A well-defined property rights system would define exclusive rights to the stock rather than to a flow from the asset (Lueck, 1995), and would enable groundwater users to internalize any spatial externalities as well, for example by defining exclusive rights to the groundwater stock in the entire aquifer (Bertone Oehninger and Lin Lawell, 2021; Sears et al., 2025b). The first-best groundwater management policy can be complicated and require a high level of monitoring and enforcement, rendering it unattractive due to the high economic cost as well as political infeasibility (Guilfoos et al., 2016). Equity concerns may also pose a barrier to the use of property rights for managing common pool resources (Ryan and Sudarshan, 2020).

The security of property rights to a common pool resource is predicted to have a positive impact on productive use of the resource (Grossman, 2001). Browne and Ji (2021) measures the value created by clarifying property rights for water in Idaho. Tsvetanov and Earnhardt (2020) find that water right retirement in High Priority Areas in Kansas substantially reduced groundwater extraction. In addition, how water rights are measured and bounded within a property rights system can influence water resource development and productivity as well (Smith, 2021).

Zilberman et al. (2017) argue that water rights in California, and the Western US, have developed within a broader context of rapid development of arid land, arising more out of concerns for encouraging the settlement and productive use of arable land than for issues of allocative or dynamic efficiency. Ayres et al. (2021) analyze a major aquifer in the Mojave Desert in southern California, and find that groundwater property rights led to substantial net benefits, as capitalized in land values. McLaughlin (2021) finds that basins that formalize property rights experience an improvement in groundwater levels. Rimsaite et al. (2021) examine the degree to which U.S. western water market prices in nine states act as asset pricing theory would predict, and find that water market efficiency is highest in one of the most active U.S. water rights markets located in the Mojave Basin Area, where markets have lower barriers to trade. Nevertheless, Regnacq et al. (2016) find that transfer costs may limit the benefits from tradable water rights in California.

We also build on the literature on dynamic structural econometric models,[2] and in particular on

[2]Related applications and extensions of the seminal dynamic structural econometric model developed by Rust (1987) include applications to water management (Timmins, 2002), energy (Rothwell and Rust, 1997; Rapson, 2014; Cook and Lin Lawell, 2020; Feger et al., 2020; Langer and Lemoine, 2022; Cullen, 2015; Cullen et al., 2017; Weber, 2022; Butters et al., 2025; Bradt, 2024), natural resource management (Aguirregabiria and Luengo, 2016; Reeling et al., 2020; Oliva

the literature on structural econometric models of dynamic games. Most models in this literature assume a Markov perfect equilibrium in which players maximize their present discounted value based on expectations about the evolution of state variables (Ericson and Pakes, 1995; Pakes et al., 2007; Aguirregabiria and Mira, 2007; Pesendorfer and Schmidt-Dengler, 2008; de Paula, 2009; Aguirregabiria and Mira, 2010; Srisuma and Linton, 2012; Egesdal et al., 2015; Iskhakov et al., 2016; Adusumilli and Eckardt, 2020; Dearing and Blevins, 2025).[3] Finding an equilibrium is computationally costly even for problems with a simple structure. In more complex problems – as in the case of our dynamic game between groundwater users, where many agents are involved – the computational burden is even more important, particularly if there may be multiple equilibria. We apply the method proposed by Bajari et al. (2007) for recovering the dynamic parameters of the payoff function without having to compute any single equilibrium. This model has also been applied to environmental policy (Ryan, 2012; Fowlie et al., 2016; Yi et al., 2025; Zakerinia and Lin Lawell, 2025), energy markets (Gerarden, 2023; Kheiravar et al., 2025), development (Rojas Valdés et al., 2018, 2025), and digital applications (Uetake and Yang, 2022; Leyden, 2019).

We innovate upon the literature by drawing from and combining the erstwhile separate literatures on groundwater management and on structural econometric models of dynamic games; by estimating a structural econometric model of the dynamic common pool extraction game among agricultural, recreational, and municipal groundwater users under open access; and by using our structural model to calculate welfare and to simulate a counterfactual scenario of continued open access.

3 Empirical Setting

3.1 Background and Institutional Setting

There are two main categories of groundwater users in California: overlying users and appropriators. Overlying users are the owners of land 'overlying' the groundwater resource who use their water on their own land; these users include farmers who use groundwater for agricultural irrigation, and recreational users such as golf courses and housing developments who use water for landscaping. Appropriators extract water for beneficial uses outside of the land, and may also divert water from multiple basins. In most cases in California, the appropriator is a municipal water district that sells its appropriated groundwater to residential household consumers in their administrative zones

et al., 2020; Wu et al., 2025; Araujo et al., 2020), agriculture (Carroll et al., 2019, 2025a; Meneses et al., 2025; Yeh et al., 2025; Carroll et al., 2025b; Sambucci et al., 2025), transportation (Li et al., 2022; Gillingham et al., 2022; Donna, 2021), environmental regulations (Blundell et al., 2020), and health (Agarwal et al., 2021; Iskhakov, 2010).

[3] The model developed by Pakes et al. (2007) has been applied to the multi-stage investment timing game in offshore petroleum production (Lin, 2013), to ethanol investment decisions (Thome and Lin Lawell, 2025), and to the decision to wear and use glasses (Ma et al., 2025). The model developed by Aguirregabiria and Mira (2007) has been applied to oligopoly retail markets (Aguirregabiria et al., 2007). Structural econometric models of dynamic games have also been applied to fisheries (Huang and Smith, 2014), dynamic natural monopoly regulation (Lim and Yurukoglu, 2018), Chinese shipbuilding (Kalouptsidi, 2018), industrial policy (Barwick et al., 2021), coal procurement (Jha, 2023), ethanol investment (Yi and Lin Lawell, 2025b,a), preemption (Fang and Yang, 2024), and the U.S. Supreme Court (Bagwe, 2021).

(California State Water Resources Control Board, 2017; Bartkiewicz et al., 2006).

California's groundwater resources have operated under a de-facto open access environment for much of the state's history, with groundwater users able to extract as much as they desire without being required to obtain or verify that they possess any formal property right. When disputes arise between groundwater users, parties may sue one another over competing claims to property rights and ask the court system to settle their dispute. The adjudication process is often lengthy, costly, and unpredictable (Enion, 2013; Landridge et al., 2016). Despite being the method through which property rights are quantified, adjudications have been clustered in Southern California, and have not been a feature of other water-stressed agricultural regions like the Central Valley (Landridge et al., 2016).

In this paper, we analyze the groundwater extraction decisions of groundwater users in the Beaumont Basin in Southern California during a period of open access. The Beaumont Basin exhibits spatial heterogeneity in its hydrological features such as saturated hydraulic conductivity, which measures the ability of sediments or rocks to transmit water (Fryar and Mukherjee, 2021); as a consequence, the costs of extraction and availability of groundwater may vary significantly within the basin for a given quantity of total groundwater remaining in the basin. For much of its history, groundwater was the only source of water in the Beaumont Basin area, and during the 20th century the water table level declined by over 100 feet due to overdraft (Rewis et al., 2006). The Beaumont Basin was adjudicated when the basin's four municipal water companies formed the San Timoteo Watershed Management Authority and brought suit in January 2001, with a settlement reached and property rights instituted in February 2004 (Landridge et al., 2016).

The Beaumont Basin provides groundwater to a mix of farmers, recreational users (golf courses and housing developments), and municipalities in the area, including the cities of Banning, Beaumont, Calimesa, and Yucaipa. Groundwater in the basin was appropriated, or sold for use outside of the land on which it was extracted, by four municipal water companies: Beaumont-Cherry Valley Water District, City of Banning, South Mesa Water Company, and Yucaipa Valley Water District.

Figure A.1 in Appendix A shows the adjudicated boundaries of the Beaumont Basin following the institution of property rights in 2004. As is clear in the map, the adjudication and the resulting system of quantified property rights it implemented only covered part of the region's set of groundwater basins. Appropriators included in the adjudication extracted groundwater from wells both inside and outside the boundaries of the Beaumont Basin, both before and after the judgment. Their adjudicated property rights only pertained to groundwater extracted from wells inside the Beaumont Basin. There were overlying groundwater users with wells both inside and outside the boundaries of the Beaumont Basin before and after the adjudication. Only overlying users inside the Beaumont Basin were given adjudicated property rights. Thus, appropriator wells outside of Beaumont Basin and farmers located outside of Beaumont Basin extract groundwater from basins that remain in open access during the entire period of our data set, even after the institution of quantified property rights in Beaumont Basin.

We model the groundwater extraction decisions of the agricultural, recreational, and municipal groundwater users in the Beaumont Basin in Southern California over the period 1991-1996, when groundwater was an open access resource and property rights were not anticipated. Farmers and recreational users are overlying users who use their water on their own land. Municipal water districts are appropriators who sell water to others, and may own wells both inside and outside the Beaumont Basin. All recreational users are based inside Beaumont Basin. We include farmers based outside Beaumont Basin in addition to farmers based inside of Beaumont Basin because the actions of farmers outside Beaumont Basin help to determine depth to groundwater at wells outside the Beaumont Basin for appropriators with wells both inside and outside the Beaumont Basin through nearby extraction variables. Farmers outside Beaumont Basin may also be of interest in our study due to any spillover benefits they receive through the effect of the property rights regime on extraction at wells outside the Beaumont Basin by appropriators with wells both inside and outside the Beaumont Basin.

We use data on all the groundwater users in the Beaumont Basin during 1991-1996 to estimate our open access dynamic game. Since no well drilling occurred in the Beaumont Basin over the period 1991-1996, we focus on modeling the groundwater extraction decisions of the groundwater users in the Beaumont Basin, and take the actual number of wells and actual well characteristics as given. The parameters we estimate are structural parameters under open access. We use our parameter estimates to simulate a counterfactual scenario of continued open access, and compare our open access counterfactual with the actual extraction decisions that were made after the institution of quantified property rights in order to quantify the welfare gains and losses from shifting to a quantified property rights system for the different groundwater users in Beaumont Basin.

3.2 Data

Our annual groundwater user-level panel data set includes all the groundwater users in the Beaumont Basin over the years 1991-2014. These users include agricultural, recreational, and municipal groundwater users.

Our data set includes all the overlying users, including all the farmers and all the recreational users in the Beaumont Basin who extracted more than 10 acre-feet per year during the open access period (1991-1996). Our data set also includes all appropriators in the Beaumont Basin who extracted water during the open access period (1991-1996). All other parties were not subject to the Beaumont Basin adjudication and do not have reliable data for the period before and after the adjudication.

There are four appropriators (municipal water districts), five farmers (two based inside Beaumont Basin, three based outside Beaumont Basin), and five recreational users in the Beaumont Basin during the open access period (1991-1996).

The Beaumont Basin was adjudicated when the basin's four municipal water companies formed the San Timoteo Watershed Management Authority and brought suit in January 2001, with a settlement reached and property rights instituted in February 2004 (Landridge et al., 2016). Thus, our dataset covers the years leading up to, during, and following the adjudication of property rights in the

Beaumont Basin.

We focus on modeling the first period of our dataset, 1991-1996, when groundwater was an open access resource and property rights were not anticipated. Although property rights were not instituted until 2004, groundwater users may have altered their behavior in anticipation of an adjudication. We choose the construction of the East Branch Extension Pipeline as the event which precipitated the Beaumont Basin's adjudication; we therefore assume that once this project was anticipated, so too was adjudication. We do this because of the importance of managing imported water in the eventual property rights design, as well as its role in instigating other adjudications in the region historically (Landridge et al., 2016). The East Branch Extension Pipeline construction project was formally approved in 1999, although the project was already part of the State Water Project's capital plan in 1998 (PR Newswire, 1998). We conservatively allow for anticipation of the project to begin in 1997, and thus allow the open access period to end in 1996.

We use data on all the groundwater users in the Beaumont Basin during 1991-1996 to estimate our open access dynamic game. We make use of the later period in our dataset from 1997-2014 by comparing the actual evolution of the groundwater system to a counterfactual simulation of the system, had the system remained in open access.

3.3 Data Sources

We rely on a number of sources. Summary statistics for data we have incorporated into our estimation can be found in Tables A.1-A.3 in Appendix A.

First, for extraction data we use a mix of data from the San Timoteo Watershed Management Authority, the San Gorgonio Pass Water Agency, and the Beaumont Basin Watermaster. Our observation for extraction is annual extraction by an owner either inside or outside the boundaries of the Beaumont Basin. Thus, for appropriators in the judgment we have two extraction observations each year (i.e., extraction inside Beaumont Basin and extraction outside Beaumont Basin), while for other groundwater users we have one observation per year (i.e., extraction either inside or outside Beaumont Basin).

Second, we collect and construct a database of well characteristics and location for each owner in each year from detailed handwritten hard-copy historical records on well location, well characteristics such as the depth of the well, and the maximum extraction rate in gallons per minute from the California State Water Resources Control Board's Groundwater Recordation Program (California State Water Resources Control Board, 2021). We merge the handwritten hard-copy historical records wells location data from the Groundwater Recordation Program and a well completion report dataset from the California Department of Water Resources with the well's state well identification number to determine the location of each the wells, and then merge the resulting well characteristics and location data with reported data from the Beaumont Basin Watermaster and the San Timoteo Watershed Management Authority. We map our well locations data to data from the US Department of Agriculture (USDA) Web Soil Survey and calculate an average saturated hydraulic conductivity value for each owner's wells inside and outside the Beaumont Basin; these data are fixed over time.

For data on depth to groundwater, we use observations from the US Geological Survey (USGS) Historical observations dataset. We collapse our data into annual depth to groundwater near each owner's wells inside or outside the boundaries of the Beaumont Basin. In order to do this we average over the nearest neighbor monitoring observations for each well owned by an owner either inside or outside the basin. Thus each well owned by one of our groundwater extractors has a corresponding monitoring well in the dataset. We interpolate for missing years in our depth to groundwater data by using the inverse-distance weighted annual change in depth to groundwater at other nearby wells with available data.

We obtain prices for relevant agricultural crops (apples, cherries, grapes, alfalfa, olives, and strawberries) from the USDA National Agricultural Statistics Service (NASS) Monthly Agricultural Prices survey. We use end-of-March surveys in each year to map a price. We choose this month to correspond to the price data available at the time of the planting decision for farmers. For our policy function and state transition estimation involving electricity prices, we use data from the Southern California Edison on annual end-use price by sector. For real GDP per capita, we use statewide annual data from the US BEA, with chained 1997 prices. For data on unemployment rate and CPI, we use state-level data from the Federal Reserve Economic Data supplied by the Federal Reserve Bank of St. Louis. For county-level personal income, we use data from the State of California Franchise Tax Board. We take prices for untreated water from the Metropolitan Water District, a large State Water Project Contractor in Southern California. We take equivalent use price and delivery data from the State Water Project's annual Bulletin 132 report.

We make use of precipitation and daily maximum temperature data from the PRISM Climate Group (PRISM Climate Group and Oregon State University, 2018). We use 4 km resolution data from the PRISM's historical dataset, and map it to the extraction wells in our dataset based on location. We then collapse our data into annual and growing season (April-October) averages across wells inside or outside the Beaumont Basin for each owner.

In our water demand estimation, we use data on monthly per-household residential water consumption, fixed charges, variable prices, and connection fees from the California/Nevada Water Rate Survey conducted by the American Water Works Association. This survey is conducted once every two years and covers a large sample of municipal water districts in California. We use data on household size and population by city and county from the California Department of Finance; data on median adjusted gross income by county from the California Franchise Tax Board; and data on the industrial average electricity price for California from the US Energy Information Administration (EIA).

4 Open Access Dynamic Game

We model the open access dynamic game among farmers, other overlying users, and appropriators in the Beaumont Basin area of Southern California. An open access regime is one in which there is a lack of property rights and no one can prevent another from using the natural resource (Hartwick and Olewiler, 1998). Under open access, groundwater users are able to extract as much as they desire without being required to obtain or verify that they possess any formal property right.

We model the dynamic and strategic decision-making behavior of the groundwater users i in the Beaumont Basin under open access. There are three types $j \in \{F, R, A\}$ of players i in our open access dynamic game: farmers F, recreational users (golf course and housing developments) R, and municipal water districts (appropriators) A. Farmers and recreational users are overlying users who use their water on their own land. Municipal water districts are appropriators who sell water to others, and may own wells both inside and outside the Beaumont Basin. All recreational users are based inside Beaumont Basin. We include farmers based outside Beaumont Basin in addition to farmers based inside of Beaumont Basin because the actions of farmers outside Beaumont Basin help to determine depth to groundwater at wells outside the Beaumont Basin for appropriators with wells both inside and outside the Beaumont Basin through nearby extraction variables. Farmers outside Beaumont Basin may also be of interest in our study due to any spillover benefits they receive through the effect of the property rights regime on extraction at wells outside the Beaumont Basin by appropriators with wells both inside and outside the Beaumont Basin.

Each year t, each player i of each type j chooses their groundwater extraction decision a_{ij}. The per-period payoffs for each player i depend on the player's type (or use) j, where j is either farming ($j = F$), recreational ($j = R$), or municipal ($j = A$); the player's action a_{ij}; and the publicly observable state variables x_{ij}.

Owing to the spatial heterogeneity in the Beaumont Basin of hydrological features such as saturated hydraulic conductivity, which measures the ability of sediments or rocks to transmit water (Fryar and Mukherjee, 2021), the costs of extraction and availability of groundwater may vary significantly within the basin for a given quantity of total groundwater remaining in the basin. We therefore do not measure the stock of the resource using a single aggregate measure of the total quantity of groundwater in the basin, but instead use a player-specific state variable, depth to groundwater s_{ij}, to measure the groundwater stock for each player: a greater depth to groundwater s_{ij} indicates a lower groundwater stock. The state variables x_{ij} therefore include depth to groundwater s_{ij}, saturated hydraulic conductivity h_i, economic factors, and weather conditions.

Since very little well drilling occurred in the Beaumont Basin over the open access period 1991-1996,[4] we focus on modeling the groundwater extraction decisions of the groundwater users in the Beaumont Basin, and take the actual number of wells and actual well characteristics as given. For

[4]The only player in our data set who drilled wells during the open access period 1991-1996 was Yucaipa Valley Water District, an appropriator who drilled wells in 1991, 1993, and 1994.

farmers and recreational users, whose wells are all located in one area (i.e., either all inside Beaumont Basin or all outside Beaumont Basin), the action a_{ij} is a single extraction decision, while for water districts whose wells are located both inside and outside the Beaumont Basin, the action a_{ij} is a vector of extraction inside and outside of Beaumont. For water districts, the state vector x_{ij} similarly includes information about conditions both inside and outside the basin.

Groundwater users under open access are not legally limited in their extraction choice. Nevertheless, extraction must be feasible, and is therefore constrained to be less than or equal to the groundwater stock, as given by the following function of depth to groundwater s_{ij}:

$$a_{ij} \leq B_a \cdot \left(\overline{s_{ij}} - s_{ij}\right), \tag{1}$$

where $\overline{s_{ij}}$ is the maximum depth of the aquifer (in feet) for player i of type j , extraction a_{ij} is in units of acre-feet, depth to groundwater s_{ij} is in units of feet, and B_a is the area of Beaumont Basin in acres.[5]

Formally, the per-period profit function $\pi_{ij}(a_{ij}, x_{ij})$ for each player i of each type j is given by:

$$\pi_{ij}(a_{ij}, x_{ij}) = R_{ij}(a_{ij}, x_{ij}) - C_{ij}(a_{ij}, x_{ij}), \tag{2}$$

where $R_{ij}(a_{ij}, x_{ij})$ is the revenue or benefit to player i from using water for use j and $C_{ij}(a_{ij}, x_{ij})$ is the cost of groundwater extraction to player i.

We assume that the players believe that the open access regime will continue indefinitely. Since the adjudication process is often lengthy, costly, and unpredictable due to the lack of consistent data collection in the state, the number of parties involved in basin-wide adjudications, and the inconsistent record of court rulings in the state (Enion, 2013; Landridge et al., 2016), we think this is a reasonable assumption. We further justify this assumption below. We therefore model the open access dynamic game as an infinite-horizon dynamic game.

For each farmer i (all of whom are of type $j = F$), the revenue function $R_F(a_{iF}, x_{iF})$ measures the agricultural revenue from groundwater extraction used for farming, and is a function of the average crop price p_c for relevant crops as well as factors that affect crop yield, including precipitation $r_{gs,i}$ during the growing season and the number of high heat days $d_{gs,i}$ during the growing season. We define a 'high heat day' as a day when the maximum temperature was greater than 90 degrees Fahrenheit. The crop yield from groundwater extraction is also a function of factors that affect

[5]The Beaumont Basin is approximately 79 square miles in area, or 50,560 acres, so we set B_a to 50,560. The Beaumont Basin consists of two layers of aquifers. The upper aquifer goes until around 1,000 feet below the ground surface, while the lower aquifer begins at around 1,100 feet below surface and ends at 1,400 feet below the surface. Some of the wells owned by City of Banning, Beaumont-Cherry Valley Water District, South Mesa Water Company, and California Oak Valley Golf Resort are deep enough to reach the lower aquifer (Beaumont Basin Watermaster, 2020). Thus, for these 4 players i we allow extraction to depths up to 1,400 feet and therefore set their maximum depth $\overline{s_{ij}}$ to 1,400. As of the 2013 Re-evaluation of Beaumont Basin Safe Yield, the remaining wells in Beaumont Basin are not deep enough to reach the lower layer (Beaumont Basin Watermaster, 2020). Thus, for the remaining players i, we allow extraction for depths up to 1,000 ft and therefore set their maximum depth $\overline{s_{ij}}$ to 1,000.

irrigation efficiency, which is defined as the fraction of the extracted groundwater that is beneficially used by a crop (Pfeiffer and Lin, 2014; Lin Lawell, 2016; Sears et al., 2018a). Having more wells may enable a farmer to locate more wells closer to irrigation points on the farmer's plot of land, thus reducing losses from evaporation and other causes, and thereby increasing irrigation efficiency, possibly at a diminishing rate. We thus include the total number of wells W_i the farmer owns before time t and a quadratic polynomial in the number of wells $W_{BB,i}$ the farmer owns inside Beaumont Basin before time t. Agricultural revenue is therefore a function of both the prices for crops as well as the yield, which is determined by growing season weather conditions, applied irrigation from groundwater, and irrigation efficiency. In particular, the revenue function $R_{iF}(a_{iF}, x_{iF})$ for farming is given by the following polynomial:

$$\begin{aligned} R_{iF}(a_{iF}, x_{iF}) = [&\theta_1^F p_c + \theta_2^F r_{gs,i} + \theta_3^F p_c d_{gs,i} + \theta_4^F p_c r_{gs,i} + \theta_5^F p_c d_{gs,i} r_{gs,i} \\ &+\theta_6^F W_i + \theta_7^F I\{W_{BB,i} > 0\} + \theta_8^F W_{BB,i}^2] \cdot a_{iF}, \end{aligned}$$

where $I\{W_{BB,i} > 0\}$ is an indicator (dummy) variable for the farmer owning wells in Beaumont Basin (and therefore a dummy variable for the farmer being inside Beaumont Basin instead of outside Beaumont Basin), and where the farmer marginal revenue parameters $\theta^F = (\theta_1^F, ..., \theta_8^F)$ are among the structural parameters we estimate.

For each recreational user i (all of whom are of type $j = R$), the revenue function $R_{iR}(a_{iR}, x_{iR})$ measures the revenue from groundwater extraction used in landscaping, and is a function of the number of wells $W_{BB,i}$ the recreational user owns inside Beaumont Basin, saturated hydraulic conductivity h_i, precipitation $r_{gs,i}$ during the growing season, the number of high heat days $d_{gs,i}$ during the growing season, the population l_B of Beaumont, real GDP per capita y in California, and a dummy variable b_i for planned construction. Precipitation $r_{gs,i}$ during the dry season, which corresponds to the growing season in California, affects applied water. The number of high heat days $d_{gs,i}$ during the growing season, which is nearly the same as the number of high heat days over the full year,[6] city population, and GDP per capita affect the overall demand for recreational services, and thus applied irrigation. We use a polynomial of the form:

$$\begin{aligned} R_{iR}(a_{iR}, x_{iR}) = [&\theta_1^R W_{BB,i} h_i d_{gs,i} + \theta_2^R W_{BB,i} h_i r_{gs,i} + \theta_3^R W_{BB,i} h_i d_{gs,i} r_{gs,i} \\ &+\theta_4^R W_{BB,i} \ln l_B + \theta_5^R W_{BB,i} y_i + \theta_6^R W_{BB,i}^2 + \theta_7^R b_i] \cdot a_{iR}, \end{aligned}$$

where the golf course / housing development marginal revenue parameters $\theta^R = (\theta_1^R, ..., \theta_7^R)$ are among the structural parameters we estimate.

For each municipal water district (or appropriator) i (all of whom are of type $j = A$), we allow municipal water districts to care about both consumer surplus $CS_{iA}(a_{iA}, x_{iA})$ and the profits from

[6]We define a 'high heat day' as a day when the maximum temperature was greater than 90 degrees Fahrenheit. The correlation coefficient between the number of high heat days during the growing season and the number of high heat days over the full year is 1.0000.

water sales, where the profits from water sales is given by the water sale revenues $RW_{iA}(a_{iA}, x_{iA})$ minus extraction costs $C_A(a_{iA}, x_{iA})$. This structure reflects the multiple objectives that water districts may have as municipally owned firms (Peltzman, 1971; Baron and Myerson, 1983; Timmins, 2002). In particular, we allow the per-payoffs for municipal water districts to be a weighted quadratic function of consumer surplus $CS_{iA}(a_{iA}, x_{iA})$, and the profits from water sales. We allow consumer surplus to enter the function quadratically to allow for the possibility that the appropriator may value benefits to their customers, but at a diminishing rate.

The benefit function $R_{iA}(a_{ij}, x_{ij})$ for municipal water districts is therefore given by:

$$R_{iA}(a_{iA}, x_{iA}) = w_{CS} \cdot CS_{iA}(a_{iA}, x_{iA}) + w_{CS2} \cdot (CS_{iA}(a_{iA}, x_{iA}))^2 + RW_{iA}(a_{iA}, x_{iA}),$$

where w_{CS} and w_{CS2} are the weights on consumer surplus and on consumer surplus squared, respectively, and where we normalize the weight on the profits from water sales to 1. Since extraction costs $C_{ij}(a_{ij}, x_{ij})$ enter the per-payoffs with a coefficient of 1, normalizing the weight on the profits from water sales to 1 is equivalent to normalizing the weight on the revenues from water sales $RW_{iA}(a_{iA}, x_{iA})$ to 1. The appropriator weights w_{CS} and w_{CS2} on consumer surplus and on consumer surplus squared are among the structural parameters we estimate.

Monthly residential water consumption per household in each municipal water district i is given by the following function for residential water demand $D_{iA}(P_{iA})$:

$$D_{iA}(P_{iA}) = A_0 \left(P_{iA}\right)^{\alpha_1} \left(f_{iA}\right)^{\alpha_2}, \tag{3}$$

where P_{iA} is the residential water price and f_{iA} is the average household size in municipal water district i; and where A_0, α_1, and α_2 are demand parameters to be estimated.

Water price in each municipal water district i is given by inverse demand. Inverting the demand for residential water yields the following inverse demand function $P_{iA}(q_{iA}, f_{iA})$ for residential water for each municipal water district i:

$$P_{iA}(q_{iA}, f_{iA}) = \left(\frac{q_{iA}}{A_0 \left(f_{iA}\right)^{\alpha_2}}\right)^{\frac{1}{\alpha_1}}, \tag{4}$$

where q_{iA} is monthly residential water consumption per household in municipal water district i.

The per-household monthly water consumption $q_{iA}(a_{ij}, n_{iA})$ in municipal water district i implied by extraction a_{iA} is given by:

$$q_{iA}(a_{iA}, n_{iA}) = B_q B_m \frac{a_{iA}}{n_{iA}}, \tag{5}$$

where B_q is a conversion factor from acre-feet (the units for groundwater extraction a_{iA}) to hundred cubic-feet (the units for per-household monthly residential water consumption q_{iA}), $B_m = \frac{1}{12}$ is a conversion factor from annual (the frequency for groundwater extraction a_{iA}) to monthly (the frequency for per-household monthly residential water consumption q_{iA}), and n_{iA} is the number of households in municipal water district i, a. Evaluating the inverse demand function $P_{iA}(q_{iA}, f_{iA})$ at the per-household monthly water consumption $q_{iA}(a_{ij}, n_{iA})$ in municipal water district i implied by extraction a_{iA} yields the market-clearing residential water price $P^*_{iA}(q_{iA}(a_{iA}, n_{iA}), f_{iA})$ in municipal water district i.

We calculate the consumer surplus $CS_{iA}(a_{iA}, x_{iA})$ in municipal water district i by integrating the area under the inverse residential demand function $P_{iA}(q_{iA}, f_{iA})$ above the price $P^*_{iA}(q_{iA}(a_{ij}, n_{iA}), f_{iA})$ from a lower limit necessity quantity $\underline{q}$ to the monthly household quantity $q_{iA}(a_{ij}, n_{iA})$. Formally:

$$CS_{iA}(a_{iA}, x_{iA}) = n_{iA} \int_{\underline{q}}^{q_{iA}(a_{ij}, n_{iA})} \left(P_{iA}(z, f_{iA}) - P^*(q_{iA}(a_{ij}, n_{iA}), f_{iA})\right) dz. \tag{6}$$

We allow marginal revenues from water sales to be determined by a combination of residential water demand driven by population and household size, and additional costs or benefits related to weather conditions. This reflects additional costs water districts may incur related to conservation efforts due to weather conditions in a given year. We model the effect of these weather conditions as a linear function of the number of high heat days $d_{gs,i}$ during the growing season,[7] and annual rainfall r_i. The revenues from water sales $RW_{iA}(a_{iA}, x_{iA})$ is given by:

$$RW_{iA}(a_{iA}, x_{iA}) = \left[P^{AF}_{iA}(a_{iA}, f_{iA}, n_{iA}) + \theta^A_1 d_{gs,i} + \theta^A_2 r_i\right] \cdot a_{iA},$$

where the appropriator marginal revenue parameters $\theta^A = (\theta^A_1, \theta^A_2)$ are among the structural parameters we estimate; and where $P^{AF}_{iA}(\cdot)$ is the price of water per acre-foot in municipal water district i and is given by:

$$P^{AF}_{iA}(a_{ij}, f_{iA}, n_{iA}) = B_q \cdot P_{iA}(q_{iA}(a_{ij}, n_{iA}), f_{iA}), \tag{7}$$

which scales the price per hundred cubic feet $P_{iA}(q_{iA}(a_{ij}, n_{iA}), f_{iA})$ determined by the per-household monthly consumption implied by extraction a_{iA} and the number of households n_{iA}, and by the average household size f_{iA} in the district.

The extraction cost function $C_{ij}(a_{ij}, x_{ij})$ for each groundwater user i of each type j includes a common component and a type-specific quadratic effects. The quadratic component represents adjustment costs necessary to ramp up extraction and transmission of water for each groundwater user i of each type j. Following Rogers and Alam (2006) and Sears et al. (2019), we model the common component of the cost of water extraction as a function of the price of electricity P_E (in dollars per kwh), depth to groundwater s_{ij} (in feet), and the amount of electricity $E_L = 1.551$ (in kwh) required to lift one acre-foot of water one foot. The extraction cost function $C_{ij}(a_{ij}, x_{ij})$ is given by:

$$C_{ij}(a_{ij}, x_{ij}) = P_E E_L s_{ij} a_{ij} + c^j_2 (a_{ij})^2, \tag{8}$$

[7] We define a 'high heat day' as a day when the maximum temperature was greater than 90 degrees Fahrenheit. The correlation coefficient between the number of high heat days during the growing season and the number of high heat days over the full year is 1.0000.

where the cost parameters c_2^j in the quadratic component for each type $j \in \{F, R, A\}$ are among the structural parameters we estimate. We estimate a separate cost function for farmers ($j = F$) and a separate cost function for recreational users ($j = R$), both of whose wells are only located on their property. As water districts ($j = A$) have wells both inside and outside the Beaumont Basin, we calculate one cost function for appropriator extraction inside the Beaumont Basin, and a separate cost function for appropriator extraction outside the Beaumont Basin.

For each player i of each type j, the state variables x_{ij} include depth to groundwater s_{ij}; saturated hydraulic conductivity h_i, which measures the ability of sediments or rocks to transmit water (Fryar and Mukherjee, 2021) and affects the transition density $f_{ij}^s(s'_{ij}|x_{ij}, a_{ij}, a_{-i})$ for the depth to groundwater s_{ij} of player i; price of electricity P_E, which affects the extraction costs $C_{ij}(a_{ij}, x_{ij}$ of all types j of players; real GDP per capita y in California; and state variables that affect the type-specific revenue or benefit $R_{ij}(a_{ij}, x_{ij}$ from using water for use j. Thus, for each farmer i (all of whom are of type $j = F$), the state variables x_{ij} include not only depth to groundwater s_{ij}, saturated hydraulic conductivity h_i, electricity price P_E, and real GDP per capita y in California, but also average crop price p_c for relevant crops, precipitation $r_{gs,i}$ during the growing season, the number of high heat days $d_{gs,i}$ during the growing season, the total number of wells W_i the farmer owns before time t, the number of wells $W_{BB,i}$ the farmer owns inside Beaumont Basin before time t, and an indicator (dummy) variable $I\{W_{BB,i} > 0\}$ for the farmer owning wells in Beaumont Basin (i.e., a dummy variable for the farmer being inside Beaumont Basin instead of outside Beaumont Basin). For each recreational user i (all of whom are of type $j = R$), the state variables x_{ij} include not only depth to groundwater s_{ij}, saturated hydraulic conductivity h_i, electricity price P_E, and real GDP per capita y in California, but also the number of wells $W_{BB,i}$ the recreational user owns inside Beaumont Basin, precipitation $r_{gs,i}$ during the growing season, the number of high heat days $d_{gs,i}$ during the growing season, the population l_B of Beaumont, and a dummy variable b_i for planned construction. For each municipal water district (or appropriator) i (all of whom are of type $j = A$),the state variables x_{ij} include not only depth to groundwater s_{ij}, saturated hydraulic conductivity h_i, electricity price P_E, and real GDP per capita y in California, but also the average household size f_{iA} in municipal water district i, the number n_{iA} of households in municipal water district i, the number of high heat days $d_{gs,i}$ during the growing season, and annual rainfall r_i.

For the transition density for depth to groundwater, we assume that depth to groundwater s_{ij} of each player i is stochastic and follows a first-order controlled Markov process:

$$s'_{ij} \overset{iid}{\sim} f_{ij}^s(\cdot|x_{ij}, a_{ij}, a_{-i}), \tag{9}$$

where the state transition density $f_{ij}^s(s'_{ij}|x_{ij}, a_{ij}, a_{-i})$ for the depth to groundwater s_{ij} of each player i depends on the depth to groundwater this period s_{ij}; the value of the other state variables (including saturated hydraulic conductivity h_i, which measures the ability of sediments or rocks to transmit water (Fryar and Mukherjee, 2021)) this period; and the groundwater extraction action variables of all players this period, including players other than player i.

Strategic interactions arise owing to the common pool nature of the groundwater resource. Since players all share the same aquifer, the future value s'_{ij} of depth to groundwater of each player i of each type j depends not only on the current depth to groundwater s_{ij} and current groundwater extraction a_{ij} of player i, but also on the current extraction decisions a_{-i} of all other players, where a_{-i} is the vector of the extraction decisions of all other players other than player i. The depth to groundwater for each player i (which is a measure of player i's groundwater stock) in turn affects player i through two channels: (1) since extraction must be feasible, and is therefore constrained to be less than or equal to the groundwater stock, depth to groundwater s_{ij} affects the feasible values of extraction a_{ij}, as seen in equation (1); and (2) depth to groundwater s_{ij} affects the extraction cost $C_{ij}(a_{ij}, x_{ij})$, as seen in equation (8). Thus, owing to the common pool nature of the groundwater resource, the payoffs and actions of each player i of each type j depend on the extraction decisions a_{-i} of all other players.

The equilibrium concept we use for our open access dynamic game is a Markov perfect equilibrium (MPE). Vespa (2020) provides experimental evidence that behavior in a dynamic common pool game can be rationalized with equilibrium Markov strategies that do not condition on history. In a Markov perfect equilibrium, the strategy (or policy function) $\sigma_{ij}(x)$ of each player i of each type j is a best-response function conditional on their expectations about the future state implied by the current state, the behavior of all other players, and the transition dynamics of the system.

We assume the full state vector $x = \{x_{ij}\}$, which is the vector of the state variables x_{ij} for all players i of all types j, is common knowledge. The state variables x affect our game through the state transition densities and the player policy functions $\sigma_{ij}(x)$.

There are several sources of uncertainty in our model of the open access dynamic game. First, the future values of the depth to groundwater s_{ij} state variable for each player i drawn from the transition densities $f^s_{ij}(s'_{ij}|x_{ij}, a_{ij}, a_{-i})$ are stochastic. Second, the actual extraction actions a_{ij} drawn from the mixed strategies given by the policy functions $\sigma_{ij}(x)$ are stochastic.

Each player i of type j chooses its action a_{ij} to maximize the expected present discounted value of its entire stream of per-period payoffs, given the state variables x and the strategies σ_{-i} of the other players, yielding the following value function:

$$V_{ij}(x; \sigma_{-i}) = \max_{a_{ij}} \left[\pi_{ij}(a_{ij}, x_{ij}) + \beta E[V_{ij}(x'; \sigma_{-i})|a_{ij}, \sigma_{-i}, x] \right], \tag{10}$$

where σ_{-i} are the strategies of all other players other than player i and β is the discount factor. Each player takes into account their expectations about the evolution of the full vector of state variables in their decision-making process and chooses a strategy over the full set of states that optimizes the expected present discounted value of per-period profits from the extraction of groundwater over their extraction path.

5 Structural Econometric Estimation

To estimate the parameters for the open access dynamic game, we use the two-step forward simulation-based approach developed by Bajari et al. (2007). In the first step of our estimation strategy, we estimate residential water demand, policy functions $\sigma_{ij}(x)$ for each player type j, and state transition densities $f^s_{ij}(s'_{ij}|x_{ij}, a_{ij}, a_{-i})$ for depth to groundwater s_{ij}. In the second step, we use forward simulation to estimate the value function at a set of states under the policies and transition functions estimated in the first stage and find parameters that minimize any profitable deviations from the optimal strategy as given by the policy functions estimated in the first step. The estimated parameters are then consistent with Markov perfect equilibrium behavior in a game in which player expectations are consistent with the observed first-stage state transitions and policy functions (Bajari et al., 2007).

5.1 Residential Water Demand

As part of the first step of our estimation strategy, we empirically estimate the residential household water demand function in equation (3), which is then used in the second stage of our estimator to estimate consumer surplus and water sales revenue for water districts. Our observational unit here is a water district in a given year. Our regression model is given by:

$$\ln[q_{iA}] = \alpha_0 + \alpha_1 \ln[P_{iA}] + \alpha_2 \ln[f_{iA}] + X_i'\alpha_3 + \epsilon_i, \tag{11}$$

where q_{iA} is the quantity of monthly water consumption per household in water district i; P_{iA} is the residential water price in water district i; f_{iA} is the average household size in district i; and X_i is a vector of controls, which include median per capita income, state-wide unemployment, precipitation, and rate structure design.

Since residential water price is endogenously determined by both supply and demand for water, we employ an instrumental variables approach, as is common in the literature on residential water demand (Worthington and Hoffman, 2008). Here we instrument for the price of water with supply shifters. Specifically, our instruments for price are the annual equivalent unit price charged by the State Water Project (SWP) for water delivery to the water district's nearest State Water Project contractor, and the product of the average depth to groundwater in the district and the price of electricity. These supply shifters are correlated with price because water district costs are generally included in the pricing formula for the district. Since water districts draw on groundwater, surface water, and water imports to meet their supply needs, these instruments clearly affect the cost of the water district's supply.

We believe that these instruments also satisfy the exclusion restriction. The State Water Project (SWP) price for water delivery to the district's nearest State Water Project contractor is determined by the State Water Project, and reflects the costs of transporting water, obtaining supplies, and maintenance (California Department of Water Resources, 2016b). Since the State Water Project does not sell directly to water districts, but rather to large contractors who then sell water to the water districts, no single district can fully determine the demands of a contractor, and the pricing rule used by the SWP is not driven by the demands of any single contractor. Furthermore, differences across contractors in price are driven mainly by differences in location, and the maintenance and capital costs of the pipelines that transport water to each district. Thus, the State Water Project (SWP) price for water delivery to the district's nearest State Water Project contractor is a supply shifter that does not affect residential water demand except through its effect on the residential water price. The average depth to groundwater in the district interacted with the price of electricity is similarly a supply shifter that does not affect residential water demand except through its effect on the residential water price. We conduct several tests of both correlation and the exclusion restriction, and find evidence that is consistent with our instruments being both relevant and valid. The Sanderson-Windmeijer first-stage F-statistic (Sanderson and Windmeijer, 2016), which is a modification and improvement of the Angrist-Pischke first-stage F-statistic (Angrist and Pischke, 2009), is equal to 199, which is greater than the threshold of 10 used in current practice (Staiger and Stock, 1997; Stock and Yogo, 2005; Andrews et al., 2019), and also greater than the threshold of 104.7 for a true 5 percent test (Lee et al., 2021).

To estimate household water demand, we use pooled data from the bi-annual California/Nevada Water Rate Survey conducted by the American Water Works Association. We do not treat our data as a panel due to the infrequency of repeated observations in our data. We use data on household size by city and county from the California Department of Finance; data on median adjusted gross income by county from the California Franchise Tax Board; and data on the industrial average electricity price for California from the US EIA. Our dataset covers the years 2007-2015.[8] Summary statistics are presented in Table A.3 in Appendix A.

Our empirical results for residential water demand per household can be found in Table A.4 in Appendix A. We find elasticities of price and household size that fit with our prior belief that household water demand should be inelastic with regard to each, and fit within the bounds of prior results in the literature (Worthington and Hoffman, 2008; Wichman, 2014), which suggests that the results of our structural model and counterfactual simulations are likely robust to whether we use water demand elasticities from the literature rather than those we estimate ourselves. Since the coefficients on the variables in the vector X_i of controls are not significant at a 5% level, we do not include these variables as determinants of water demand in our structural model, but instead account for them by solving for the constant $\hat{A}_0$ that equates mean predicted household consumption (using

[8]We assume that monthly water demand per household does not change over our period of analysis (1991-2014) and therefore that our household water demand function estimated using data from 2007-2015 applies over our entire period of analysis (1991-2014). Our assumption that demand per household did not change is reasonable since it still allows aggregate water demand to increase as the number of households n_{iA} in the water district increases. We unfortunately were unable to find data from earlier years to use to estimate water demand. Reassuringly, our estimated elasticities are nevertheless consistent with estimates from the literature, which includes estimates from earlier years (Worthington and Hoffman, 2008). We hope to obtain the data to better examine any changes in water demand per household in future work.

only price and household size as predictors) with actual consumption.

5.2 Policy Functions

To estimate the strategy (or policy function) $\sigma_{ij}(x)$ of each player i of each type j, we estimate type-specific policy functions for each type j of player that correlate actions to states, using data from the open access period of our dataset. These extraction policy functions are parametric functions of state variables that are chosen based on their ability to accurately predict groundwater extraction in sample. While we can not argue for the ability of these functions to predict extraction outside of our sample set of states, we can evaluate our estimators based on the fit of our simulated data with the actual data. Our policy function regression results can be found in Table A.5 in Appendix A.

We estimate policy functions for groundwater extraction by appropriators, farmers, and recreational users. We also estimate a separate policy function for the share of groundwater extraction at wells inside the Beaumont Basin for appropriators. For each policy function, we regress the action on state variables, including depth to groundwater, physical features of the area surrounding the player's wells, characteristics of the wells and pumping technology, planned operational activities, prices, and weather conditions. Our results, found in Table A.5, show the significant coefficients in each model, which we then use in our policy functions to simulate extraction choices. Since we only use a subset of variables included in the estimated model, we choose a constant term that equates mean predicted extraction in each case with mean actual extraction in the data. We account for unobserved factors that affect extraction decisions by adding an error term drawn at random from a normal distribution with mean zero and standard deviation equal to the root-mean squared prediction error from this adjusted predicted value.

5.3 State Transition Densities

We estimate transition densities $f^s_{ij}(s'_{ij}|x_{ij}, a_{ij}, a_{-i})$ for depth to groundwater s_{ij} for each type j of player. We separately estimate transition densities for depth inside and outside of Beaumont for appropriators (water districts) with wells both inside and outside of the basin.

For the transition densities for depth to groundwater for each type of player, we estimate models that include lagged values of depth to groundwater, extraction by the player, extraction by other players, physical features of the area surrounding the player's wells (including saturated hydraulic conductivity h_i, which measures the ability of sediments or rocks to transmit water (Fryar and Mukherjee, 2021)), economic factors, and weather conditions, and we let the data tell us what the transition density is. We only use variables that prove significant in our state transition regressions in the second stage simulation. We adjust our constant to equate predicted values with values in the data. We account for unobserved factors that affect state transitions by adding an error term drawn at random from a normal distribution with mean zero and standard deviation equal to the root-mean squared prediction error from this adjusted predicted value. Our transition densities for depth to groundwater are presented in Table A.6 in Appendix A. We run robustness checks that vary our specifications for the transition densities for depth to groundwater, such as excluding economic factors from the groundwater transition densities, in Section 8.

For crop prices, well characteristics, and weather, we assume rational expectations (and perfect foresight) by players in the base case model. We relax this assumption in our robustness checks in Section 8. We also assume that none of our players can influence crop prices, well characteristics, or weather through their behavior. This is a reasonable assumption given the relatively small size of operations in the Beaumont Basin relative to other nearby population centers and agricultural operations.

5.4 Estimating the Structural Parameters

For the second step of our estimation strategy, following Bajari et al. (2007), we forward simulate the value functions for each player in the open access period, and we estimate our structural parameters θ by minimizing the sum of profitable deviations from the optimal strategy as estimated by our policy functions. The structural parameters θ we estimate include revenue and cost parameters for farmers, recreational users, and appropriators; and parameters governing the relative weights that appropriators place on consumer surplus versus the profits from water sales. We set the discount factor β to 0.9.[9] To generate deviations from the optimal strategy, we perturb our policy functions using random draws to increase and decrease the level of the policy function; these perturbations are normally distributed with a standard deviation equal to the standard deviation of the relevant player-type extraction decision in the data. To ensure that we find a global minimum, we iterate over multiple initial guesses, searching over the set of combinations of parameter values, in order to find the parameters that minimize the sum of profitable deviations.

Identification of the parameters in the marginal revenue and costs of extraction for each player type (farmers, recreational users, appropriators) come from variation in extraction and state variables across players and across years for each player type. Identification of the weights in the per-period payoff on consumer surplus come from variation in water sale profits and consumer surplus across appropriators and across years. Water sale profits depend on the revenue and costs of extraction, whose parameters are identified from variation in extraction, number of high heat days, and precipitation across appropriators and across years. Consumer surplus is calculated by integrating the area under the inverse residential water demand above price, using the parameters in the residential water demand function estimated in the first stage. Variation in consumer surplus comes from variation in extraction, the number of households, and the average household size across water districts and across years.

[9] An annual discount factor of 0.9 is commonly assumed in the literature using dynamic models (see e.g., Ryan (2012); Lin (2013); Sears et al. (2019); Cook and Lin Lawell (2020)).

5.5 Calculating Welfare

We use our estimated structural parameters to calculate the welfare generated from groundwater extraction under open access. Welfare is the present discounted value of the entire stream of per-period payoffs over the period 1991-1996. Average annual welfare is welfare divided by the number of years. For farmers and recreational users, average annual welfare is equal to average annual profits, where profits are calculated as revenues minus costs. For appropriators, profits are the profits from water sales given by the water sale revenues minus extraction costs, while the per-payoffs are a weighted quadratic function of consumer surplus and the profits from water sales.

For each player and player type, we calculate the actual welfare generated based on the observed player actions and state variables, the model predicted welfare generated from 100 simulation runs of the open access period, and the difference between model predicted and actual welfare. Both actual and model predicted welfare are calculated using the parameter estimates from the structural model. Actual welfare is calculated using actual values of actions and states in the data. Model predicted welfare is calculated using model predicted actions and states generated from 100 simulation runs of the open access period.

In addition to welfare, we also calculate the actual consumer surplus faced by each appropriator over the period 1991-1996 based on the observed player actions and state variables, the model predicted consumer surplus generated from 100 simulation runs of the open access period, and the difference between model predicted and actual consumer surplus. Consumer surplus is the consumer surplus faced by each appropriator over the period 1991-1996. Average annual consumer surplus is consumer surplus divided by the number of years. Both actual and model predicted consumer surplus are calculated using the water demand parameter estimates. Actual consumer surplus is calculated using actual values of actions and states in the data. Model predicted consumer surplus is calculated using model predicted actions and states. Since consumer surplus is calculated from our first-stage demand function and from values of the state and action variables, it therefore does not depend on any structural parameters.

In addition to player welfare and consumer surplus, we also calculate social welfare. Social welfare is equal to the sum of producer surplus and consumer surplus. For each player, producer surplus is the present discounted value of the entire stream of their profits from groundwater extraction, where the profits from groundwater extraction is given by the revenue from groundwater extraction minus the costs of groundwater extraction. For farmers, golf courses and housing developments, producer surplus is equal to welfare. For appropriators, appropriator producer surplus is the present discounted value of the entire stream of profits from water sales, while appropriator welfare is a weighted quadratic sum of producer surplus and the consumer surplus faced by the appropriator. We allow appropriators to apply unequal weights to producer surplus and consumer surplus in their objective function. When calculating social welfare, however, consumer surplus is weighted equally to producer surplus. Thus, social welfare may differ from the total welfare over all players if appropriators do not put equal weights on the profits from water sales and consumer surplus in their payoff function.

5.6 Model Validation

In Appendix B, we conduct several analyses to validate our model. To assess the goodness of fit of our structural econometric model, we compare the action and state variables predicted by our model with the actual values in the data. We also compare actual welfare and model predicted welfare. We conduct leave-one-out cross-validation to evaluate model performance and determine whether our model is overfitted to our dataset. We also examine each player's profitable deviations from their estimated optimal strategy under our estimated structural parameters. As described in detail in Appendix B, we find that, overall our model appears robust and appears to do a good job matching the actual data and explaining groundwater extraction behavior of the groundwater users in the Beaumont Basin prior to the institution of quantified property rights.

6 Results

6.1 Structural Parameters

We now examine our structural parameter estimates from the open access dynamic game. The parameter estimates for the coefficients on terms in the payoff functions for each player, as well as the total average effect of key variables evaluated at the mean values of the variables in the data, are reported in Table 1; the standard errors are reported in Tables A.7-A.8 in Appendix A.

For farmers, whose marginal revenue parameters are found in Table A.7, we find that rainfall during the dry season (which coincides with the growing season) increases the marginal value of extraction. The coefficient in farmer marginal revenue on the interaction between crop price, number of high heat days during the growing season, and precipitation during the growing season is significant and negative, however, which means that additional growing season rainfall during a relatively warmer year tends to lower the value of irrigation water. Thus, as expected, groundwater is more valuable to farmers when rainfall does not meet the needs of their crops. Crop price in general lowers the marginal revenue to farmers from irrigation, which is likely due to either expansion of farming activities to more marginal land, or less productive increases in applied water during years in which crop prices are relatively high: the total average effect is negative, and statistically significant. We find that the total number of wells owned by the farmer has a significant positive effect on marginal revenue (likely due to the ability to more agilely manage irrigation across space), and that this effect is amplified for farmers inside the Beaumont Basin. We also find that farmers in the Beaumont Basin generally earn higher returns on their groundwater extraction than their counterparts outside of Beaumont.

For golf courses and housing developments, whose marginal revenue parameters are found in Table A.7, we find that rainfall during the dry season (which coincides with the growing season) increases the marginal value of extraction. Here we see that the number of high heat days has a negative effect on revenues, but a positive interaction with rainfall, suggesting that while hot days during a drought may damage the profitability of applied groundwater, they improve it during relatively wetter years.

Results show that increased population and real income lead to more profitable extraction, likely due to the effect these factors have on increasing overall demand for these overlying users' services. We find no significant effect on revenue of years in which these users used water for construction.

For appropriators, whose marginal revenue parameters are found in Table A.7, we see that marginal revenues were higher for appropriators during relatively cooler years, and years with more precipitation. This is likely due to increased costs of conservation activities during drought years in which rainfall is low and temperatures are high. It may also reflect increased costs of transmission to customers during drought years, when applied water for landscaping may need to be purchased more frequently, and additional wells must be brought online.

We allow municipal water districts to care about both consumer surplus and the profits from water sales, and the appropriator weights and on consumer surplus and on consumer surplus squared are among the structural parameters we estimate. As seen in the estimated weights in Table A.7, we find that appropriators tend to value the interests of their customers more than water sale profits, albeit with diminishing returns. Using the average annual consumer surplus generated by appropriators over the open access period (1991-1996), as calculated using the actual data, we find that municipal water districts on average value \$1 in consumer surplus 2.07 times as much as they do \$1 in profits from water sales,[10] which emphasizes the importance of modeling municipal water districts as mixed objective institutions.

Moving next to the cost function terms in Table A.8, we see that the quadratic term is estimated to be positive and significant for each type of user. Thus, extraction costs are convex in extraction for all users. These terms are an order of magnitude smaller for appropriators than for each of the other types of users. For farmers and recreational users who have a more limited set of wells, increasing pumping involves bringing less efficient wells into operation, which could increase costs. In contrast, appropriators have several wells in each basin, thus increasing extraction levels may involve just slightly increasing pumping marginally at several wells. We also do not see a significant difference between quadratic costs of extraction inside and outside the Beaumont Basin for appropriators. This suggests that differences in returns to scale resulting from differences in the convexity of extraction costs are not likely to explain changes in the pattern of extraction across space during our sample period.

6.2 Welfare

We use our structural parameters to examine the magnitude and distribution of welfare generated from groundwater extraction under open access. Table 2 presents the average annual welfare, consumer surplus, and profits.

As seen in Table 2, welfare is overwhelmingly tilted towards the appropriators. The average annual

[10]When using consumer surplus over the open access period (1991-1996) calculated using the model simulated actions and states instead of the actual data for actions and states, we find that municipal water districts on average value \$1 in consumer surplus 2.02 times as much as they do \$1 in profits from water sales.

welfare for an individual appropriator under open access during the period 1991-1996 ranges from 5.6 million dollars to 19.4 million dollars. In contrast, the average annual welfare ranges from 400 dollars to 5,000 dollars for individual farmers inside Beaumont Basin; 0 dollars to 800 dollars for individual farmers outside Beaumont Basin; and 300 dollars to 24,300 dollars for individual golf courses and housing developments.

Also as seen in Table 2, the average annual consumer surplus faced by an individual appropriator under open access during the period 1991-1996 ranges from 2.5 million dollars to 10.4 million dollars. Thus, a large share of appropriator welfare is from the consumer surplus they generate for their customers.

Our estimated structural parameters show that appropriators tend to value the interests of their customers more than water sale profits, albeit with diminishing returns. In Figure A.2 in Appendix A, we plot, for each appropriator-year, annual estimated water sale profits against the marginal payoffs to the appropriator of consumer surplus generated, as calculated using actual data. We find that during the open access period (1991-1996), the marginal payoffs to the appropriator of an additional $1 in consumer surplus are above the $1 line for all appropriator-years, and water sales profits tend to be centered around close to 0.

In our structural estimation of player payoff function parameters, we find that appropriators tend to overweight consumer surplus relative to profits. When calculating social welfare, however, consumer surplus should be weighted equally to producer surplus, or the sum of profits produced from groundwater extraction by players in the game. In Table 3, we calculate social welfare as the sum of producer surplus and consumer surplus. We find that after re-weighting, model predicted social welfare is still large in magnitude, around $25.5 million annually, with $24 million of this coming from consumer surplus. Thus, benefits primarily accrue to residential consumers in the region's cities, with appropriators earning relatively small profits.

Here it is important to note that our social welfare estimate should be considered a lower bound, due to the fact that it does not include consumer surplus derived from the water consumption of overlying players' groundwater extraction, but instead focuses only on the consumer surplus from groundwater extraction by municipal water districts. The consumer surplus derived from the water consumption of overlying players' groundwater extraction would include benefits related to access to recreational sites, housing developments, and the consumption of agricultural products.

7 Counterfactual Open Access Scenarios

7.1 Open Access Counterfactual

In order to measure the welfare gains associated with shifting from an open access environment to one of property rights, we perform a simple counterfactual simulation exercise. Taking the evolution of all other state variables as given in the data, we simulate a counterfactual scenario of continued open access from 1997-2014 using our open access policy functions, open access transition densities for depth to groundwater, and open access structural parameter estimates applied to the same set of all groundwater users in the Beaumont Basin during the open access period (1991-1996) that we used to estimate our structural econometric model of the open access dynamic game. When we simulate counterfactual open access behavior during the years following the open access period, we keep this group constant and ignore any entry by additional players, since we do not model the entry decision. In two cases of exit by players, we model the exit as planned and known, and thus treat their extraction as 0 in the years following their exit in the actual data.

We then compare our open access counterfactual with the actual extraction decisions that were made after the institution of quantified property rights in order to quantify the welfare gains and losses from shifting to a quantified property rights system for different groundwater extractors in our empirical setting. Since the model we have developed and estimated is a model of behavior under open access, we do not use our model to model behavior under quantified property rights, but instead use actual data on extraction decisions that were made after the institution of quantified property rights, and compare the actual data with our counterfactual scenario of continued open access. In particular, we use our structural parameter estimates to quantify the welfare generated by players in the counterfactual open access scenario, and compare the counterfactual open access welfare with the actual welfare realized after the institution of quantified property rights, as calculated using their actual extraction decisions and the actual evolution of the groundwater stock after the institution of quantified property rights.

We find a stark difference between our counterfactual scenario of continued open access and the actual extraction decisions that were made after the institution of quantified property rights. In Table A.9 in Appendix A, we compare the actual and counterfactual groundwater extraction and depth to groundwater across different types of players during this period using two-sample t-tests. In Figures 1-3 we plot the actual and simulated counterfactual trajectories of mean extraction and depth to groundwater for each type of user from 1997-2014. In each graph, we indicate the end of open access in 1996 and the end of the adjudication in 2004 using red vertical dashed lines.

Our open access counterfactual results show that under the counterfactual scenario of continued open access, appropriators would generally abandon the Beaumont Basin over time, and instead shift extraction to outside the basin (Figure 1). This is in part due to increased costs of extraction driven by lower water table levels. Continued open access extraction inside Beaumont Basin decreases the groundwater stock inside Beaumont Basin, thus increasing the depth to groundwater inside Beaumont Basin. In addition, increased extraction at wells outside the Beaumont Basin in turn depresses the water table in these other basins, leading to the spatial flow of groundwater from inside Beaumont to outside of it, which further decreases the groundwater stock inside Beaumont Basin, thus further increasing the depth to groundwater inside Beaumont Basin. Since there is no artificial recharge of imported water under our open access counterfactual, the stock inside Beaumont Basin was not able to match these losses, or recover over the later part of our sample period.

We also see a strong decline in extraction inside Beaumont Basin by golf courses and housing developments under the counterfactual scenario of continued open access (Figure 3). We interpret this as these users relinquishing the practice of groundwater extraction in favor of purchasing connections to appropriator networks, and relying on purchased water to meet their needs. An expectation about the unsustainability of the stock due to a lack of property rights and a lack of imported water may lead these users to abandon groundwater extraction in favor of purchased water.

For farmers, who rely on more precise irrigation of their crops, groundwater extraction is still used under the counterfactual scenario of continued open access, and groundwater extraction inside and outside the Beaumont Basin increases under the counterfactual scenario of continued open access (Figure 2). Under open access, farmers facing lower groundwater stocks may race to extract water before the groundwater stock runs out.

To examine the welfare implications of instituting the property rights regime in Beaumont, in Table 4 we compare the actual estimated annual welfare generated after the institution of quantified property rights with the annual welfare generated under the open access counterfactual. To adjust for the bias of our model relative to the actual data, we subtract the upward bias of the model relative to the actual data, as measured by the difference between our model prediction and the actual data for the respective welfare statistic over the open access period 1991-1996, from our difference between the open access counterfactual and the actual data over 1997-2014; this bias-corrected statistic is a measure of the difference between the open actual counterfactual and the actual data over 1997-2014 over and above any upward bias from the model relative to the actual data.

For appropriators, we find that, after correcting for the bias of our model relative to the actual data, appropriators did not receive any statistically significant gains in welfare under the property rights regime relative to the open access counterfactual. For farmers, we find that, after correcting for bias, farmers outside Beaumont Basin experienced welfare gains from the property rights regime relative to our open access counterfactual, while farmers in Beaumont Basin did not.

For recreational users, we find that, after correcting for bias, each of the golf course and housing development players that remained in business after the open access period had precisely estimated welfare gains from the property rights regime relative to our open access counterfactual. This is perhaps not surprising, given a welfare loss from the institution of quantified property rights might have been a factor that contributed to the exit of the one recreational overlying user that did not remain in business in the actual data after the institution of quantified property rights.

Since our counterfactual scenario of continued open access does not model overlying users finding alternative sources of water, such as obtaining connections to appropriator water providers, our result may be an upper bound of the welfare gains these users realized from the institution of quantified property rights. The welfare gains for overlying users are relatively small in magnitude compared to the gains of appropriators, although the latter are not precisely estimated. Thus, the welfare gains to overlying users from the institution of quantified property rights were relatively small.

We examine the impact of the property rights regime on profits, again correcting for bias, in Table A.10 in Appendix A. We find that while there were statistically significant differences in profit and its components for appropriators, they were either relatively small in magnitude or actually the opposite sign of the overall welfare change. Thus, after accounting for model simulation bias, we find that the welfare impact can largely be ascribed to the larger increase in consumer surplus under the property rights regime, and moreover to the high value that appropriators placed on consumer surplus for their customers. This is likely due to the fact that appropriators could continue to access groundwater inside the Beaumont Basin under the property rights regime. It is important to take these results with a caveat that we are not including the additional costs of imported water used for artificial recharge in the later period under the property rights regime.

We find that profits for farmers were generally higher under the property rights regime than under the open access counterfactual, due to generally lower costs, although the overall difference in profits is not statistically significant. For golf courses and housing developments, profits were higher under the property rights regime than under the open access counterfactual, and this difference in profits is statistically significant, but relatively small in magnitude, as it likely to due to higher extraction and consequently higher revenues as well as higher costs.

The statistically insignificant gains that appropriators received under the property rights regime relative to the open access counterfactual were largely due to losses in consumer surplus generated under continued open access (Table 5). As seen in Figure A.2 in Appendix A, which plots annual estimated water sale profits against the marginal payoffs to the appropriator of consumer surplus generated for each appropriator-year, as calculated using actual data both over the open access period (1991-1996) as well as after the institution of quantified property rights (1997-2014), we find that, while all observations of the marginal payoffs to the appropriator of an additional \$1 in consumer surplus are above the \$1 line in the figure during the open access period (1991-1996), this changes somewhat after the institution of quantified property rights (1997-2014). Since appropriator payoffs are concave in consumer surplus, and since consumer surplus increases with extraction, this means that if the payoff parameters for appropriators remain the same after the institution of quantified property rights as they were during open access, then, following the end of open access, water districts actually pursued the interests of their customers to an even greater degree, and beyond the point at which consumer surplus was providing equal marginal payoffs as profits. Indeed, we find that water sales profits tend to be centered around close to 0 during the open access period (1991-1996), but are lower on average after the institution of quantified property rights (1997-2014).

To examine the effects of shifting from an open access environment to one of property rights on social welfare, we re-weight consumer surplus equally with producer surplus and calculate the effect of property rights on social welfare. As seen in Table 5, we find that, after accounting for model simulation bias, the social welfare gain is under \$1 million per year and statistically insignificant. Producer surplus is lower on average under property rights than under open access, owing to lower appropriator producer profits and lower profits for farmers inside Beaumont Basin. The overall social welfare gain from shifting from an open access environment to one of property rights is not statistically significant, and only about 5 percent of the social welfare observed in the actual data.

7.2 Open Access with Equal Consumer Surplus Weighting Counterfactual

Our open access counterfactual results suggest that the welfare gains from instituting quantified property rights are minor. Moreover, our estimates of welfare impacts do not account for the additional costs of importing water and using it to artificially recharge the Beaumont Basin, meaning that the welfare gains from instituting quantified property rights were likely even less positive. This suggests that quantified property rights were not particularly useful in promoting greater social welfare. One possible reason is that these property rights do not directly address the issue of socially inefficient consumer surplus overweighting by appropriators. As seen in our structural parameter estimates, the weight appropriators place on consumer surplus relative to water sale profits is significantly greater than the socially efficient weight of one.

To better understand the welfare implications of consumer surplus weighting, we simulate an open access with equal consumer surplus weighting counterfactual by solving an approximation of the open access dynamic game under a counterfactual scenario in which appropriators place equal weight on consumer surplus and water sale profits. To approximate the solution of the open access dynamic game, we solve for the static payoff maximizing extraction values for appropriators. For our open access with equal consumer surplus weighting counterfactual, we solve our approximation of the open access dynamic game under a counterfactual scenario in which appropriators place equal weight on consumer surplus and water sale profits in each year after the institution of quantified property rights (1997-2014). We simulate the action choices of overlying players using our estimated policy functions, and simulate state transitions using our state transition densities as in the case of the open access counterfactual. Thus, we are not including the additional potential benefits and costs from artificial recharge, or the implementation of quantified property rights. Nor are we eliminating the effects of spatial externalities. Our open access with equal consumer surplus weighting counterfactual gives us an estimate of just the impact of altering the preferences of appropriators with respect to consumer surplus. As a result, the welfare effects of this change will be an underestimate of the full welfare effect of shifting to socially optimal behavior. We therefore interpret this as a lower bound on the efficiency gains from socially optimal extraction.

In Table A.11 in Appendix A, we compare counterfactual and actual levels of extraction and depth to groundwater in the period after the institution of quantified property rights (1997-2014). We find, unsurprisingly, that extraction by appropriators is dramatically lower in our open access with equal consumer surplus weighting counterfactual. While players do not abandon the Beaumont Basin entirely, they extract significantly less from it as well as from other regional basins. This indicates a dramatic change in water use in the region.

In Table A.12 in Appendix A, we compare producer profits, revenues, and costs between our counterfactual simulation and what was observed in the data during the period after the institution of quantified property rights (1997-2014). To adjust for the bias of our model relative to the actual data, we subtract the bias of the model relative to the actual data, as measured by the difference between the prediction of our model (using static payoff maximization problem for appropriators and weights on consumer surplus given by our parameter estimates) and the actual data for the respective profit component over the open access period 1991-1996, from our difference between the equal consumer surplus weighting counterfactual and the actual data over 1997-2014; this bias-corrected statistic is a measure of the difference between the equal consumer surplus counterfactual and the actual data over 1997-2014 over and above any bias from the model relative to the actual data. We see in Table A.12 that the implications of higher water prices are dramatic. Profits from water sales are now economically and statistically significantly higher when consumer surplus is weighted equally in the player's payoff function. By removing the incentive to over-extract, appropriators would bring in around $13 million dollars more per year in producer profits. By extracting less they would also lower their costs by about $165 thousand per year.

This translates directly to social welfare. In Table 6 we show a comparison of social welfare from groundwater extraction under the property rights regime in the actual data, and that under the open access with equal consumer surplus weighting counterfactual. We find that the higher counterfactual water prices have a significant negative impact on consumer surplus, but that this is far outweighed by the positive impact on producer profits. After accounting for simulation bias, we find that changing appropriator preferences from their status quo consumer surplus overweighting to socially efficient consumer surplus weighting leads to an increase in social welfare of $3.4 million per year.

Since our estimate of the welfare impact is a lower bound on achievable social welfare gains from improved water pricing, or more efficient consumer surplus weighting, our results suggest that potential gains from weighting consumer surplus equally with producer surplus are potentially quite large. This suggests that mechanisms that can induce appropriators to change the rate at which they weight consumer surplus could have a more significant impact on social welfare than the property rights regime. On the other hand, equally weighting instead of overweighting consumer surplus relative to water sale profits would lead to increases in water prices and decreases in water consumption, which may be undesirable to the customers of these water districts. Nevertheless, by equally weighting instead of overweighting consumer surplus, municipal water districts would be able to operate more efficiently and feel less of a need to raise additional revenues through alternative methods like connection fees and tax assessments.

8 Robustness Checks

In order to verify that our results are robust to changing or weakening the assumptions in our structural model, we perform five separate robustness checks on assumptions related to the state transition densities for the crop prices, the weather variables (precipitation and high heat days), the well capital stock of each player (number of wells and average distance between each player's wells), and the depth to groundwater. The tables and figures for these robustness checks are presented in Appendix C. In addition, as explained and described in detail in Appendix B, we also test for the presence of over-fitting to our dataset by conducting a leave-out analysis.

In the first robustness check, we relax the assumption of rational expectations (and perfect foresight) for crop prices, which include alfalfa price, grape price, strawberry price, cherry price, and olive price. Instead of assuming rational expectations (and perfect foresight) for crop prices, we allow crop prices to be uncertain and stochastic, with a joint distribution that is known to the players. In particular, we assume that the joint distribution for crop prices for alfalfa, grapes, strawberries, cherries, and olives is a multivariate normal distribution, and we parameterize this distribution using the empirical distribution of the prices for these crops from 1991-1996. We then forward simulate the prices for these crops by taking random draws from this multivariate normal distribution.

The results of the structural estimation for the first robustness check are presented in Table C.1 in Appendix C. We find that our parameter estimates are generally robust to our assumptions related to the state transition densities for these crop price variables. The signs and statistical significance of the total average effects of each variable are robust to these changes as well, except for crop prices and growing season precipitation for farmers, neither of which have statistically significant total average effects. In Figures C.1-C.3 and Tables C.2-C.3 in Appendix C, we show the results of our counterfactual simulation of open access from 1997-2014 under this assumption regarding state transitions for crop prices. Our results from the open access counterfactual in this first robustness check are similar to our baseline results. For appropriators, as in our base case results, the estimated welfare gains from the property rights regime relative to our open access counterfactual are statistically insignificant after correcting for model simulation bias. For recreational users, as in our base case results, we find that, after correcting for model simulation bias, each of the golf course / housing development players that remained in business after the open access period had precisely estimated welfare gains from the property rights regime relative to our open access counterfactual. When we turn to social welfare, we find that gains under property rights are slightly higher ($1.1 million per year) and statistically significant. Thus, our results are directionally similar to our baseline results for this case.

In the second robustness check, we relax the assumption of rational expectations (and perfect foresight) for weather variables, which include the number of high heat days during the growing season (which is nearly the same as the number of high heat days over the full year[11]), growing season precipitation, and annual precipitation. Instead of assuming rational expectations (and perfect foresight) for the weather variables, we allow the weather variables for the number of high heat days during the growing season, growing season precipitation, and annual precipitation to be uncertain and stochastic, with a joint distribution that is known to the players. In particular, we assume that the joint distribution for the number of high heat days during the growing season, growing season precipitation, and annual precipitation is a multivariate normal distribution, and we parameterize this distribution using the empirical distribution of these weather variables from 1991-1996. We then forward simulate these weather variables by taking random draws from this multivariate normal

[11]The correlation coefficient between the number of high heat days during the growing season and the number of high heat days over the full year is 1.0000.

distribution. The resulting structural parameter estimates are presented in Table C.4 in Appendix C. We summarize results from our counterfactual simulation under these assumptions in Figures C.4-C.6 and Tables C.5-C.6 in Appendix C. Here we find that welfare for appropriators is generally in line with our findings in the base case. However we do find that in this case overlying users tended to do worse off under the property rights regime compared with how they fared under our counterfactual of continued open access. This leads to a somewhat lower social welfare gain from property rights, that like our base case, is statistically insignificant.

Third, instead of modeling the capital stock of each player (number of wells and average distance between each player's wells) as evolving according to the actual data, we assume that the capital stock remains fixed in the initial year level of 1991. Thus, we assume that player's believe the capital stock will not change at all during the open access game.[12] The resulting structural parameter estimates are presented in Table C.7 in Appendix C. The results of our counterfactual simulation of 1997-2014 are found in Figures C.7-C.9 and Tables C.8-C.9 in Appendix C. Here we find similar results for appropriators as in our base case. For farmers we find that the property rights regime diminished their welfare relative to continued open access, while recreational users had welfare gains similar to our baseline result. Social welfare impacts were similar to our baseline findings.

In our fourth robustness check, we include lagged depth to groundwater inside Beaumont Basin as an additional regressor in the transition density for depth to groundwater for appropriators inside Beaumont Basin. The transition densities for depth to groundwater are presented in Table C.10 and the resulting structural parameter estimates are presented in Table C.11 in Appendix C. The results of our counterfactual simulation of 1997-2014 are found in Figures C.10-C.12 and Tables C.12-C.13 in Appendix C. When we simulate the counterfactual we find that while extraction at appropriator wells inside the Beaumont basin follows the same pattern as before, this time it causes depth at these wells to rise much faster than before and reach unrealistically high levels. This drives total extraction and extraction outside Beaumont to unrealistic levels. Results for farmers inside of Beaumont are not affected, while for farmers outside Beaumont depth rises somewhat higher than before. Recreational users are not affected.

When we examine welfare, we find that both actual and counterfactual welfare for appropriators are now lower, and appropriators now have a welfare gain from property rights and artificial recharge of about \$18.2 million which is significant. Farmer welfare losses are now estimated to be positive and significant, while recreational user welfare is similar to before. The bias-corrected social welfare gains from the property rights and artificial recharge relative to our open access counterfactual are now statistically significant, and, owing to the large appropriator welfare gain, the social welfare gains are large.

[12] The only player whose capital stock changed in the data during the open access period 1991-1996 was Yucaipa Valley Water District, who drilled wells in 1991, 1993, and 1994 (and therefore new wells are observed for this player in the following year). In the wells robustness check, we assume that the number of wells and average distance between each player's wells for Yucaipa Valley Water District remain the same as they were in 1991, rather than allow them to evolve according to the actual data.

In our fifth robustness check, we do not use any economic variables (CA GDP per capita and retail price of untreated water) as regressors in any groundwater transition density; and we once again include lagged depth to groundwater inside Beaumont Basin as an additional regressor in the transition density for depth to groundwater for appropriators inside Beaumont Basin. The transition densities for depth to groundwater are presented in Table C.14 and the resulting structural parameter estimates are presented in Table C.15 in Appendix C. The results of our counterfactual simulation of 1997-2014 are found in Figures C.13-C.15 and Tables C.16-C.17 in Appendix C.

When we run our counterfactual simulations, we find that appropriator depth is slightly rising inside Beaumont and slightly decreasing outside Beaumont, in line with the estimated transition densities. Extraction follows a similar pattern to our base case. For farmers we find that extraction is similar to our base case, but that depth to groundwater follows more closely with the actual data than it did in our base case counterfactual. For recreational users we find a flatter projected depth to groundwater path than before with none of the later increase we found in the base case. Extraction for these players follows a similar path. When we turn to welfare, we find that for appropriators and recreational users, results are close to the base case. For farmers, however, welfare under property rights are significantly lower than under continued open access, leading to significant welfare gains under the counterfactual relative to the actual data. The bias-corrected social welfare gains from the property rights regime relative to our open access counterfactual are statistically insignificant and the same sign as in our baseline.

We find that our parameter and welfare estimates are generally consistent across our robustness results that deal with the state transitions of variables unrelated to the depth to groundwater in the system. We do find that the results for farmers welfare are generally less consistent than those of other players, likely due to the greater sensitivity of their decision making to their expectations about crop prices, weather, and their ability to drill wells. The parameters that generate the largest share of welfare in our model, those dealing with appropriator revenue, are robust to all the robustness checks we impose. Furthermore, our parameters related to quadratic costs of extraction are also robust in sign across our each of our robustness checks. Finally, in all but one robustness check we find that bias-corrected social welfare gains from the property rights regime relative to our open access counterfactual are around the same magnitude as our base case. The exception, our robustness check which includes the lagged dependent variable in the depth to groundwater transition densities for all players does show a statistically significant social welfare gain, however simulation results suggest show unreasonable changes in depth to groundwater that go well beyond the state space used to estimate our model. Thus, our transition densities for depth to groundwater for appropriators do appear to be somewhat sensitive to specification. For these players, depth to groundwater represents an average of many wells over a larger geographic space than the overlying property owners. The sensitivity of their results points to both the importance that economic variables play in the evolution of the stock across a larger share of the basin.

9 Discussion and Conclusion

9.1 Welfare Impacts

Our welfare results make a clear point regarding the distribution of net benefits from groundwater in the Beaumont Basin: municipal water districts receive significantly higher payoffs from groundwater extraction than overlying agricultural and recreational groundwater users do. Nevertheless, we do not find that municipal water districts gained any statistically significant additional net benefits from switching to a quantified property rights system. We find moreover that social welfare gains from the imposition of property rights and imported water, relative to a counterfactual of continued open access, were not statistically significant either. We do find that there are potentially much larger welfare gains that regulators can make by devising policies that better align water pricing with socially optimal levels. We find that if water utilities had priced water using a payoff function with equal weights on consumer surplus and producer profits, instead of overweighting consumer surplus and underpricing water, social welfare could have increased by $3.4 million per year. Thus, the property rights system's gains appear to be only a very small portion of achievable gains from improved water pricing.

Furthermore, since we do not include the added cost of operating the property rights system, or the significant cost of importing water used for artificial recharge, our estimate of the joint effect of the property rights system and the introduction of artificial recharge on municipal water districts is likely to be more positive than the true effect. As part of the artificial recharge arrangement, appropriators paid to import outside water and use it to recharge the groundwater system, which allowed all users to continue to use the Beaumont Basin as a source of groundwater as population grew in the area. This had a positive external benefit both for other groundwater users in the basin, including golf courses and housing developments who were able to continue to use the basin, and for groundwater users from basins outside of Beaumont who were not impacted by changes in the pattern of extraction of appropriators as seen in our open access counterfactual. In future work, we hope to more explicitly model the dynamic game among groundwater users under the quantified property rights system, including the decisions of appropriators to import outside water and use it to recharge the groundwater system.[13]

Our finding of relatively limited welfare gains from management is generally in line with the results of Gisser and Sánchez (1980). These authors find that in cases in which groundwater storage is large in an aquifer, the benefits from switching from competition for groundwater to temporal optimal controlled extraction are negligible. In comparing our results to those of these authors, it

[13] In ongoing work in Sears et al. (2025c), for example, we develop a structural model of the dynamic game among groundwater users under quantified property rights, wherein groundwater users make decisions about groundwater extraction, well drilling, and water imports; estimate parameters in the model using data from the Beaumont Basin in the years following implementation of its adjudicated property rights system; and use the model to simulate counterfactuals to evaluate the welfare impacts of the property rights regime, and to understand the factors either amplified or diminished the impact of the program.

is important to note that the regulation we consider in our paper was not a single optimal control policy, but rather formal property rights limits on extraction. In addition, these authors make several assumptions in their theoretical model which we relax, including using a so-called "bathtub" model of the groundwater stock's evolution, in which a single groundwater stock determines extraction costs equally across space and is equally affected by extraction across space. Owing to the spatial heterogeneity in the Beaumont Basin of hydrological features such as saturated hydraulic conductivity, which measures the ability of sediments or rocks to transmit water (Fryar and Mukherjee, 2021), the costs of extraction and availability of groundwater may vary significantly for a given quantity of total groundwater remaining in the basin. As a consequence, a property rights system like the adjudicated property rights system in the Beaumont Basin that treats rights as fungible across space may not be appropriate since it may allocate rights to water that cannot be exercised at given well locations, even when the total quantity of rights is consistent with the total quantity of water remaining in the system. Subsequent research has suggested that the results of Gisser and Sánchez (1980) might not incorporate important factors that may increase the benefits from management, including ecosystem benefits, non-linearities in the impact of stock on extraction cost, and risk preferences of users (Koundouri, 2004; Tomini, 2014; Esteban and Albiac, 2011). These factors may help to explain the reasons why appropriators in Southern California generally, and Beaumont in particular, sought the adjudication of property rights. In future work, we hope to incorporate some of these relevant factors and to more explicitly model the dynamic game among groundwater users under the quantified property rights system.

In addition, our welfare impact estimates are short-run impacts, for several reasons. First, our estimation procedure uses only the period from 1991-1996 when the basin operated under open access to approximate each player's value function, and thus may not fully account for longer term interests of players under open access. Second, our counterfactual simulation only covers the first couple of decades after the regulation is implemented. Some of the gains from improved groundwater management may not be realized until later years, meaning that long-term welfare gains could be more significant. In future work, we hope to develop and apply methods that enable us to use longer time horizons to improve these estimates of long-term welfare benefits. Third, our structural econometric model of the open access dynamic game is estimated using data on all groundwater users in the Beaumont Basin during the open access period (1991-1996). When we simulate counterfactual open access behavior during the years following the open access period, we analyze the same set of players. Although entry and exit are potential responses to counterfactual continued open access, especially over the longer term, we ignore any entry by additional players, since we do not observe entry during the open access period (1991-1996) and therefore do not model the entry decision; and in two cases of exit by players, one of which took place during the open access period, we model the exit as planned and known, and thus treat their extraction as 0 in the years following their exit in the actual data. In future work, we hope to develop techniques to enable us to more fully model entry and exit decisions when entry and exit are either not observed or observed with limited frequency in the data. Fourth, in using forward simulation to approximate each player's infinite horizon value function, we implicitly assume that any dependence of the continuation value at the final period of our forward simulation on the groundwater stock remaining is negligible in present discounted value. In future work, we hope to develop and apply methods that enable us to improve these estimates of long-term value functions and long-term welfare benefits.[14]

9.2 Objectives of Appropriators

In this paper we explicitly model appropriators as having multiple objectives, namely earning profits and generating benefits for their customers. In line with the results of Timmins (2002) for the San Joaquin Valley in Central California, we find that, for municipal water utilities, groundwater extraction decisions and the resulting water prices do not maximize profits. Instead, in the payoff function of municipal water utilities, a significant weight is placed on the benefits generated for customers. Similar to Timmins (2002), we find that water districts tend to overweight the interests of their consumers relative to producer profits, leading to socially inefficient underpricing of water.

We further advance this understanding by allowing for this weight to vary with consumer surplus and find that the appropriator's payoff function is concave with respect to consumer surplus. Our results show that municipal water districts on average value \$1 in consumer surplus twice as much as they do \$1 in profits from water sales. The social welfare impact of this is at least \$3.4 million per year on average. Thus, consumer surplus overweighting is a significant distortion preventing higher levels of social welfare.

Remedying the overweighting of consumer surplus and the resulting underpricing of water likely requires changes in pricing that may be politically unpopular due to their impact on consumer surplus. Furthermore, while higher water prices may be more socially efficient, they would have at least some undesirable effects on the distribution of benefits across consumers with different levels of income. Indeed, while the implied prices from our open access with equal consumer surplus weighting counterfactual are within the range found in California, they would be a significant increase from the levels implied by our dataset. Cardoso and Wichman (2022) find that water bills represent around 8 percent of annual income for the bottom income decile. Using pricing strategies like increasing block tariffs that attempt to more progressively distribute the price increase across income levels may be a more equitable way of reaching socially efficient water pricing.

Nevertheless, by equally weighting instead of overweighting consumer surplus, municipal water districts would be able to operate more efficiently and feel less of a need to raise additional revenues through alternative methods that may also be unpopular with consumers, such as connection fees and tax assessments, and it is possible that some of these alternative methods of raising revenues may

[14]In ongoing work in Sears et al. (2025e), for example, we solve for long-term value functions by assuming a moment-based Markov equilibrium (MME) in which knowledge of the state space is limited to the private state and the distribution of the states of all other players (Ifrach and Weintraub, 2017), and find that the welfare results obtained from solving for long-term value functions are consistent with the short-run welfare results in this paper.

not necessarily be progressive. With richer data on the political and economic processes governing these companies, further research can investigate the role that consumer benefits and profits play in determining their pricing rules as well as their financing and investment decisions.

To a lesser extent, our findings in regards to differences in the point estimates and total average effects of weather variables for agricultural users versus recreational users also show an important distinction in how we should model the profit functions of different types of overlying users as well. In addition, with more recent improved data on specific crop choices, we may also be able to further identify variation within different farmers.

9.3 Spatial Patterns of Groundwater Extraction

Using our counterfactual analysis we are able to measure how groundwater pumping would have developed across space in the absence of the property rights regime. What we find contrasts with a traditional spatial leakage story, in which activity that is regulated in one area picks up in areas left unregulated. Instead, we find that the property rights regime and the importing of outside water kept the Beaumont Basin as a viable resource for appropriators, and thus kept pumping at nearby basins lower than it would have been under continued open access. By preventing a shift in groundwater extraction to wells outside of Beaumont, these policies also had a positive spillover effect on the level of groundwater stocks at neighboring basins. This reliance on imported water may be unsustainable in the long term, however, if surface water supplies become less predictable. Our work then shows the important role that these policies play in maintaining the groundwater stock not only inside the Beaumont Basin, but also at other basins in the region.

9.4 Conclusion

The sustainable management of groundwater, a common pool resource, is a critical issue worldwide. This paper analyzes groundwater extraction decisions under an open access regime. We develop a structural econometric model of the open access dynamic game among agricultural, recreational, and municipal users, and estimate our model using data from the Beaumont Basin in Southern California prior to the institution of quantified property rights for groundwater. We take advantage of variation across players over space and over time in key hydrological and economic drivers of groundwater extraction to identify parameters of the payoff functions of agricultural, recreational, and municipal users. Our dynamic structural econometric model enables us to analyze groundwater extraction decision-making behavior and its outcome under open access. We use our parameter estimates to simulate a counterfactual scenario of continued open access, and compare our open access counterfactual with the actual extraction decisions after the institution of quantified property rights in order to quantify the welfare gains and losses from shifting to a quantified property rights system for different groundwater extractors in our empirical setting.

We find that water districts and municipalities derive significant benefits from groundwater extraction, despite earning little in profits, by providing benefits to their customers. Both before and after the introduction of property rights, municipal water providers received most of their benefits in the form of being able to sell cheaper water to their customers. Municipal water districts on average value \$1 in consumer surplus twice as much as they do \$1 in profits from water sales.

We estimate that, for municipal water districts and farmers inside Beaumont Basin, short-run welfare gains from the imposition of property rights and imported water, relative to a counterfactual of continued open access, were statistically insignificant. Moreover, short-run social welfare gains from the imposition of property rights and imported water, relative to a counterfactual of continued open access, were statistically insignificant as well. Nevertheless, we do find that these policy changes helped to prevent a collapse in groundwater use in the Beaumont Basin, as well as a rush to pump from nearby basins. With formalized property rights and imported outside water, appropriators were able to continue to draw on water from the Beaumont Basin rather than having to exploit other stocks.

Our research allows us to estimate how groundwater managers and farmers manage a resource both spatially and dynamically, and how they respond to the legal and economic structure governing competition for the resource. Our research also provides a welfare analysis of how the institution of quantified property right actually fares in practice. The ability to examine the welfare effects of each of these issues is a direct result of the structural econometric approach we employ in our paper, and is therefore an important advantage of our dynamic structural econometric model. Our research has important implications for the design of regional policies for water conservation and management, and is of interest to academics, regional scientists, policymakers, water management specialists, agricultural producers, and industry practitioners.

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Table 1: Structural Parameter Estimates

	Appropriators		Farmers	Golf Course /
	Inside Beaumont	Outside Beaumont		Housing Development
Coefficient in Farmer Marginal Revenue on:				
Average crop price (dollars per unit)			-5.603***	
Precipitation, Apr-Oct (inches)			161.077***	
Average crop price (dollars per unit) X High heat days			0.067***	
Average crop price (dollars per unit) X Precipitation (inches)			-0.341***	
Average crop price (dollars per unit) X High heat days X Precipitation (inches)			-0.018***	
Number of wells in Beaumont Basin, squared			11.909***	
Total wells owned before t			17.061***	
Has wells in Beaumont Basin (dummy)			11.915***	
Total Average Effect on Farmer Marginal Revenue:				
Average crop price (dollars per unit)			-4.385**	
Precipitation, Apr-Oct (inches)			0.430	
Number of high heat days (> 90 F), Apr-Oct			2.157	
Coefficient in Golf Course / Housing Development Marginal Revenue on:				
Number of wells X Hydraulic conductivity (feet per day) X High heat days				-0.014***
Number of wells X Hydraulic conductivity (feet per day) X Precipitation (inches)				0.393***
Number of wells X Hydraulic conductivity (feet per day) X High heat days X Precipitation (inches)				0.004***
Number of wells X Log Population of Beaumont				5.049***
Number of wells X Real GDP per capita				1.230***
Number of wells in Beaumont Basin, squared				-34.519***
Planned construction (dummy)				82.657
Total Average Effect on Golf Course / Housing Development Marginal Revenue:				
Number of wells in Beaumont Basin				86.313
Precipitation, Apr-Oct (inches)				290.320
Number of high heat days (> 90 F), Apr-Oct				-2.678
Saturated hydraulic conductivity (feet per day)				4.194
Coefficient in Appropriator Marginal Revenue on:				
Number of high heat days (> 90 F)	-2.642*			
Precipitation (inches)	5.262*			
Weight in Appropriator Per-Period Payoffs on:				
Consumer surplus	2.427***			
Consumer surplus squared	-5.33E-08*			
Profits from water sales	1.000 (normalization)			
Coefficient in Water Extraction Cost on:				
Extraction (acre-feet) squared	0.003*	0.004***	0.032***	0.025***

Notes: Per-period payoffs, revenue, marginal revenue, and costs are in dollars. Standard errors are reported in Tables A.7-A.8 in Appendix A. Significance codes: *** p<0.001, ** p<0.01, * p<0.05

Table 2: Model Predicted Average Annual Welfare, Consumer Surplus, and Profits, 1991-1996

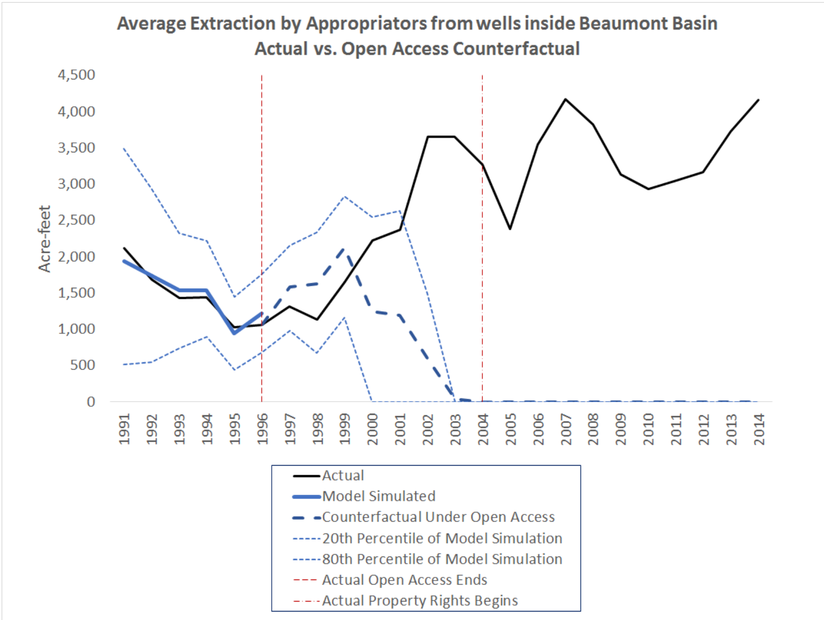
	Model Predicted Average Annual				
	Welfare (dollars)	*Consumer Surplus (dollars)*	*Profits (dollars)*	*Revenues (dollars)*	*Costs (dollars)*
Appropriators					
Beaumont-Cherry Valley Water District	8.0 million	3.6 million	0.04 million	0.21 million	0.17 million
City of Banning	14.2 million	7.5 million	-0.20 million	0.04 million	0.24 million
South Mesa Water Company	5.6 million	2.5 million	-0.05 million	0.02 million	0.07 million
Yucaipa Valley Water District	19.4 million	10.4 million	1.7 million	1.8 million	150.6 thousand
Total appropriators	**47.2 million**	**24.0 million**	**1.5 million**	**2.1 million**	**0.6 million**
Farmers in Beaumont Basin					
Murray	0.4 thousand		0.4 thousand	3.9 thousand	3.5 thousand
Riedman	5.0 thousand		5.0 thousand	23.1 thousand	18.0 thousand
Total farmers in Beaumont Basin	**5.5 thousand**		**5.5 thousand**	**26.9 thousand**	**21.5 thousand**
Farmers outside Beaumont Basin					
Dowling	0.3 thousand		0.3 thousand	3.5 thousand	3.2 thousand
Illy	0.8 thousand		0.8 thousand	9.2 thousand	8.4 thousand
Summit Cemetery District	0.0 thousand		0.0 thousand	1.0 thousand	1.0 thousand
Total farmers outside Beaumont Basin	**1.1 thousand**		**1.1 thousand**	**13.7 thousand**	**12.6 thousand**
Golf Course / Housing Development					
California Oak Valley Golf and Resort LLC	8.2 thousand		8.2 thousand	53.1 thousand	44.9 thousand
Coscan Stewart Partnership	0.3 thousand		0.3 thousand	4.7 thousand	4.4 thousand
Oak Valley Partners	24.3 thousand		24.3 thousand	62.4 thousand	38.1 thousand
Plantation on the Lake	2.0 thousand		2.0 thousand	9.5 thousand	7.6 thousand
Sharondale Mesa Owners Association	1.3 thousand		1.3 thousand	5.6 thousand	4.4 thousand
Total golf course / housing development	**36.0 thousand**		**36.0 thousand**	**135.3 thousand**	**99.4 thousand**

Notes: Average annual welfare, profits, revenues, and costs are the present discounted value of the entire stream over the period 1991-1996 of per-period payoffs, profits, revenues, and costs, respectively, divided by the number of years. Consumer surplus is the consumer surplus faced by each appropriator over the period 1991-1996. Average annual consumer surplus is consumer surplus divided by the number of years. For farmers and recreational users, average annual welfare is equal to average annual profits. For appropriators, profits are the profits from water sales given by the water sale revenues minus extraction costs, while the per-payoffs are a weighted quadratic function of consumer surplus and the profits from water sales. Model predicted welfare and profit components are calculated using the parameter estimates from the structural model, and the model predicted actions and states. Model predicted consumer surplus is calculated using the water demand parameter estimates, and the model predicted actions and states.

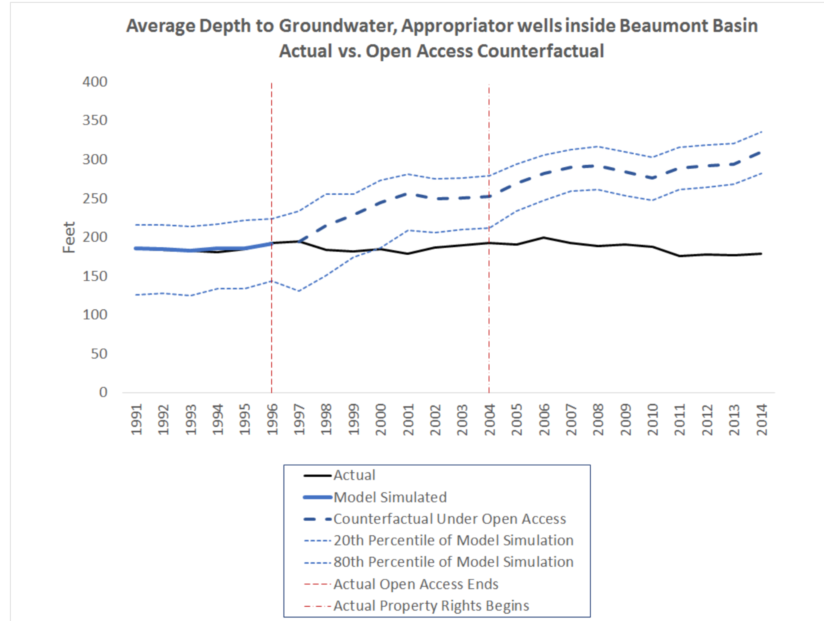
Table 3: Model Predicted Average Annual Social Welfare from Groundwater Extraction, 1991-1996

	Model Predicted
Average Annual Producer Surplus (dollars)	
Appropriator profits	1.5 million
Farmer profits inside Beaumont Basin	5.5 thousand
Farmer profits outside Beaumont Basin	1.1 thousand
Golf Course / Housing Development profits	36.0 thousand
Total Producer Surplus	**1.5 million**
Average Annual Consumer Surplus (dollars)	
Beaumont-Cherry Valley Water District	3.6 million
City of Banning	7.5 million
South Mesa Water Company	2.5 million
Yucaipa Valley Water District	10.4 million
Total Consumer Surplus	**24.0 million**
Average Annual Social Welfare (dollars)	
Social Welfare	**25.5 million**

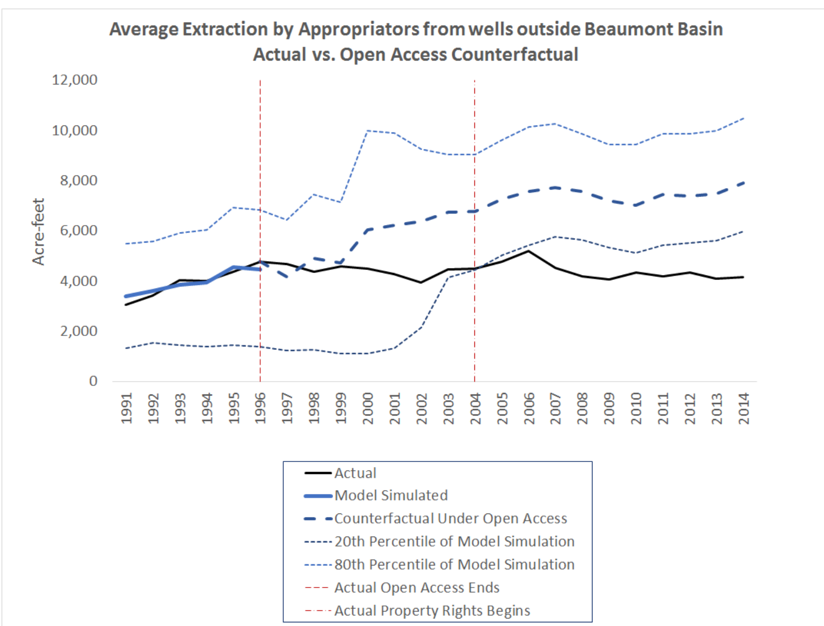
Notes: Components of social welfare are the present discounted value of the entire stream of per-period payoffs related to each component over the period 1991-1996. Producer surplus is equal to the profits from groundwater extraction summed over all players. Consumer surplus is the consumer surplus faced by each appropriator, and is not weighted by parameters in the payoff function of the appropriator. Social welfare is equal to the sum of producer surplus and consumer surplus. Average annual values of these components are equal to the total value of the component divided by the number of years. Model predicted profits are calculated using the parameter estimates from the structural model. Model predicted consumer surplus are calculated using the water demand parameter estimates. Model predicted values are calculated using model predicted actions and states generated from 100 simulation runs of the open access period.



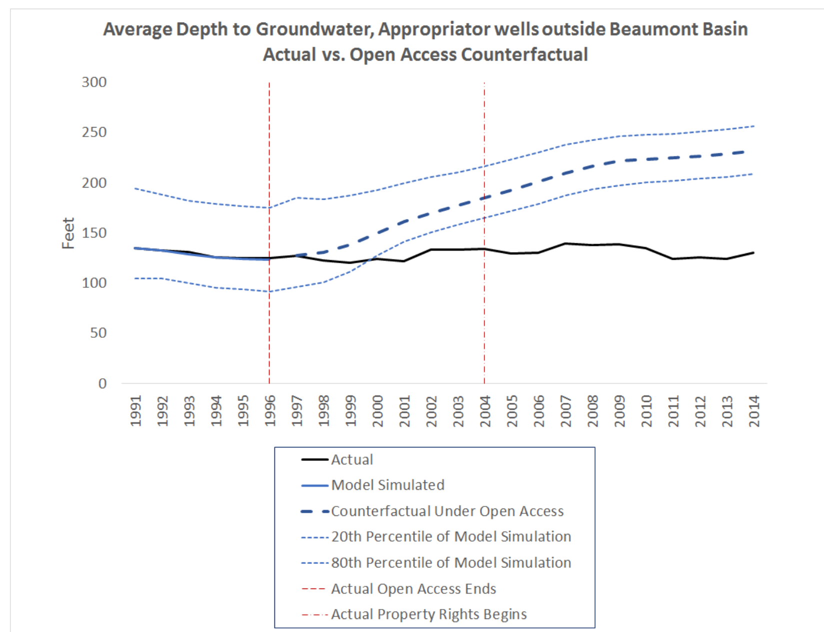
(a) Appropriator Extraction in Beaumont Basin



(b) Appropriator Depth to Groundwater in Beaumont Basin

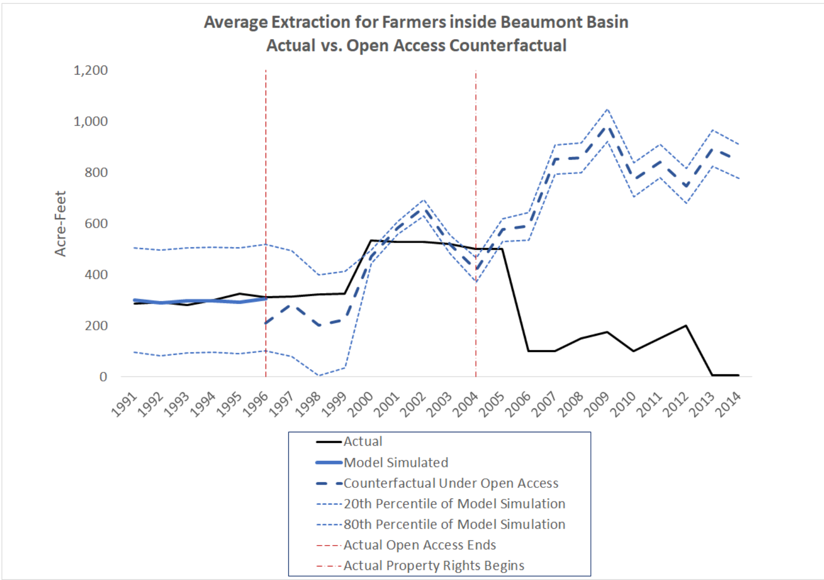


(c) Appropriator Extraction outside Beaumont Basin

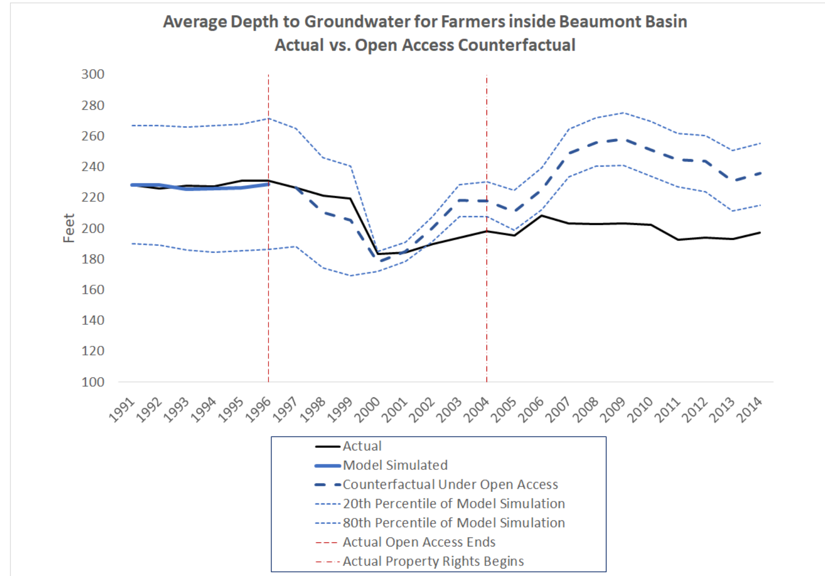


(d) Appropriator Depth to Groundwater outside Beaumont Basin

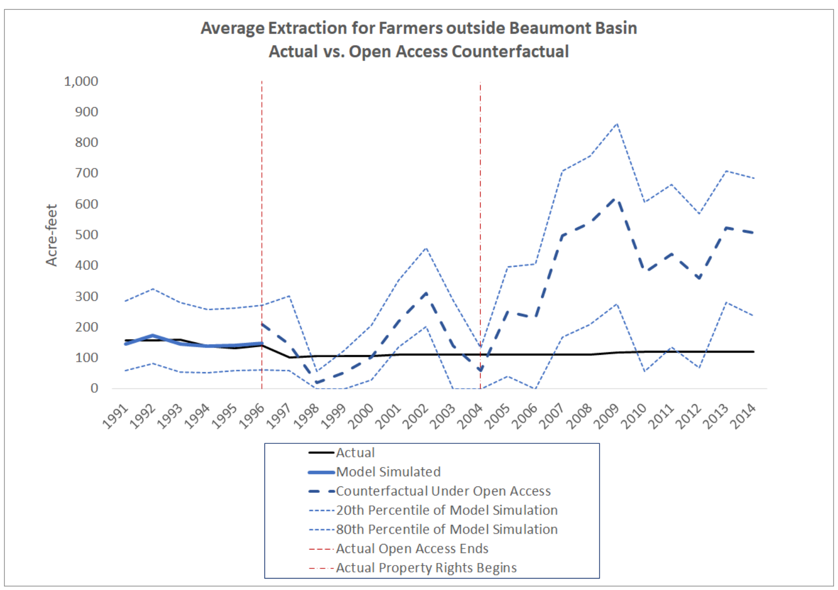
Figure 1: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Appropriators, 1991-2014



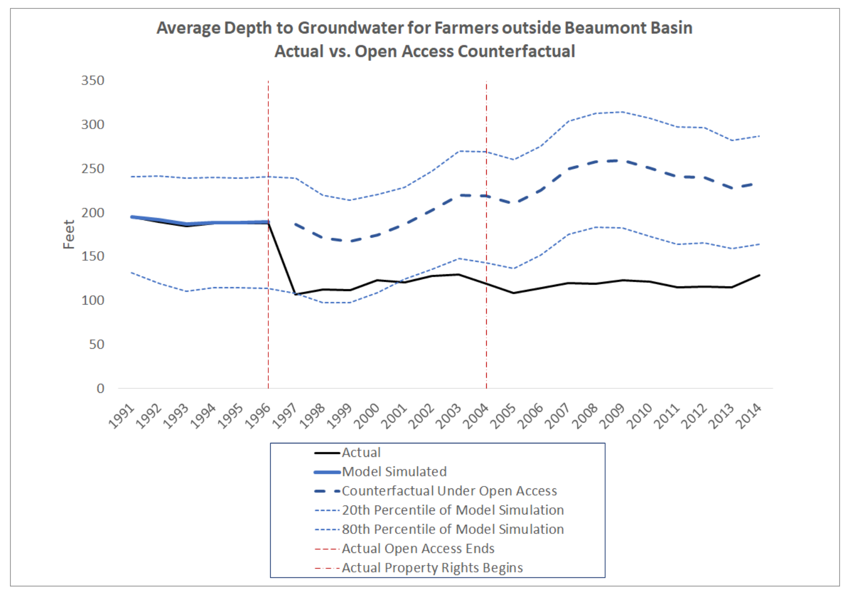
(a) Farmer Extraction in Beaumont Basin



(b) Farmer Depth to Groundwater in Beaumont Basin

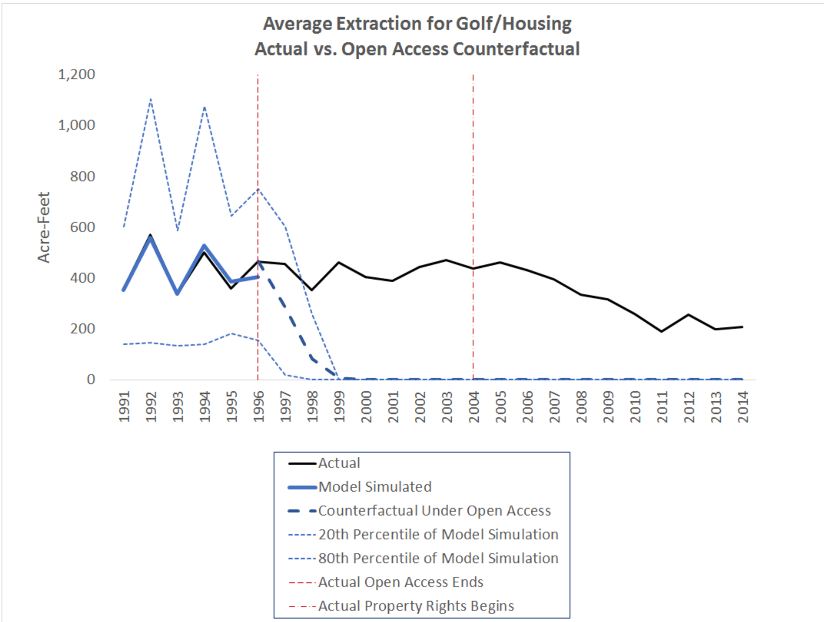


(c) Farmer Extraction outside Beaumont Basin

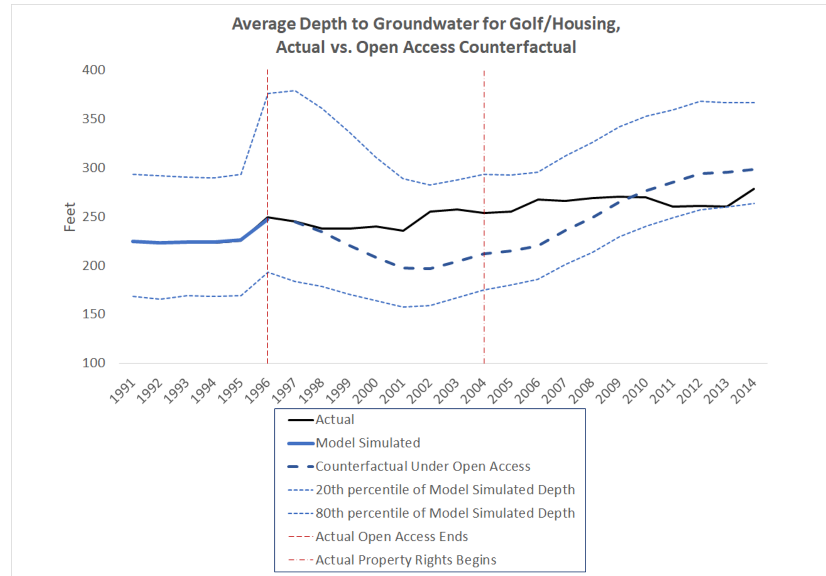


(d) Farmer Depth to Groundwater outside Beaumont Basin

Figure 2: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Farmers, 1991-2014



(a) Golf Course / Housing Development Extraction



(b) Golf Course / Housing Development Depth to Groundwater

Figure 3: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Golf/Housing, 1991-2014

Table 4: Open Access Counterfactual vs. Actual Welfare After Institution of Property Rights, 1997-2014

	Average Annual Welfare (dollars)			
	Actual	Open Access Counterfactual	Open Access Counterfactual Minus Actual	Open Access Counterfactual Minus Actual, Bias Corrected
Appropriators				
Beaumont-Cherry Valley Water District	6.3 million	7.2 million	0.8 million	42.1 thousand
City of Banning	8.1 million	8.9 million	0.8 million	-634.5 thousand
South Mesa Water Company	3.6 million	3.9 million	0.3 million	-280.7 thousand
Yucaipa Valley Water District	11.5 million	13.0 million	1.5 million	-487.3 thousand
Total appropriators	**29.6 million**	**32.9 million**	**3.4 million**	**-1.4 million**
Farmers in Beaumont Basin				
Murray, Cecil Merle	-2.0 thousand	-0.3 thousand	1.7 thousand	1.7 thousand
Riedman, Fred L. And Richard M.	-2.6 thousand	-3.2 thousand	-0.6 thousand	-1.1 thousand
Total farmers in Beaumont Basin	**-4.6 thousand**	**-3.6 thousand**	**1.0 thousand****	**0.6 thousand**
Farmers outside Beaumont Basin				
Francis M Dowling Jr	-0.9 thousand	-2.4 thousand	-1.5 thousand	-1.5 thousand
Katharina Illy	-4.4 thousand	-8.8 thousand	-4.3 thousand	-4.8 thousand
Summit Cemetery District	-1.5 thousand	-1.3 thousand	0.2 thousand	0.0 thousand
Total farmers outside Beaumont Basin	**-6.8 thousand**	**-12.4 thousand**	**-5.6 thousand*****	**-6.3 thousand*****
Golf Course / Housing Development				
California Oak Valley Golf and Resort LLC	21.7 thousand	8.3 thousand	-13.5 thousand***	-13.9 thousand***
Coscan Stewart Partnership	N/A	N/A	N/A	N/A
Oak Valley Partners	8.8 thousand	0.5 thousand	-8.2 thousand***	-11.0 thousand***
Plantation on the Lake	2.7 thousand	0.2 thousand	-2.5 thousand***	-2.6 thousand***
Sharondale Mesa Owners Association	6.6 thousand	0.1 thousand	-6.5 thousand***	-6.7 thousand***
Total golf course / housing development	**39.8 thousand**	**9.1 thousand**	**-30.7 thousand*****	**-34.1 thousand*****

Notes: Welfare is the present discounted value of the entire stream of per-period payoffs over the period 1997-2014. Average annual welfare is welfare divided by the number of years. 'Open Access Counterfactual Minus Actual' is the difference between counterfactual and actual welfare values. Both actual and open access counterfactual welfare are calculated using the parameter estimates from the structural model. Actual welfare is calculated using actual values of actions and states in the data. Open access counterfactual welfare is calculated using model predicted actions and states generated from 100 simulation runs. The standard errors for the open access counterfactual welfare values and for the difference between counterfactual and actual welfare values are calculated using the parameter estimates from each of 100 bootstrap samples. To adjust for the bias of our model relative to the actual data, we subtract the upward bias of the model relative to the actual data, as measured by the difference between our model prediction and the actual data for the respective welfare statistic over the open access period 1991-1996, from our difference between the open access counterfactual and the actual data over 1997-2014; this bias-corrected statistic is a measure of the difference between the open actual counterfactual and the actual data over 1997-2014 over and above any upward bias from the model relative to the actual data. Significance stars next to the difference between counterfactual and actual welfare values denote the significance level of the difference between counterfactual and actual average annual welfare. Significance codes: *** $p<0.001$, ** $p<0.01$, * $p<0.05$

Table 5: Open Access Counterfactual vs. Actual Social Welfare After Institution of Property Rights, 1997-2014

	Actual	Open Access Counterfactual	Open Access Counterfactual Minus Actual	Open Access Counterfactual Minus Actual, Bias Corrected
		Average Annual Producer Surplus (dollars)		
Appropriator profits	-180.3 thousand	-28.8 thousand	151.5 thousand	312.4 thousand
Farmer profits inside Beaumont Basin	-4.6 thousand	-3.6 thousand	1.0 thousand**	0.6 thousand
Farmer profits outside Beaumont Basin	-6.8 thousand	-12.4 thousand	-5.6 thousand***	-6.3 thousand***
Golf course / housing development profits	39.8 thousand	9.1 thousand	-30.7 thousand***	-34.1 thousand***
Total Producer Surplus	**-0.2 million**	**0 million**	**0.1 million**	**0.3 million**
		Average Annual Consumer Surplus (dollars)		
Beaumont-Cherry Valley Water District	3.6 million	3.9 million	267.6 thousand***	-95.1 thousand***
City of Banning	4.7 million	5.2 million	558.4 thousand***	-184.6 thousand***
South Mesa Water Company	1.7 million	2.0 million	276.9 thousand***	27.9 thousand
Yucaipa Valley Water District	7.1 million	7.4 million	393.0 thousand***	-945.1 thousand***
Total Consumer Surplus	**17.0 million**	**18.5 million**	**1.5 million*** **	**-1.2 million*** **
		Average Annual Social Welfare (dollars)		
Social Welfare	**16.9 million**	**18.5 million**	**1.6 million**	**-0.9 million**

Notes: Components of social welfare are the present discounted value of the entire stream of per-period payoffs related to each component over the period 1997-2014. Producer surplus is equal to the profits from groundwater extraction summed over all players. Consumer surplus is the consumer surplus faced by each appropriator, and is not weighted by parameters in the payoff function of the appropriator. Social welfare is equal to the sum of producer surplus and consumer surplus. Average annual values of these components are equal to the total value of the component divided by the number of years. 'Open Access Counterfactual Minus Actual' is the difference between counterfactual and actual component values. Both actual and open access counterfactual profits are calculated using the parameter estimates from the structural model. Both actual and open access counterfactual consumer surplus are calculated using the water demand parameter estimates. Actual values are calculated using actual values of actions and states in the data. Open access counterfactual values are calculated using model predicted actions and states generated from 100 simulation runs. The standard errors for the difference between open access counterfactual and actual welfare values are calculated using the parameter estimates from each of 100 bootstrap samples. To adjust for the bias of our model relative to the actual data, we subtract the upward bias of the model relative to the actual data, as measured by the difference between our model prediction and the actual data for the respective welfare statistic over the open access period 1991-1996, from our difference between the open access counterfactual and the actual data over 1997-2014; this bias-corrected statistic is a measure of the difference between the open actual counterfactual and the actual data over 1997-2014 over and above any upward bias from the model relative to the actual data. Significance stars next to the difference between counterfactual and actual values denote the significance level of the difference between counterfactual and actual average annual values. Significance codes: *** $p<0.001$, ** $p<0.01$, * $p<0.05$
2

Table 6: Open Access with Equal Consumer Surplus Weighting Counterfactual vs. Actual Social Welfare After Institution of Property Rights, 1997-2014

	Actual	Open Access Equal CS Weight Counterfactual	Open Access Equal CS Weight Counterfactual Minus Actual	Open Access Equal CS Weight Counterfactual Minus Actual, Bias Corrected
		Average Annual Producer Surplus (dollars)		
Appropriator profits	-180.3 thousand	17.0 million	17.2 million	13.1 million***
Farmer profits inside Beaumont Basin	-4.6 thousand	-3.4 thousand	1.2 thousand	0.9 thousand
Farmer profits outside Beaumont Basin	-6.8 thousand	-10.2 thousand	-3.4 thousand	-4.3 thousand
Golf course / housing development profits	39.8 thousand	9.3 thousand	-30.5 thousand	-34.1 thousand
Total Producer Surplus	**-0.2 million**	**17 million**	**17.2 million*** **	**13 million*** **
		Average Annual Consumer Surplus (dollars)		
Beaumont-Cherry Valley Water District	3.6 million	1.6 million	-2.1 million***	-2.3 million***
City of Banning	4.7 million	1.5 million	-3.2 million***	-3.4 million***
South Mesa Water Company	1.7 million	698.2 thousand	-990.4 thousand***	-839.4 thousand***
Yucaipa Valley Water District	7.1 million	2.6 million	-4.5 million***	-3.0 million*
Total Consumer Surplus	**17.0 million**	**6.3 million**	**-10.7 million*** **	**-9.6 million*** **
		Average Annual Social Welfare (dollars)		
Social Welfare	**16.9 million**	**23.3 million**	**6.5 million*** **	**3.4 million*** **

Notes: Components of social welfare are the present discounted value of the entire stream of per-period payoffs related to each component over the period 1997-2014. Producer surplus is equal to the profits from groundwater extraction summed over all players. Consumer surplus is the consumer surplus faced by each appropriator, and is not weighted by parameters in the payoff function of the appropriator. Social welfare is equal to the sum of producer surplus and consumer surplus. Average annual values of these components are equal to the total value of the component divided by the number of years. 'Open Access with Equal CS Weight Counterfactual Minus Actual' is the difference between counterfactual and actual component values. Both actual and counterfactual profits are calculated using the parameter estimates from the structural model. Both actual and counterfactual consumer surplus are calculated using the water demand parameter estimates. Actual values are calculated using actual values of actions and states in the data. The open access with equal consumer surplus weighting counterfactual values are calculated using static payoff maximizing actions for appropriators, model predicted actions for overlyers, and model predicted states generated from 100 simulation runs of the equal consumer surplus weighting counterfactual scenario. In the static payoff maximization problem for appropriators, action choices are discretized and the weight on consumer surplus is set to 1. The standard errors for the difference between counterfactual and actual welfare values are calculated using the parameter estimates from each of 100 bootstrap samples. To adjust for the bias of our model relative to the actual data, we subtract the bias of the model relative to the actual data, as measured by the difference between the prediction of our model (using static payoff maximization problem for appropriators and weights on consumer surplus given by our parameter estimates) and the actual data for the respective welfare statistic over the open access period 1991-1996, from our difference between the counterfactual and the actual data over 1997-2014; this bias-corrected statistic is a measure of the difference between the counterfactual and the actual data over 1997-2014 over and above any bias from the model relative to the actual data. Significance stars next to the difference between counterfactual and actual values denote the significance level of the difference between counterfactual and actual average annual values. Significance codes: *** p<0.001, ** p<0.01, * p<0.05

Appendix A. Supplementary Tables and Figures

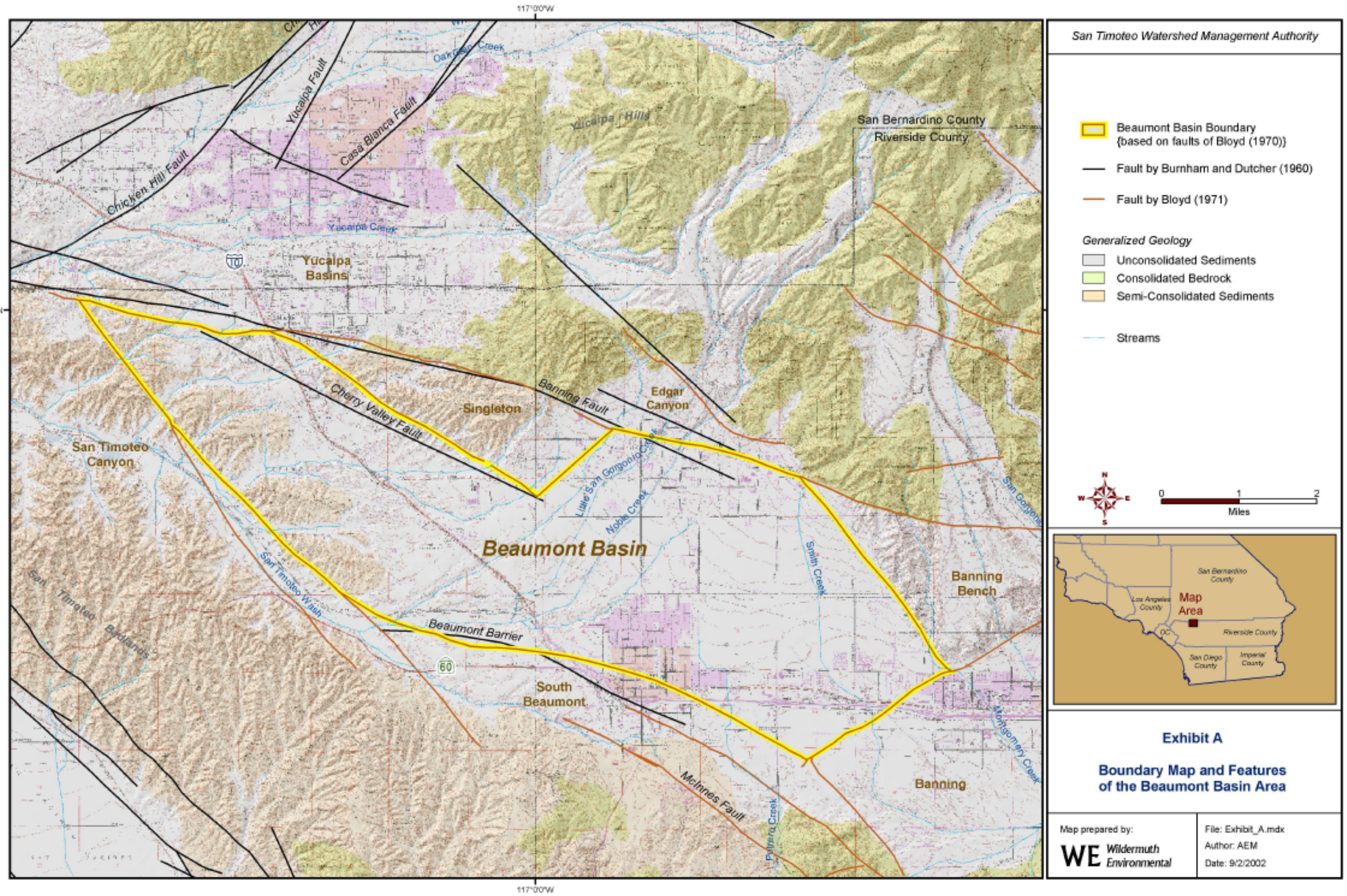


Figure A.1: Adjudicated Boundaries of the Beaumont Basin
Source: Exhibit A of Beaumont Basin Adjudication Judgment

Table A.1: Summary Statistics for Groundwater Variables by Player Type, 1991-1996

	Mean	Min	Max	Std.Dev.	Obs
Appropriators					
Appropriator extraction in Beaumont (acre-feet)	1,461.13	387.00	4,219.00	1,012.82	24
Appropriator extraction outside Beaumont (acre-feet)	3,944.25	932.00	8,317.00	2,260.33	24
Average depth to groundwater (feet)	143.94	103.93	196.38	30.19	24
Average depth to groundwater, wells in Beaumont Basin (feet)	185.29	123.82	237.82	36.87	24
Average depth to groundwater, wells outside Beaumont Basin (feet)	129.23	94.23	194.74	36.55	24
Number of wells	21.38	5.00	45.00	12.08	24
Number of wells inside Beaumont Basin	5.75	2.00	11.00	3.64	24
Number of wells outside Beaumont Basin	15.63	3.00	42.00	11.85	24
Average depth of wells (feet)	668.51	598.58	753.56	64.20	24
Average pump strength inside Beaumont Basin (gallons per minute)	1605.83	1300.00	1797.50	224.90	18
Average pump strength outside Beaumont Basin (gallons per minute)	901.35	142.50	1623.65	582.24	24
Appropriator population	18,932.11	7,502.95	36,789.55	11,171.08	24
Appropriator average household size	2.65	2.50	2.78	0.09	24
Farmers					
Farmer extraction (acre-feet)	208.80	55.00	550.00	170.63	30
Average depth to groundwater (feet)	204.83	100.60	269.41	54.41	30
Average depth to groundwater, wells in Beaumont Basin (feet)	228.59	187.83	269.41	40.11	12
Average depth to groundwater, wells outside Beaumont Basin (feet)	189.00	100.60	244.06	57.84	18
Number of wells	1.60	1.00	3.00	0.81	30
Number of wells inside Beaumont Basin	0.40	0.00	1.00	0.50	30
Number of wells outside Beaumont Basin	1.20	0.00	3.00	1.19	30
Average depth of wells (feet)	235.50	171.00	300.00	67.37	12
Average pump strength (gallons per minute)	410.51	127.80	1043.02	378.74	24
Golf course / Housing development action and state variables					
Golf course / Housing development extraction (acre-feet)	430.59	13.00	1,570.00	380.94	29
Average depth to groundwater (feet)	225.24	143.49	382.67	77.72	30
Average depth to groundwater, wells in Beaumont Basin (feet)	225.24	143.49	382.67	77.72	30
Average depth to groundwater, wells outside Beaumont Basin (feet)	.	.	.	.	0
Number of wells	1.40	1.00	2.00	0.50	30
Number of wells inside Beaumont Basin	1.40	1.00	2.00	0.50	30
Number of wells outside Beaumont Basin	0.00	0.00	0.00	0.00	30
Average depth of wells (feet)	941.50	415.00	1,370.00	407.47	18
Average pump strength (gallons per minute)	941.50	415.00	1370.00	407.47	18

Data Sources: AWWA CA/Nevada Survey 2007-2015; CA Franchise Tax Board; USGS; CA-SWP; CA Dept. Finance; PRISM; FRED; BEA; USDA; SGPWA; STWMA; Beaumont Watermaster; Groundwater Recordation Program.

Table A.2: Summary Statistics for Additional State Variables, 1991-1996

	Mean	Min	Max	Std.Dev.	Obs
Annual state variables					
Agricultural price of electricity (dollars per kwh)	0.10	0.10	0.11	0.01	6
Price alfalfa (dollars per ton)	88.17	73.70	97.30	8.37	6
Price grapes (dollars per ton)	129.17	123.00	135.00	4.71	6
Price untreated imported water (dollars per acre-foot)	295.25	213.00	344.00	53.11	6
Price strawberries (dollars per pound)	0.78	0.65	0.90	0.09	6
Price cherries (dollars per ton)	126.00	115.00	140.00	10.08	6
Price olives (dollars per ton)	96.50	94.40	99.10	1.68	6
Average crop price (dollars per unit)	96.50	94.40	99.10	1.68	6
Price untreated imported water (dollars per acre-foot)	295.25	213.00	344.00	53.11	6
Population of Beaumont	10,422.83	9,996	10,673	264.05	6
Other player-level state variables					
Saturated hydraulic conductivity (feet per day)	33.00	4.61	92.00	33.53	84
Saturated hydraulic conductivity in Beaumont Basin (feet per day)	29.71	4.61	92.00	29.28	66
Saturated hydraulic conductivity outside Beaumont Basin (feet per day)	40.16	5.85	120.67	43.90	42
Extraction by neighbors within 3 miles (acre-feet)	410.46	0.00	1,971.00	560.65	84
Extraction by neighbors in the Beaumont Basin within 1 mile (acre-feet)	547.15	0.00	2,351.00	717.05	84
Extraction by neighbors in the Beaumont Basin within 2 miles (acre-feet)	754.43	0.00	4,869.00	1,067.76	84
Extraction by neighbors in the Beaumont Basin within 3 miles (acre-feet)	491.20	0.00	4,219.00	838.95	84
Extraction by neighbors in the Beaumont Basin within 4 miles (acre-feet)	978.63	0.00	4,807.00	1,296.27	84
Extraction by neighbors outside the Beaumont Basin within 2 miles (acre-feet)	339.85	0.00	6,511.00	1,287.07	84
Extraction by neighbors outside the Beaumont Basin within 4 miles (acre-feet)	1,473.19	0.00	9,964.00	2,652.12	84
Precipitation, growing season (inches)	2.44	0.79	5.03	1.00	84
Precipitation, full year (inches)	22.67	10.74	42.72	7.57	84
Number of high heat days (> 90 F), growing season (Apr-Oct)	79.85	36.76	104.00	16.68	84

Data Sources: AWWA CA/Nevada Survey 2007-2015; CA Franchise Tax Board; USGS; CA-SWP; CA Dept. Finance; PRISM; FRED; BEA; USDA; SGPWA; STWMA; Beaumont Watermaster; Groundwater Recordation Program.

Table A.3: Summary Statistics for Residential Water Demand Estimation

	Mean	Min	Max	Std.Dev.	Obs
Demand estimation sample					
Monthly consumption per household (hundred cubic feet)	17.38	1.00	38.00	6.66	210
Average water price (dollars per hundred cubic feet)	1.71	0.25	19.77	2.36	210
State Water Project equivalent unit charge (dollars per acre-foot)	334.26	31.46	2,164.80	296.16	210
Electricity price (dollars per kwh) x Depth to groundwater (feet)	5.21	0.05	30.83	5.28	210
Household size	2.84	1.94	4.53	0.47	210
Median adjusted gross income (dollars)	15,986.30	11,135.96	25,277.77	2,749.63	210
Unemployment rate (percent)	8.43	5.38	11.71	2.67	210
Precipitation, full year (inches)	12.78	1.60	56.16	9.57	210

Data Sources: AWWA CA/Nevada Survey 2007-2015; CA Franchise Tax Board; USGS; CA-SWP; CA Dept. Finance; PRISM; FRED; BEA; USDA; SGPWA; STWMA; Beaumont Watermaster; Groundwater Recordation Program.

Table A.4: Residential Water Demand

	Dependent variable is: Log monthly water consumption per household (hundred cubic feet)
Log average price paid by the user (dollars per hundred cubic feet)	-0.321**
	(0.100)
Log average household size in city	0.407**
	(0.137)
Log median personal income in county (dollars)	-0.142
	(0.144)
Log unemployment rate in state	0.00281
	(0.0573)
Log precipitation in county, full year (inches)	0.0158
	(0.0304)
Structure = 2, Declining	-0.0284
	(0.204)
Structure = 3, Inclining	-0.0328
	(0.0609)
Structure = 5, Other	0.00915
	(0.0974)
Structure = 6, Uniform	-0.0652
	(0.0829)
Constant	3.792**
	(1.422)
# Observations	210
R-squared	0.645
RMSE	0.253
Instruments for residential water price	
Charge for water supply for closest SWP contractor (dollars per acre-foot)	Y
Log Depth to groundwater (feet) X Electricity price in water district (dollars per kwh)	Y
Sanderson-Windmeijer first-stage F-statistic	199
Anderson underidentification test p-value	0.000106
Stock-Wright p-value	0.0167
Hansen J test p-value	0.449

Notes: Standard errors in parentheses. Each observation is a water district in a given year. We use two supply shifters to instrument for residential water price: the annual equivalent unit price charged by the State Water Project (SWP) for water delivery to the water district's nearest State Water Project contractor; and the product of the average depth to groundwater in the district and the price of electricity. Significance codes: *** p<0.001, ** p<0.01, * p<0.05

Table A.5: Policy Function Results, 1991-1996

	Dependent variable is:			
	Appropriator total extraction (acre-feet) (1)	Appropriator share extraction in Beaumont (2)	Farmer extraction (acre-feet) (3)	Golf/Housing extraction (acre-feet) (4)
Depth to groundwater inside management zone (feet)	37.10***	0.0200***		
	(1.243)	(0.00205)		
Depth to groundwater outside management zone (feet)	-21.36***			
	(1.456)			
Number of own wells in Beaumont Basin	294.9***	-0.0939***		
	(18.58)	(0.0114)		
Number of high heat days (>90 F) in Apr-Oct	-5.937*	-0.00429***	6.564	6.210***
	(2.318)	(0.00126)	(3.230)	(1.779)
Depth to groundwater (feet)			3.872***	13.14***
			(0.825)	(1.947)
Number of wells squared			571.1***	171.7***
			(84.23)	(40.84)
CA real GDP per capita (1997 chained dollars)				-0.0564**
				(0.0174)
Hydraulic conductivity X Depth to groundwater			-0.0474***	-0.0528***
			(0.00461)	(0.00944)
Population of city of Beaumont		-0.000250***		-0.141***
		(0.000040)		(0.0312)
Precipitation, full year (inches)		-0.00522**		4.264*
		(0.00169)		(2.155)
Planned construction (dummy)				938.0***
				(44.47)
Hydraulic conductivity X Depth to groundwater in BB		-0.000190***		
		(0.000026)		
Price of untreated water (dollars/acre-foot)		0.00519***		
		(0.000822)		
Price of untreated water X Depth to groundwater in BB squared		-3.36E-07***		
		(0.42E-07)		
Population (thousands) X Price untreated water X Depth to groundwater in BB		6.24E-07***		
		(1.20E-07)		
Total wells owned by i before t			-2,598***	
			(400.4)	
Average crop price (dollars per unit)			25.53***	
			(3.180)	
Precipitation, Apr-Oct (inches)			488.3***	
			(67.99)	
Average crop price X High heat days in Apr-Oct			-0.0923*	
			(0.0354)	
Average crop price X Precipitation in Apr-Oct			-5.425***	
			(0.750)	
Has wells in Beaumont Basin (dummy)			-282.5*	
			(103.0)	
# Observations	24	24	30	29
# Players	4	4	5	5
p-value (Prob>F)	0.000	0.000	0.000	0.000
RMSE	304.3	0.180	14.87	374.3

Notes: 'Hydraulic conductivity' is saturated hydraulic conductivity in feet per day. Standard errors in parentheses.
Significance codes: *** p<0.001, ** p<0.01, * p<0.05

Table A.6: State Transition Results, 1991-1996

	Dependent variable is depth to groundwater (ft) for:			
	Farmer	Golf/ Housing	Appropriator inside Beaumont	Appropriator outside Beaumont
	(1)	(2)	(3)	(4)
Lagged values of:				
Depth to groundwater (ft)		0.808***		
		(0.0480)		
Depth to groundwater outside management zone (ft)				0.806***
				(0.0764)
Depth to groundwater (ft) X Electricity price (dollars/kwh)	1.879***	1.381**		
	(0.558)	(0.481)		
Own extraction (acre-ft) X Saturated hydraulic conductivity (ft/day)	0.00304	0.000185*		
	(0.00383)	(0.000074)		
Own extraction in Beaumont (acre-ft) X Saturated hydraulic conductivity (ft/day)			0.000191**	
			(0.000068)	
Own extraction outside Beaumont (acre-ft) X Saturated hydraulic conductivity (ft/day)				-0.000005
				(0.000004)
Neighbor extraction in Beaumont (acre-ft), 0.5 to 1 miles X Saturated hydraulic conductivity (ft/day)			8.71E-05*	
			(4.34E-05)	
Neighbor extraction in Beaumont (acre-ft), 1 to 2 miles X Saturated hydraulic conductivity (ft/day)				0.000046
				(0.000054)
Neighbor extraction (acre-ft), 2 to 3 miles X Saturated hydraulic conductivity (ft/day)	0.000108**			
	(0.000034)			
Neighbor extraction (acre-ft), 3 to 4 miles X Saturated hydraulic conductivity (ft/day)	0.0000763*			
	(0.000033)			
Neighbor extraction in Beaumont (acre-ft), 3 to 4 miles X Saturated hydraulic conductivity (ft/day)				-0.000369**
				(0.000135)
Average pump strength outside management zone (gallons per minute)				-0.00758*
				(0.00355)
Precipitation, Apr-Oct (inches)	-1.705*		1.673	
	(0.809)		(1.245)	
Number of high heat days (> 90 F), Apr-Oct		0.0982*	-0.358**	
		(0.0482)	(0.127)	
CA real GDP per capita (1997 chained dollars)	0.00241*		0.00839***	0.00125*
	(0.00103)		(0.00198)	(0.000521)
Retail price of untreated water (dollars/acre-foot)			0.0922***	
			(0.0218)	
# Observations	30	25	20	20
# Players	5	5	4	4
p-value (Prob>F)	0.000	0.000	0.000	0.000
RMSE	4.047	2.715	5.558	4.166

Notes: Standard errors in parentheses. Significance codes: *** p<0.001, ** p<0.01, * p<0.05

Table A.7: Revenue Parameters and Standard Errors

	Revenue Parameters
Coefficient in Farmer Marginal Revenue on:	
Average crop price (dollars per unit)	-5.603***
	(0.848)
Precipitation, Apr-Oct (inches)	161.077***
	(32.391)
Average crop price (dollars per unit) X High heat days	0.067***
	(0.011)
Average crop price (dollars per unit) X Precipitation (inches)	-0.341***
	(0.049)
Average crop price (dollars per unit) X High heat days X Precipitation (inches)	-0.018***
	(0.004)
Number of wells in Beaumont Basin, squared	11.909***
	(1.715)
Total wells owned before t	17.061***
	(1.975)
Has wells in Beaumont Basin (dummy)	11.915***
	(1.715)
Total Average Effect On Farmer Marginal Revenue of:	
Average crop price (dollars per unit)	-4.385**
	(1.513)
Precipitation, Apr-Oct (inches)	0.430
	(45.597)
Number of high heat days (> 90 F), Apr-Oct	2.157
	(1.315)
Coefficient in Golf Course / Housing Development Marginal Revenue on:	
Number of wells X Hydraulic conductivity (feet per day) X High heat days	-0.014***
	(0.003)
Number of wells X Hydraulic conductivity (feet per day) X Precipitation (inches)	0.393***
	(0.071)
Number of wells X Hydraulic conductivity (feet per day) X High heat days X Precipitation (inches)	0.004***
	(0.001)
Number of wells X Log Population of Beaumont	5.049***
	(0.474)
Number of wells X Real GDP per capita	1.230***
	(0.150)
Number of wells in Beaumont Basin, squared	-34.519***
	(4.106)
Planned construction (dummy)	82.657
	(4579.830)
Total Average Effect On Golf Course / Housing Development Marginal Revenue of:	
Number of wells in Beaumont Basin	86.313
	(511.434)
Precipitation, Apr-Oct (inches)	290.320
	(206.860)
Number of high heat days (> 90 F)	-2.678
	(6.842)
Saturated hydraulic conductivity (feet per day)	4.194
	(21.536)
Coefficient in Appropriator Marginal Revenue on:	
Number of high heat days (> 90 F)	-2.642*
	(1.293)
Precipitation (inches)	5.262*
	(2.054)
Weight in Appropriator Per-Period Payoffs on:	
Consumer surplus	2.427***
	(0.690)
Consumer surplus squared	-5.33E-08*
	(2.32E-08)
Profits from water sales	1.000
	(normalization)

Notes: Per-period payoffs, revenue, and marginal revenue are in dollars. Standard errors are in parentheses. Significance codes: *** p<0.001, ** p<0.01, * p<0.05

Table A.8: Cost Parameters and Standard Errors

	Appropriators		Farmers	Golf Course /
	Inside Beaumont	Outside Beaumont		Housing Development
	Coefficient in Water Extraction Cost on:			
Extraction (acre-feet) squared	0.003*	0.004***	0.032***	0.025***
	(0.001)	(0.001)	(0.004)	(0.007)

Notes: Costs are in dollars. Standard errors are in parentheses. Significance codes: *** p<0.001, ** p<0.01, * p<0.05

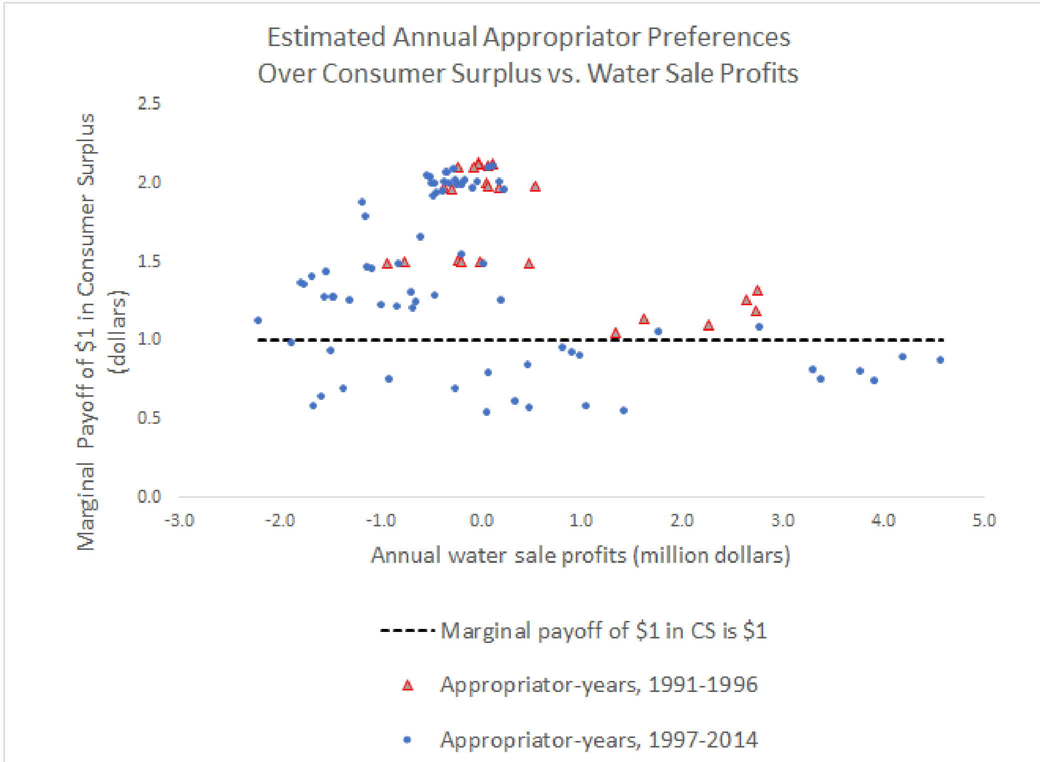


Figure A.2: Appropriator Preferences Over Consumer Surplus vs. Water Sale Profits, 1991-2014

Table A.9: Open Access Counterfactual vs. Actual Data After Institution of Property Rights, 1997-2014

	Appropriator inside Beaumont	Appropriator outside Beaumont	Farmer inside Beaumont	Farmer outside Beaumont	Golf Course / Housing Development
			Groundwater Extraction (acre-feet)		
Open Access Counterfactual					
Mean	464.52	6689.60	578.89	301.46	20.59
Std Dev	911.81	2645.75	285.49	293.14	93.72
Actual Data After Institution of Property Rights					
Mean	2964.29	4401.73	287.00	78.15	359.33
Std Dev	3186.80	2728.06	213.19	12.87	269.09
Percentage Difference from Actual Data					
Mean	-0.84	0.52	1.02	2.86	-0.94
Std Dev	1.12	0.86	1.24	3.75	0.79
			Depth to Groundwater (feet)		
Open Access Counterfactual					
Mean	264.55	189.62	224.58	218.45	242.21
Std Dev	44.98	43.59	33.27	64.79	65.40
Actual Data After Institution of Property Rights					
Mean	186.39	129.72	203.78	191.19	256.67
Std Dev	44.89	36.76	24.47	37.04	81.62
Percentage Difference from Actual Data					
Mean	0.42	0.46	0.10	0.14	-0.06
Std Dev	0.34	0.44	0.20	0.39	0.41

Notes: This table compares the counterfactual open access extraction and depth to groundwater with the actual extraction decisions that were made and the actual depth to groundwater that was realized after the institution of quantified property rights. Significance stars indicate p-values from two-sample t-tests comparing the open access counterfactual and the actual data. Significance codes: *** p<0.001, ** p<0.01, * p<0.05

Table A.10: Open Access Counterfactual vs. Actual Average Annual Profits After Institution of Property Rights, 1997-2014

	Open Access Counterfactual Minus Actual Average Annual, Bias Corrected		
	Profits (dollars)	*Revenues (dollars)*	*Costs (dollars)*
Appropriators			
Beaumont-Cherry Valley Water District	189.9 thousand	131.0 thousand	-58.9 thousand***
City of Banning	-204.6 thousand	-118.6 thousand	86.0 thousand**
South Mesa Water Company	-311.7 thousand	-195.1 thousand	116.7 thousand**
Yucaipa Valley Water District	638.9 thousand***	629.8 thousand*	-9.0 thousand
Total appropriators	**312.4 thousand**	**447.1 thousand**	**134.8 thousand**
Farmers in Beaumont Basin			
Murray	1.7 thousand	0.3 thousand	-1.3 thousand***
Riedman	-1.1 thousand	6.3 thousand	7.4 thousand***
Total farmers in Beaumont Basin	**0.6 thousand**	**6.7 thousand**	**6.1 thousand*** **
Farmers outside Beaumont Basin			
Dowling	-1.5 thousand	5.2 thousand*	6.7 thousand***
Illy	-4.8 thousand	-2.0 thousand	2.7 thousand***
Summit Cemetery District	0.0 thousand	0.5 thousand	0.5 thousand***
Total farmers outside Beaumont Basin	**-6.3 thousand*** **	**3.8 thousand**	**10.0 thousand**
Golf Course / Housing Development			
California Oak Valley Golf and Resort LLC	-13.9 thousand***	-44.2 thousand***	-30.3 thousand***
Coscan Stewart Partnership	N/A	N/A	N/A
Oak Valley Partners	-11.0 thousand***	-17.2 thousand***	-6.3 thousand***
Plantation on the Lake	-2.6 thousand***	-7.2 thousand***	-4.5 thousand***
Sharondale Mesa Owners Association	-6.7 thousand***	-9.4 thousand***	-2.7 thousand***
Total golf course / housing development	**-34.1 thousand*** **	**-80.6 thousand*** **	**-46.5 thousand*** **

Notes: Average annual profits, revenues, and costs are the present discounted value of the entire stream over the period 1997-2014 of profits, revenues, and costs, respectively, divided by the number of years. For farmers and recreational users, average annual welfare is equal to average annual profits. For appropriators, profits are the profits from water sales given by the water sale revenues minus extraction costs, while the per-payoffs are a weighted quadratic function of consumer surplus and the profits from water sales. Both actual and counterfactual profit components are calculated using the parameter estimates from the structural model. Actual profit components are calculated using actual values of actions and states in the data. Open access counterfactual profit components are calculated using model predicted actions and states under the open access counterfactual scenario. To adjust for the bias of our model relative to the actual data, we subtract the upward bias of the model relative to the actual data, as measured by the difference between our model prediction and the actual data for the respective profit component over the open access period 1991-1996, from our difference between the open access counterfactual and the actual data over 1997-2014; this bias-corrected statistic is a measure of the difference between the open actual counterfactual and the actual data over 1997-2014 over and above any upward bias from the model relative to the actual data. Table reports the bias-corrected difference between the counterfactual and actual values of the respective average annual profit component. Significance stars denote the significance level of the difference between the counterfactual and actual values of the respective average annual profit component. Significance codes: *** p<0.001, ** p<0.01, * p<0.05

Table A.11: Open Access with Equal Consumer Surplus Weighting Counterfactual vs. Actual Data After Institution of Property Rights, 1997-2014

	Appropriator inside Beaumont	Appropriator outside Beaumont	Farmer inside Beaumont	Farmer outside Beaumont	Golf Course / Housing Development
	Groundwater Extraction (acre-feet)				
Open Access with Equal Consumer Surplus Weighting Counterfactual					
Mean	167.22	1905.93	573.55	283.65	20.80
Std Dev	241.32	1104.63	281.02	266.61	94.70
Actual Data After Institution of Property Rights					
Mean	2964.29	4401.73	287.00	78.15	359.33
Std Dev	3186.80	2728.06	213.19	12.87	269.09
Percentage Difference from Actual Data					
Mean	-0.94	-0.57	1.00	2.63	-0.94
Std Dev	1.08	0.67	1.23	3.42	0.79
	Depth to Groundwater (feet)				
Open Access with Equal Consumer Surplus Weighting Counterfactual					
Mean	259.18	188.97	222.96	191.60	242.15
Std Dev	43.55	43.65	32.58	82.00	64.99
Actual Data After Institution of Property Rights					
Mean	186.39	129.72	203.78	191.19	256.67
Std Dev	44.89	36.76	24.47	37.04	81.62
Percentage Difference from Actual Data					
Mean	0.39	0.46	0.09	0.00	-0.06
Std Dev	0.34	0.44	0.20	0.47	0.41

Notes: This table compares the counterfactual open access with equal consumer surplus weighting extraction and depth to groundwater with the actual extraction decisions that were made and the actual depth to groundwater that was realized after the institution of quantified property rights. The open access with equal consumer surplus weighting counterfactual welfare is calculated using static payoff maximizing action choices for appropriators, model predicted actions for overlyers, and model predicted states generated from 100 simulation runs of the equal consumer surplus weighting counterfactual scenario. In the static payoff maximization problem for appropriators, action choices are discretized and the weight on consumer surplus is set to 1. Significance stars indicate p-values from two-sample t-tests comparing the open access counterfactual and the actual data. Significance codes: *** $p<0.001$, ** $p<0.01$, * $p<0.05$

Table A.12: Open Access with Equal Consumer Surplus Weighting Counterfactual vs. Actual Average Annual Profits After Institution of Property Rights, 1997-2014

	Open Access with Equal Consumer Surplus Weighting Counterfactual Minus Actual Average Annual, Bias Corrected		
	Profits (dollars)	*Revenues (dollars)*	*Costs (dollars)*
Appropriators			
Beaumont-Cherry Valley Water District	3.1 million***	3.0 million***	-132.8 thousand***
City of Banning	4.2 million***	4.2 million***	-20.0 thousand*
South Mesa Water Company	1.2 million***	1.2 million***	-5.8 thousand
Yucaipa Valley Water District	4.5 million*	4.5 million*	-6.6 thousand
Total appropriators	**13.1 million*** **	**12.9 million*** **	**-165.2 thousand*** **
Farmers in Beaumont Basin			
Murray, Cecil Merle	1.7 thousand	0.3 thousand	-1.4 thousand***
Riedman, Fred L. And Richard M.	-0.8 thousand	5.9 thousand	6.7 thousand***
Total farmers in Beaumont Basin	**0.9 thousand**	**6.2 thousand**	**5.4 thousand*** **
Farmers outside Beaumont Basin			
Francis M Dowling Jr	-0.8 thousand	4.9 thousand*	5.7 thousand***
Katharina Illy	-3.6 thousand	-1.8 thousand	1.7 thousand***
Summit Cemetery District	0.0 thousand	0.3 thousand	0.3 thousand***
Total farmers outside Beaumont Basin	**-4.3 thousand**	**3.4 thousand**	**7.7 thousand**
Golf Course / Housing Development			
California Oak Valley Golf and Resort LLC	-13.8 thousand	-44.8 thousand**	-31.0 thousand***
Coscan Stewart Partnership	N/A	N/A	N/A
Oak Valley Partners	-10.9 thousand	-17.4 thousand	-6.4 thousand
Plantation on the Lake	-2.6 thousand***	-7.2 thousand***	-4.6 thousand***
Sharondale Mesa Owners Association	-6.7 thousand**	-9.3 thousand***	-2.6 thousand***
Total golf course / housing development	**-34.1 thousand**	**-81.4 thousand**	**-47.2 thousand*** **

Notes: Average annual profits, revenues, and costs are the present discounted value of the entire stream over the period 1997-2014 of profits, revenues, and costs, respectively, divided by the number of years. For farmers and recreational users, average annual welfare is equal to average annual profits. For appropriators, profits are the profits from water sales given by the water sale revenues minus extraction costs. Both actual and counterfactual profit components are calculated using the parameter estimates from the structural model. Actual profit components are calculated using actual values of actions and states in the data. Open access with equal consumer surplus weighting counterfactual profit components are calculated using static payoff maximizing action choices for appropriators, model predicted actions for overlyers, and model predicted states generated from 100 simulation runs of the equal consumer surplus weighting counterfactual scenario. In the static payoff maximization problem for appropriators, action choices are discretized and the weight on consumer surplus is set to 1. To adjust for the bias of our model relative to the actual data, we subtract the bias of the model relative to the actual data, as measured by the difference between the prediction of our model (using static payoff maximization problem for appropriators and weights on consumer surplus given by our parameter estimates) and the actual data for the respective profit component over the open access period 1991-1996, from our difference between the equal consumer surplus weighting counterfactual and the actual data over 1997-2014; this bias-corrected statistic is a measure of the difference between the equal consumer surplus counterfactual and the actual data over 1997-2014 over and above any bias from the model relative to the actual data. Table reports the bias-corrected difference between the counterfactual and actual values of the respective average annual profit component. Significance stars denote the significance level of the difference between the counterfactual and actual values of the respective average annual profit component. Significance codes: *** $p<0.001$, ** $p<0.01$, * $p<0.05$

Appendix B. Model Validation

To assess the goodness of fit of our structural econometric model, we first compare the action and state variables predicted by our model with the actual values in the data. The fit of our model for the open access game by player type is summarized in Table B.1 in Appendix B. For groundwater extraction, the absolute value of the percentage difference between our model prediction and actual groundwater extraction by player type is between 0.01 and 0.03. For depth to groundwater, the absolute value of the percentage difference between our model prediction and actual depth to groundwater by player type is between 0.000 and 0.01. When comparing the actual and model predicted groundwater extraction and depth to groundwater variables by player type, our structural econometric model does a very good job matching the actual data.

To assess goodness of fit by player-year, we plot and compare individual player action choices in the data with those predicted by our model for the open access game in Figures B.1-B.4; and we also plot and compare the actual and model predicted state transitions for individual player depth to groundwater in Figures B.5-B.8. We find that our open access results capture the extraction behavior and the evolution of the groundwater stock exhibited during the open access period. In particular, we find on average that our simulation error for extraction and depth to groundwater is less than five percent for each group. Thus, when comparing the actual and model predicted groundwater extraction and depth to groundwater variables by player-year, it appears that our structural econometric model does a fairly good job matching the actual data.

We also compare actual welfare and model predicted welfare. In Table B.2, we show, for each player and player type, the actual welfare generated based on the observed player actions and state variables, the model predicted welfare generated from 100 simulation runs of the open access period, and the difference between model predicted and actual welfare. We use significance stars next to the difference between model predicted and actual average annual welfare to denote the significance level of the difference between model predicted and actual average annual welfare. As seen in Table B.2, our model simulated welfare values are somewhat higher across players than values inferred from actual behavior. For appropriators, these differences are statistically significant, but small relative to the magnitude of the model predicted and actual average annual welfare for appropriators. For farmers, these differences are quite small and economically insignificant, and statistically insignificant for all but one farmer. Similarly, for recreational users, these differences are small, economically insignificant, and statistically insignificant for all but one recreationaly user, for which the difference is small relative to the magnitude of that user's model predicted and actual average annual welfare. Thus we conclude that our model does a fairly good job of matching the welfare across players based on actual values of actions and states.[15]

We conduct leave-one-out cross-validation to evaluate model performance and determine whether our model is overfitted to our dataset. One at a time, we exclude observations from each of the years (1991-1996) from the dataset used to in our policy funciton and state transition densities, and re-simulate the two period (1991-1996 and 1997-2014). If our transition density and policy function estimates are overfitted, then removing small sources of variation from a limited number of observations in the dataset should have a significant impact on the coefficients estimated in the first stage of our model. We would expect to see different simulated behavior and evolution of the groundwater stock.

In Tables B.4-B.5, we present the range of point estimate results for our re-estimated policy functions and state transition densities from these leave-one-out regressions. Examining these functions we find that, in general, the signs of the coefficients align with our baseline results. In a number of cases, however, removing excluding a year's observations from the dataset causes our estimates to lose precision. This is more an issue for the golf courses and housing developments in our sample whose extraction functions are most sensitive to these changes. We find that variables related to high degree days and variables related to the effects of nearby extraction are most sensitive to these changes across players.

We then simulate the periods 1991-1996 and 1997-2014 using these alternative policy functions and state transition densities. In Figures B.9-B.11, we pool data from all of the separate leave-one-out analyses from leaving out each year over 1991-1996 one-at-a-time, and display the averages for each player group for extraction and depth to groundwater.

[15] In Table B.3, we show the actual consumer surplus faced by each appropriator over the period 1991-1996 based on the observed player actions and state variables, the model predicted consumer surplus generated from 100 simulation runs of the open access period, and the difference between model predicted and actual consumer surplus. Since consumer surplus is calculated from our first-stage demand function and from values of the state and action variables, and therefore does not depend on any structural parameters, our model predicted consumer surplus, whose distribution arises solely from the distribution of model predicted trajectories for the state and action variables, is fairly precisely estimated. As a consequence, while the difference between model predicted and actual consumer surplus is statistically significant, their magnitudes are small relative to the magnitudes of the model predicted and actual consumer surplus, and do not change our qualitative findings.

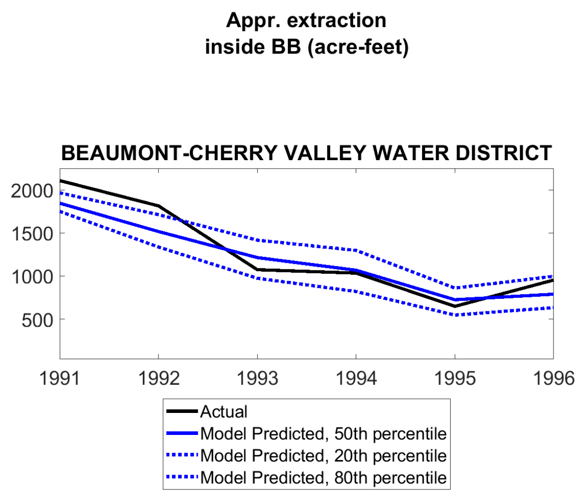
Comparing these to our baseline results we find that our results are not significantly different. We find that the year-to-year performance of the model during the open access period generally mirrors the actual data, especially for the appropriators who drive our welfare findings. We do find divergence for farmers outside the Beaumont Basin, whose depth to groundwater increases in these simulations more during the years 1991-1996 in our than in the actual data. During the later period, our results mostly mirror our baseline open access counterfactual scenario. We find that depth to groundwater for farmers outside the Beaumont is somewhat more volatile than in our baseline simulation. Our depth to groundwater simulation remains flatter for golf courses and housing developments than in our baseline simulation, though the extraction pattern is similar. We conclude that our results for depth to groundwater are somewhat sensitive to our sample, however our extraction behavior is generally robust. We also conclude that the key trends in behavior and depth to groundwater for appropriators are generally robust to this change, meaning that our key findings for these players are also not sensitive to this change.

Our econometric estimation entails finding the parameters θ that minimize any profitable deviations from the optimal strategy as given by the estimated policy functions. Table B.6 presents each player's profitable deviations from their estimated optimal strategy under our estimated structural parameters, expressed as a percentage of their welfare. The profitable deviations for the player with the highest profitable deviations, Summit Cemetery District, which is a farmer outside of Beaumont Basin, are only around 64 dollars, and thus reflect the low profitability of groundwater for this player; for all other players, the profitable deviations are less than 2.4 percent of welfare. Our model of the open access dynamic game therefore does a good job explaining the groundwater extraction behavior of the groundwater users in the Beaumont Basin prior to the institution of quantified property rights.

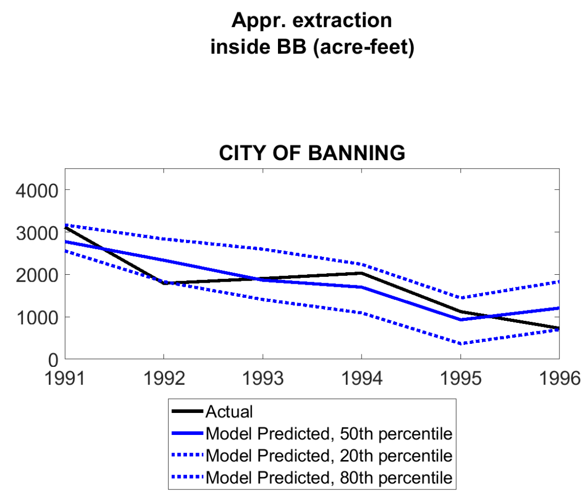
Table B.1: Model Fit, 1991-1996

	Appropriator inside Beaumont	Appropriator outside Beaumont	Farmer inside Beaumont	Farmer outside Beaumont	Golf Course / Housing Development
	Groundwater Extraction (acre-feet)				
Model Simulated Data					
Mean	1495.07	3998.10	296.72	87.13	428.39
Std Dev	967.44	2185.28	202.19	34.72	355.59
Actual Data					
Mean	1461.13	3944.25	300.33	84.22	430.59
Std Dev	991.71	2213.20	203.97	17.24	374.37
Percentage Difference from Actual Data					
Mean	0.02	0.01	-0.01	0.03	-0.01
Std Dev	0.95	0.79	0.96	0.46	1.20
	Depth to Groundwater (feet)				
Model Simulated Data					
Mean	186.98	128.60	227.43	189.95	227.60
Std Dev	37.67	35.34	39.54	55.69	75.94
Actual Data					
Mean	185.29	129.23	228.59	189.00	227.68
Std Dev	36.10	35.79	38.42	56.22	76.57
Percentage Difference from Actual Data					
Mean	0.01	0.00	-0.01	0.01	0.00
Std Dev	0.28	0.39	0.24	0.42	0.47

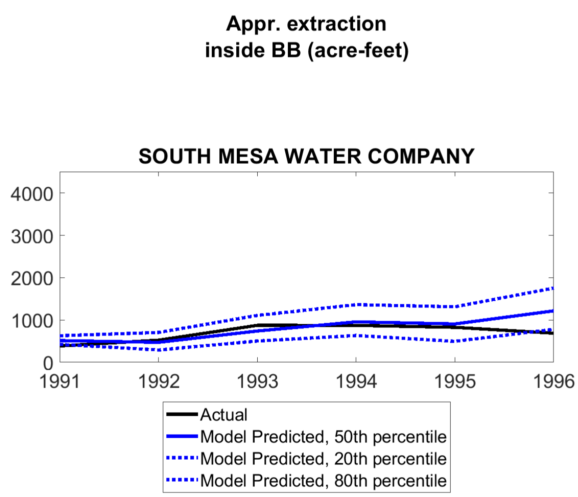
Notes: This table compares the model predicted extraction and depth to groundwater with the actual extraction decisions that were made and the actual depth to groundwater that was realized during the open access period. Significance stars indicate p-values from two-sample t-tests comparing the model predicted and actual data. Significance codes: *** $p<0.001$, ** $p<0.01$, * $p<0.05$



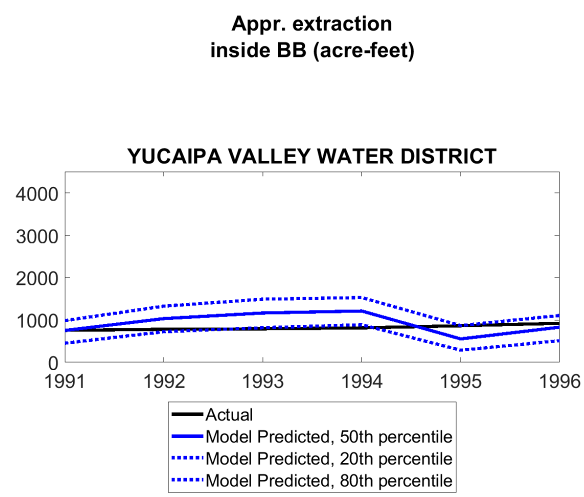
(a) Beaumont-Cherry Valley Water District



(b) City of Banning

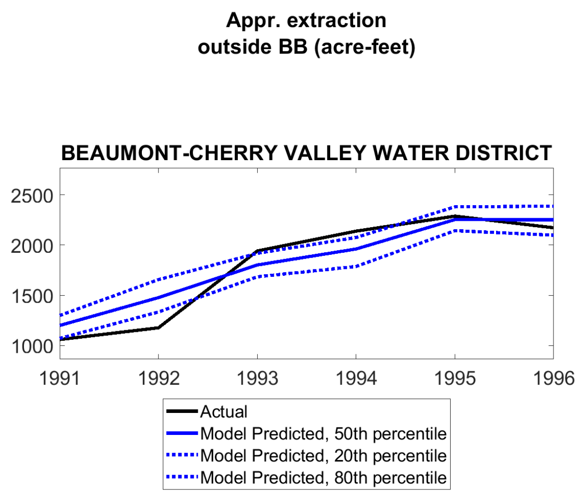


(c) South Mesa Water Company

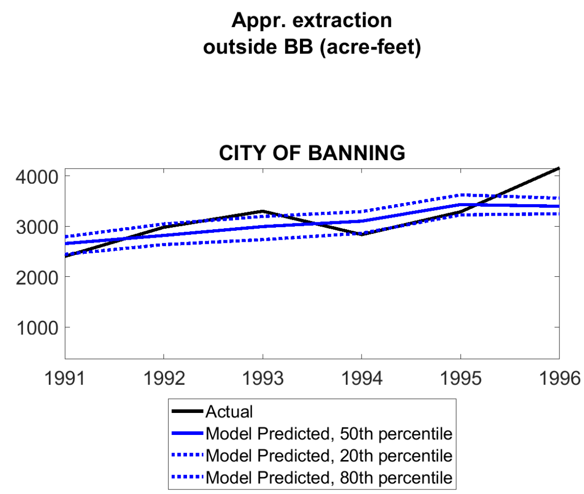


(d) Yucaipa Valley Water District

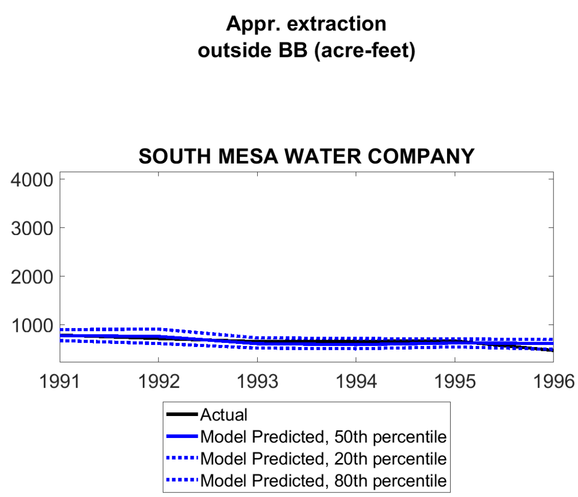
Figure B.1: Model Fit: Appropriator Extraction in Beaumont Basin



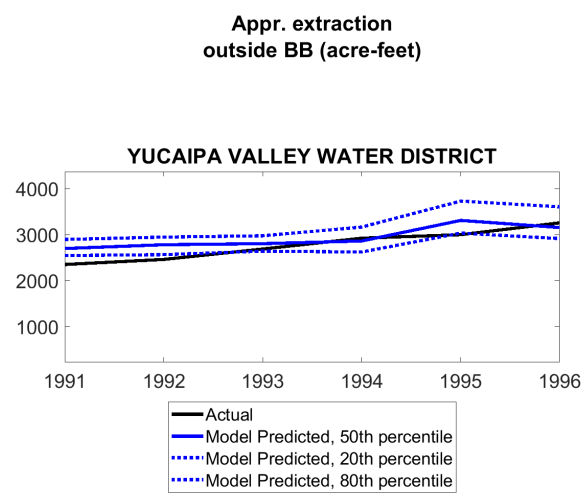
(a) Beaumont-Cherry Valley Water District



(b) City of Banning

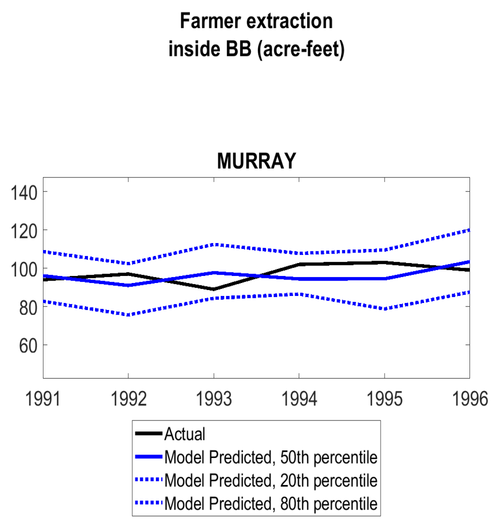


(c) South Mesa Water Company

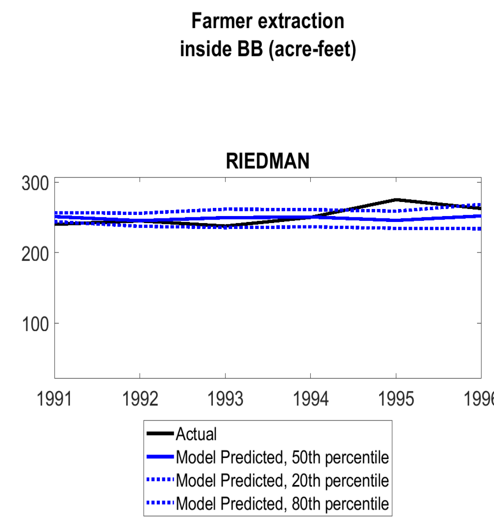


(d) Yucaipa Valley Water District

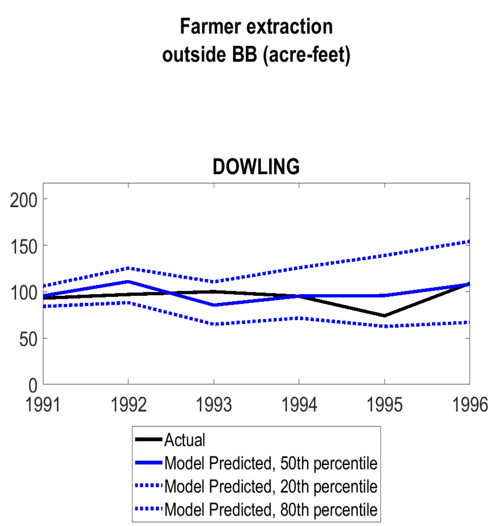
Figure B.2: Model Fit: Appropriator Extraction outside Beaumont Basin



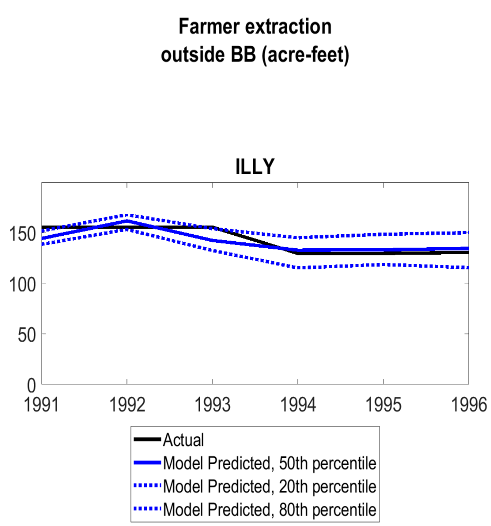
(a) Murray



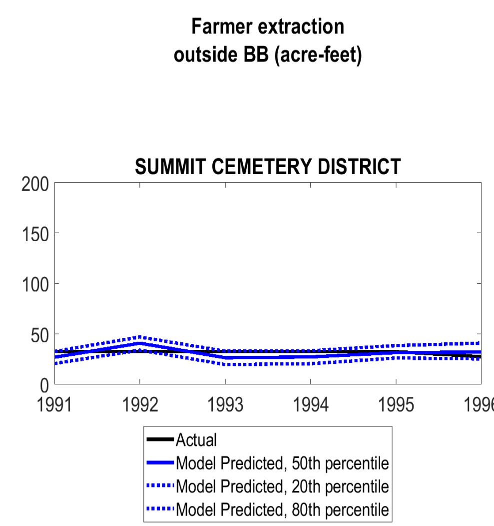
(b) Riedman



(c) Dowling

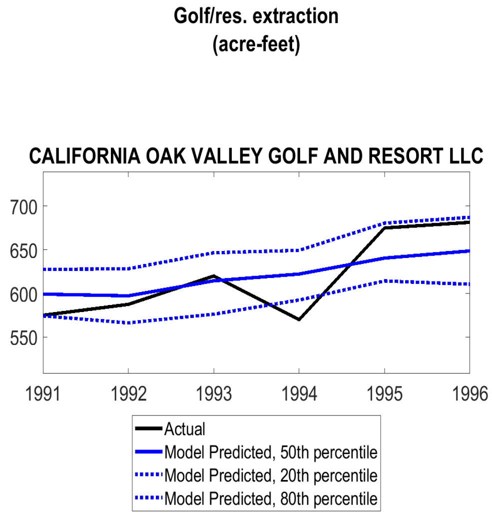


(d) Illy

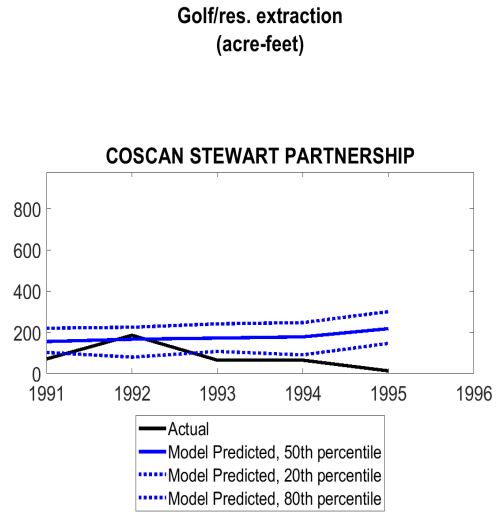


(e) Summit Cemetery District

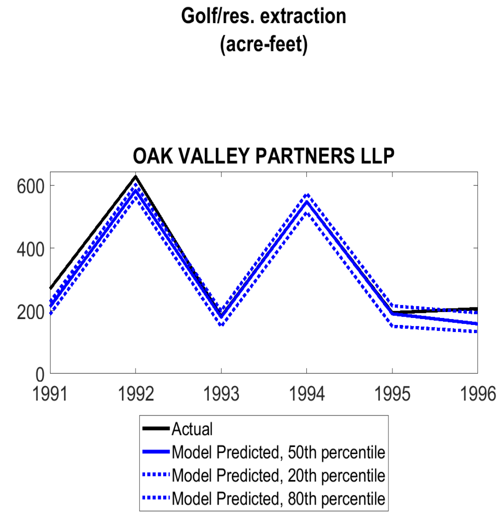
Figure B.3: Model Fit: Farmer Extraction



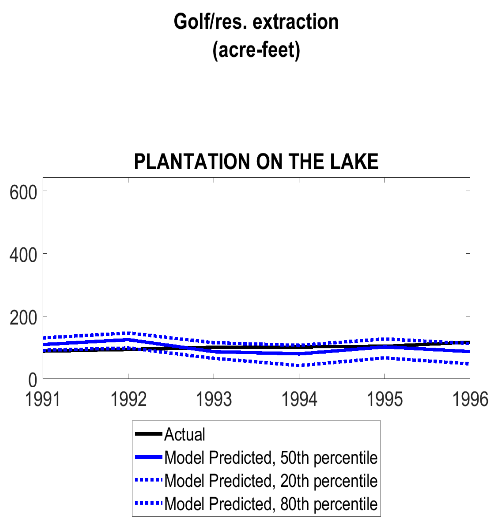
(a) California Oak Valley Golf and Resort LLC



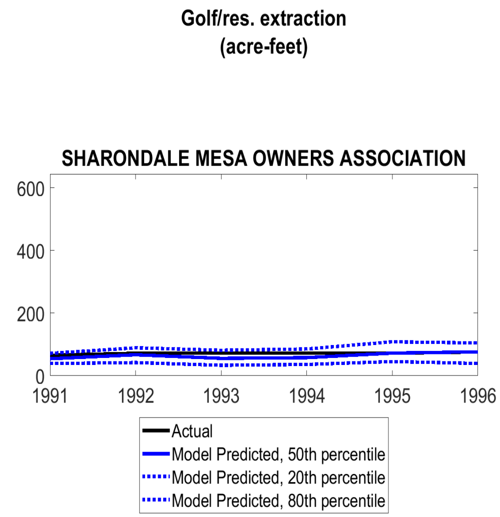
(b) Coscan Stewart Partnership



(c) Oak Valley Partners LLP

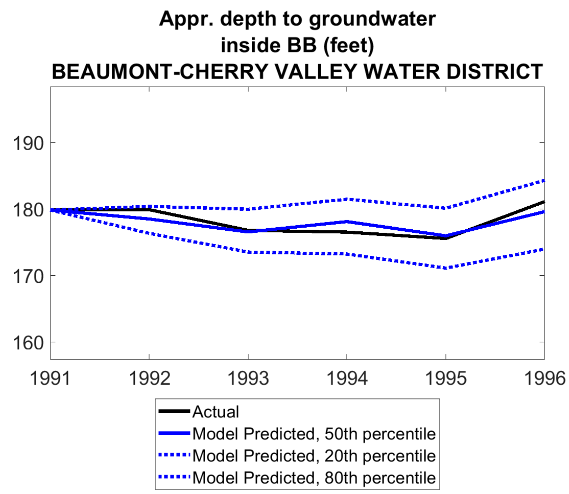


(d) Plantation on the Lake

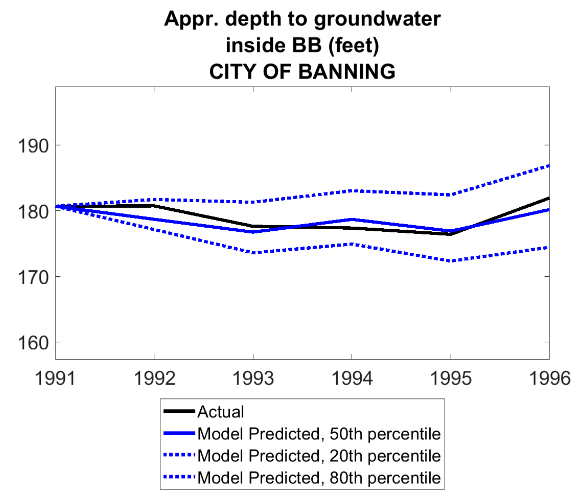


(e) Sharondale Mesa Owners Association

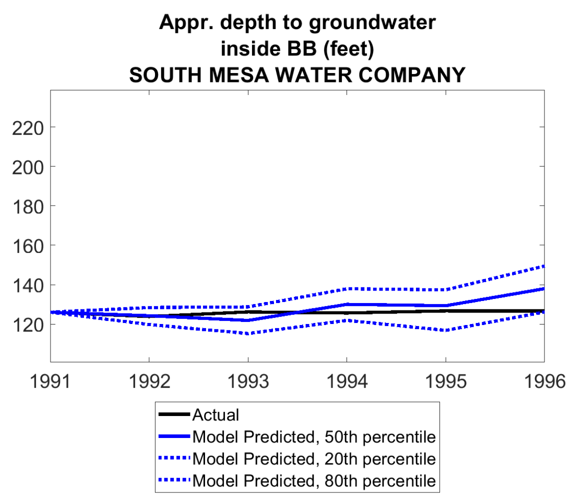
Figure B.4: Model Fit: Golf Course / Housing Development Extraction



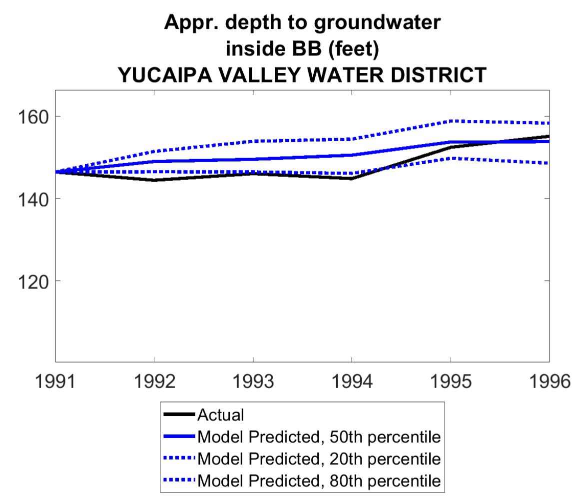
(a) Beaumont-Cherry Valley Water District



(b) City of Banning

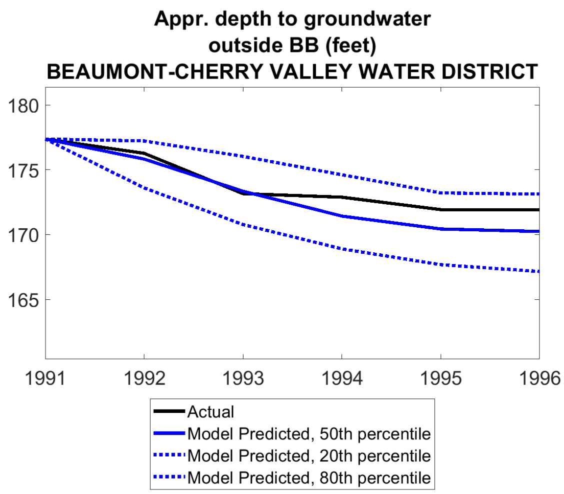


(c) South Mesa Water Company

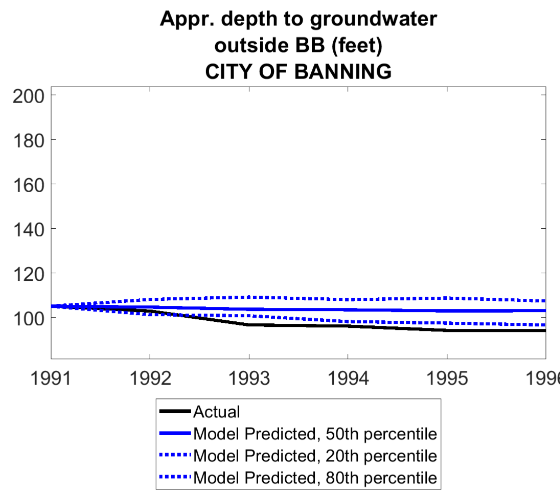


(d) Yucaipa Valley Water District

Figure B.5: Model Fit: Appropriator Depth to Groundwater in Beaumont Basin



(a) Beaumont-Cherry Valley Water District



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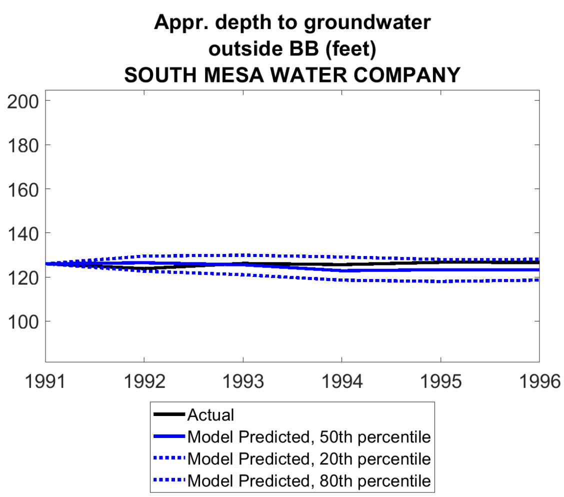
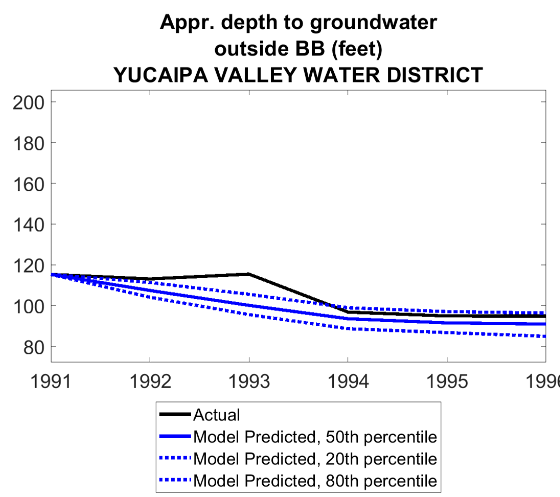
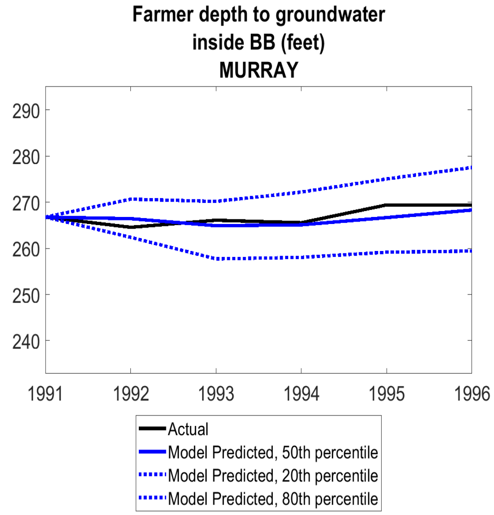


(c) South Mesa Water Company

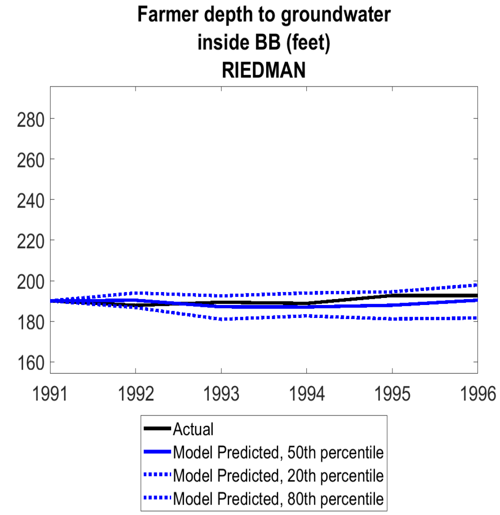


(d) Yucaipa Valley Water District

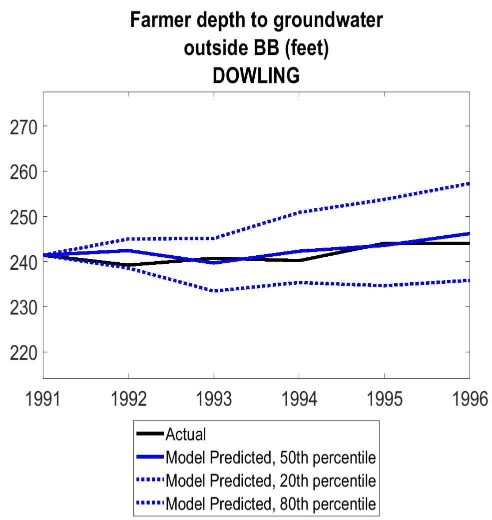
Figure B.6: Model Fit: Appropriator Depth to Groundwater outside Beaumont Basin



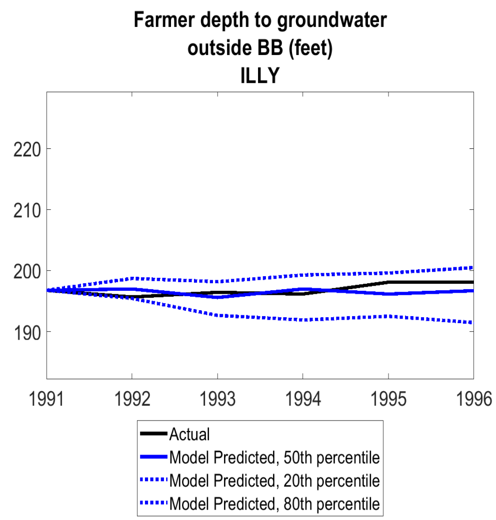
(a) Murray



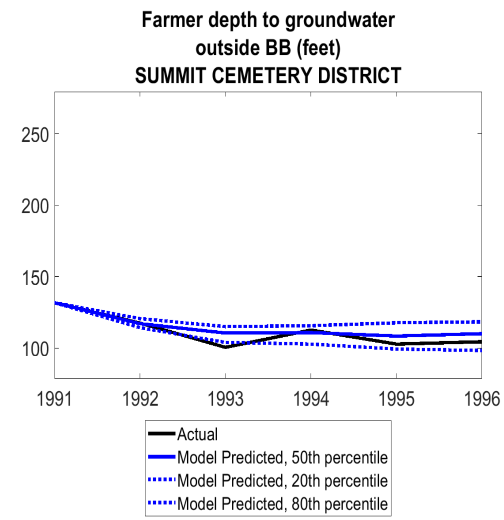
(b) Riedman



(c) Dowling

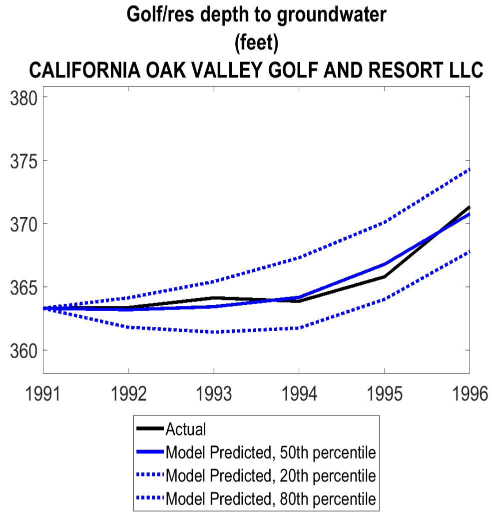


(d) Illy

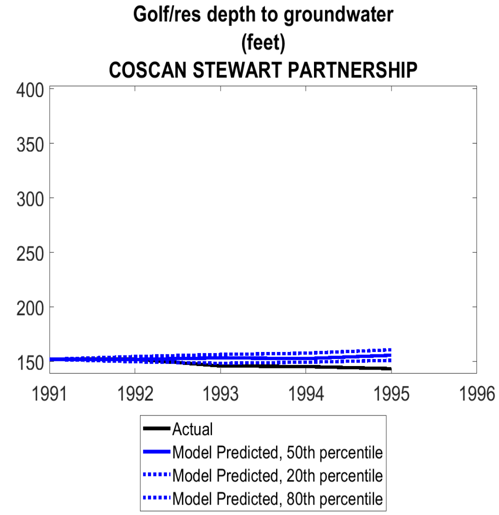


(e) Summit Cemetery District

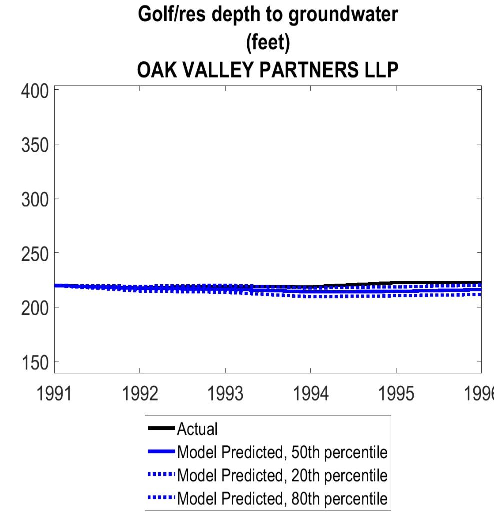
Figure B.7: Model Fit: Farmer Depth to Groundwater



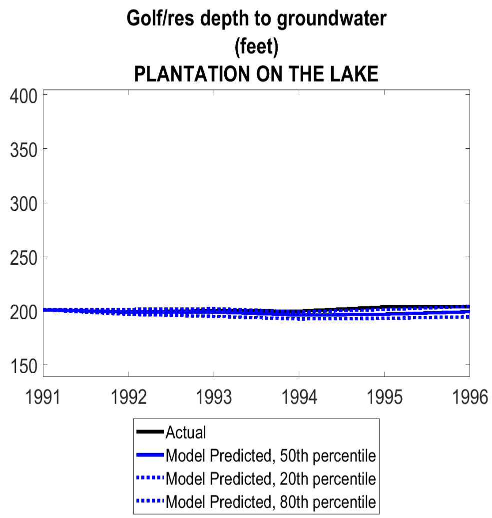
(a) California Oak Valley Golf and Resort LLC



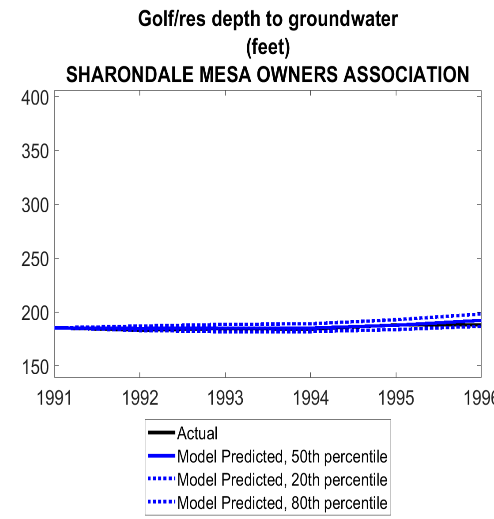
(b) Coscan Stewart Partnership



(c) Oak Valley Partners LLP



(d) Plantation on the Lake



(e) Sharondale Mesa Owners Association

Figure B.8: Model Fit: Golf Course / Housing Development Depth to Groundwater

Table B.2: Average Annual Welfare, 1991-1996

	Average Annual Welfare (dollars)		
	Actual	Model Predicted	Model Predicted Minus Actual
Appropriators			
Beaumont-Cherry Valley Water District	7.2 million	8.0 million	0.8 million***
City of Banning	12.8 million	14.2 million	1.4 million***
South Mesa Water Company	5.1 million	5.6 million	0.5 million***
Yucaipa Valley Water District	17.5 million	19.4 million	2.0 million***
Total appropriators	**42.5 million**	**47.2 million**	**4.7 million*****
Farmers in Beaumont Basin			
Murray, Cecil Merle	0.4 thousand	0.4 thousand	0.0 thousand
Riedman, Fred L. And Richard M.	4.6 thousand	5.0 thousand	0.4 thousand
Total farmers in Beaumont Basin	**5.0 thousand**	**5.5 thousand**	**0.4 thousand**
Farmers outside Beaumont Basin			
Francis M Dowling Jr	0.3 thousand	0.3 thousand	0.0 thousand
Katharina Illy	0.4 thousand	0.8 thousand	0.4 thousand
Summit Cemetery District	-0.2 thousand	0.0 thousand	0.2 thousand*
Total farmers outside Beaumont Basin	**0.5 thousand**	**1.1 thousand**	**0.7 thousand**
Golf Course / Housing Development			
California Oak Valley Golf and Resort LLC	7.8 thousand	8.2 thousand	0.4 thousand
Coscan Stewart Partnership	0.3 thousand	0.3 thousand	0.0 thousand
Oak Valley Partners	21.6 thousand	24.3 thousand	2.7 thousand**
Plantation on the Lake	1.8 thousand	2.0 thousand	0.1 thousand
Sharondale Mesa Owners Association	1.1 thousand	1.3 thousand	0.2 thousand
Total golf course / housing development	**32.6 thousand**	**36.0 thousand**	**3.4 thousand**

Notes: Welfare is the present discounted value of the entire stream of per-period payoffs over the period 1991-1996. Average annual welfare is welfare divided by the number of years. 'Difference from actual' is the difference between model predicted and actual welfare values. Both actual and model predicted welfare are calculated using the parameter estimates from the structural model. Actual welfare is calculated using actual values of actions and states in the data. Model predicted welfare is calculated using model predicted actions and states generated from 100 simulation runs of the open access period. The standard errors for the model predicted welfare values and for the difference between model predicted and actual welfare values are calculated using the parameter estimates from each of 100 bootstrap samples. Significance stars next to the difference between model predicted and actual welfare values denote the significance level of the difference between model predicted and actual average annual welfare. Significance codes: *** $p<0.001$, ** $p<0.01$, * $p<0.05$

Table B.3: Average Annual Social Welfare from Groundwater Extraction, 1991-1996

	Actual	Model Predicted	Model Predicted Minus Actual
		Average Annual Producer Surplus (dollars)	
Appropriator profits	1.6 million	1.5 million	-160.9 thousand
Farmer profits inside Beaumont Basin	5.0 thousand	5.5 thousand	0.4 thousand
Farmer profits outside Beaumont Basin	0.5 thousand	1.1 thousand	0.7 thousand
Golf course / housing development profits	32.6 thousand	36.0 thousand	3.4 thousand
Total Producer Surplus	**1.7 million**	**1.5 million**	**-0.2 million**
		Average Annual Consumer Surplus (dollars)	
Beaumont-Cherry Valley Water District	3.3 million	3.6 million	0.36 million***
City of Banning	6.8 million	7.5 million	0.74 million***
South Mesa Water Company	2.3 million	2.5 million	0.25 million***
Yucaipa Valley Water District	9.0 million	10.4 million	1.3 million***
Total Consumer Surplus	**21.3 million**	**24.0 million**	**2.7 million*** **
		Average Annual Social Welfare (dollars)	
Social Welfare	**23 million**	**25.5 million**	**2.5 million*** **

Notes: Components of social welfare are the present discounted value of the entire stream of per-period payoffs related to each component over the period 1991-1996. Producer surplus is equal to the profits from groundwater extraction summed over all players. Consumer surplus is the consumer surplus faced by each appropriator, and is not weighted by parameters in the payoff function of the appropriator. Social welfare is equal to the sum of producer surplus and consumer surplus. Average annual values of these components are equal to the total value of the component divided by the number of years. 'Model Predicted Minus Actual' is the difference between model predicted and actual component values. Both actual and model predicted profits are calculated using the parameter estimates from the structural model. Both actual and model predicted consumer surplus are calculated using the water demand parameter estimates. Actual values are calculated using actual values of actions and states in the data. Model predicted values are calculated using model predicted actions and states generated from 100 simulation runs of the open access period. The standard errors for the difference between model predicted and actual welfare values are calculated using the parameter estimates from each of 100 bootstrap samples. Significance stars next to the difference between model predicted and actual values denote the significance level of the difference between model predicted and actual average annual values. Significance codes: *** $p<0.001$, ** $p<0.01$, * $p<0.05$

Table B.4: Leave-One-Out Cross-Validation: Policy Function Results, 1991-1996

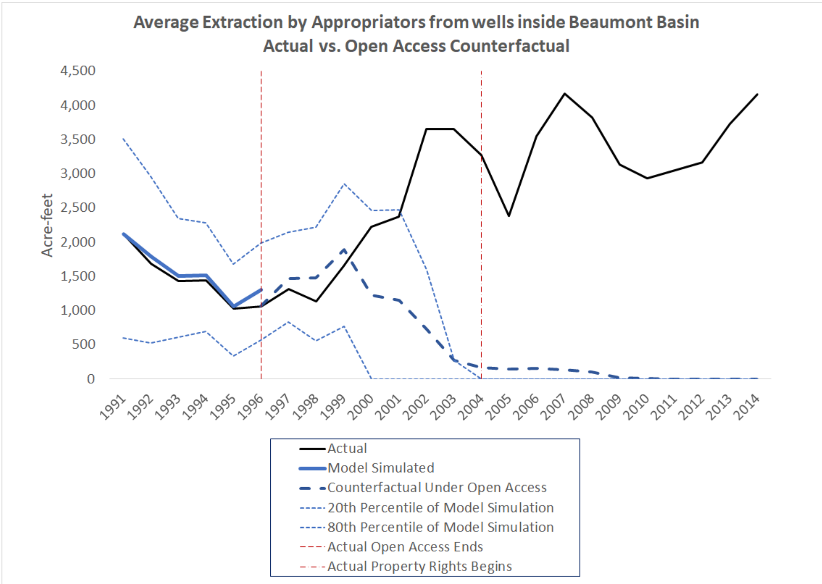
	Dependent variable is:			
	Appropriator total extraction (acre-feet)	Appropriator share extraction in Beaumont	Farmer extraction (acre-feet)	Golf/Housing extraction (acre-feet)
	(1)	(2)	(3)	(4)
Depth to groundwater inside management zone (feet)	**[34.46 to 37.09]**	**[0.00809 to 0.0244]**		
Depth to groundwater outside management zone (feet)	**[-21.59 to -20.02]**			
Number of own wells in Beaumont Basin	**[277.5 to 299.8]**	**[-0.111 to -0.0495]**		
Number of high heat days (>90 F) in Apr-Oct	[-5.892 to 0]	[-0.00531 to 0]	[0 to 8.610]	[0 to 5.581]
Depth to groundwater (feet)			[0 to 4.521]	[0 to 14.34]
Number of wells squared			**[366.9 to 629.7]**	[0 to 197.2]
CA real GDP per capita (1997 chained dollars)				[-0.0671 to 0]
Hydraulic conductivity X Depth to groundwater			**[-0.0510 to -0.0374]**	[-0.0588 to 0]
Population of city of Beaumont		[-0.000331 to 0]		[-0.191 to 0]
Precipitation, full year (inches)		[-0.00647 to 0]		[0 to 4.441]
Planned construction (dummy)				**[910.2 to 977.5]**
Hydraulic conductivity X Depth to groundwater in BB		[-0.000216 to 0]		
Price of untreated water (dollars/acre-foot)		[0 to 0.00599]		
Price of untreated water X Depth to groundwater in BB squared		**[-3.92e-07 to -1.47e-07]**		
Population (thousands) X Price untreated water X Depth to groundwater in BB		[0 to 6.97e-07]		
Total wells owned by i before t			**[-2,890 to -1,631]**	
Average crop price (dollars per unit)			**[17.65 to 28.52]**	
Precipitation, Apr-Oct (inches)			**[410.8 to 731.6]**	
Average crop price X High heat days in Apr-Oct			[-.115 to 0]	
Average crop price X Precipitation in Apr-Oct			**[-8.100 to -4.525]**	
Has wells in Beaumont Basin (dummy)			[-365.3 to 0]	
# Observations	20	20	25	24
# Players	4	4	5	5

Notes: Table presents the range of significant point estimates across the 6 separate leave-one-out regressions (which each leave out one of the 6 years from 1991-1996, respectively). Coefficients that are not significant at 5% level are treated as equal to 0. If the point estimates are statistically significant at a 5% level for each of the 6 level-one-out regressions, then the entire range is in bold. 'Hydraulic conductivity' is saturated hydraulic conductivity in feet per day.

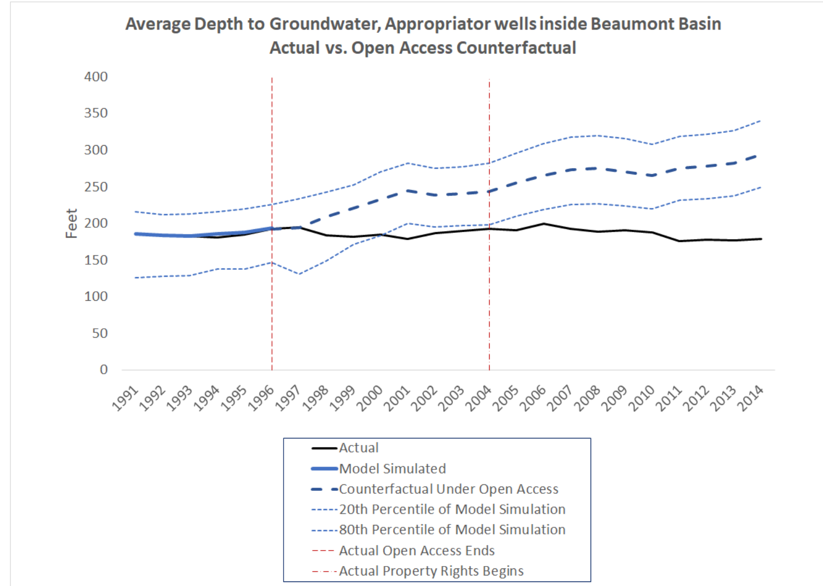
Table B.5: Leave-One-Out Cross-Validation: State Transition Results, 1991-1996

	Dependent variable is depth to groundwater (ft) for:			
	Farmer	Golf/ Housing	Appropriator inside Beaumont	Appropriator outside Beaumont
	(1)	(2)	(3)	(4)
Lagged values of:				
Depth to groundwater (ft)		**[0.784 to 0.849]**		
Depth to groundwater outside management zone (ft)				**[0.784 to 0.832]**
Depth to groundwater (ft) X Electricity price (dollars/kwh)	[0 to 3.645]	[0 to 1.564]		
Own extraction (acre-ft) X Saturated hydraulic conductivity (ft/day)	[0]	[0 to 2.09e-04]		
Own extraction in Beaumont (acre-ft) X Saturated hydraulic conductivity (ft/day)			[0 to 0.000236]	
Own extraction outside Beaumont (acre-ft), Saturated hydraulic conductivity (ft/day)				[-5.40e-06 to 0]
Neighbor extraction in Beaumont (acre-ft), 0.5 to 1 miles X Saturated hydraulic conductivity (ft/day)			[0 to 9.89e-05]	
Neighbor extraction in Beaumont (acre-ft), 1 to 2 miles X Saturated hydraulic conductivity (ft/day) X				[0]
Neighbor extraction (acre-ft), 2 to 3 miles X Saturated hydraulic conductivity (ft/day)	[0 to 0.000210]			
Neighbor extraction (acre-ft), 3 to 4 miles X Saturated hydraulic conductivity (ft/day)	[0 to 0.000164]			
Neighbor extraction in Beaumont (acre-ft), 3 to 4 miles X Saturated hydraulic conductivity (ft/day) X				[-0.000378 to -0]
Average pump strength outside management zone (gallons per minute)				[-0.00759 to 0]
Precipitation, Apr-Oct (inches)	[-5.250 to 0]		[0]	
Number of high heat days (> 90 F), Apr-Oct		[0 to 0.118]	[-0.358 to 0]	
CA real GDP per capita (1997 chained dollars)	[0 to 0.00878]		[0 to 0.00927]	[0 to 0.00130]
Retail price of untreated water (dollars/acre-foot)			[0 to 0.168]	
# Observations	25	25	20	20
# Players	5	5	4	4

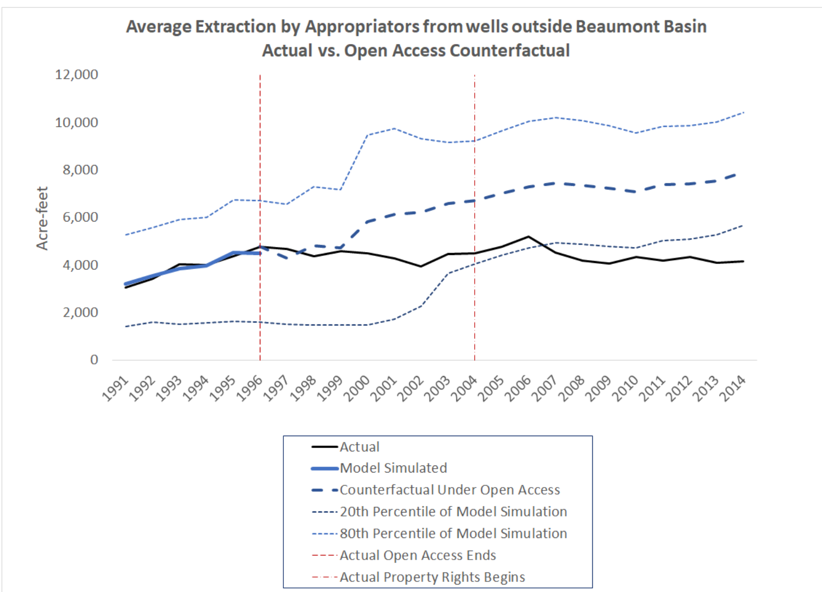
Notes: Table presents the range of significant point estimates across the 6 separate leave-one-out regressions (which each leave out one of the 6 years from 1991-1996, respectively). Coefficients that are not significant at 5% level are treated as equal to 0. If the point estimates are statistically significant at a 5% level for each of the 6 level-one-out regressions, then the entire range is in bold.



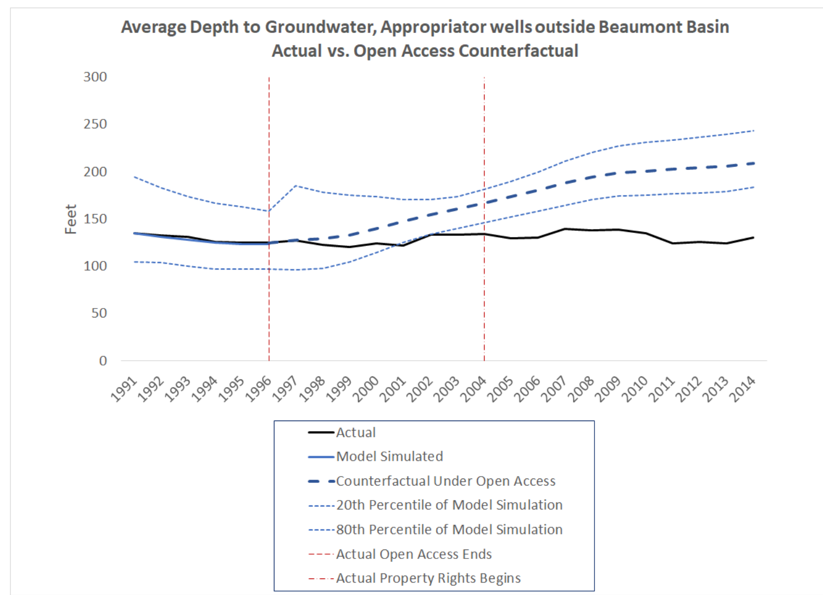
(a) Appropriator Extraction in Beaumont Basin



(b) Appropriator Depth to Groundwater in Beaumont Basin

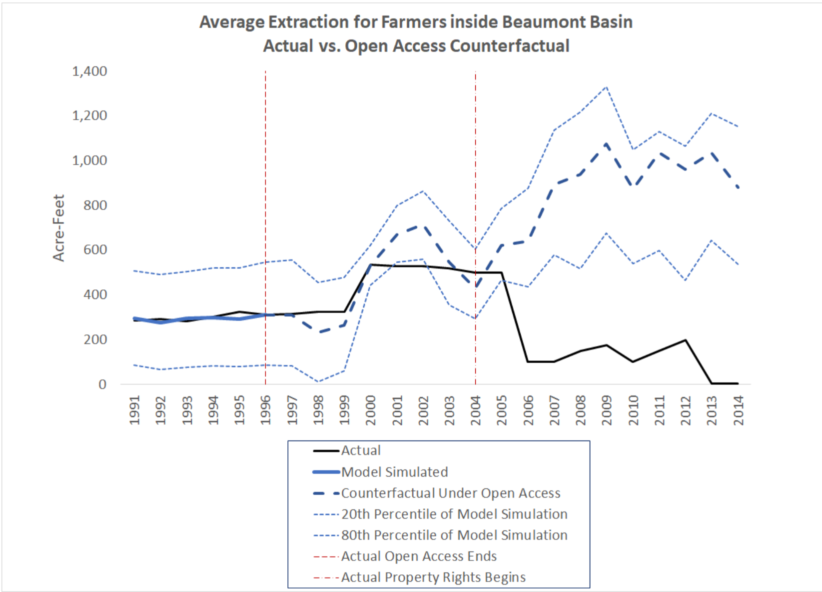


(c) Appropriator Extraction outside Beaumont Basin

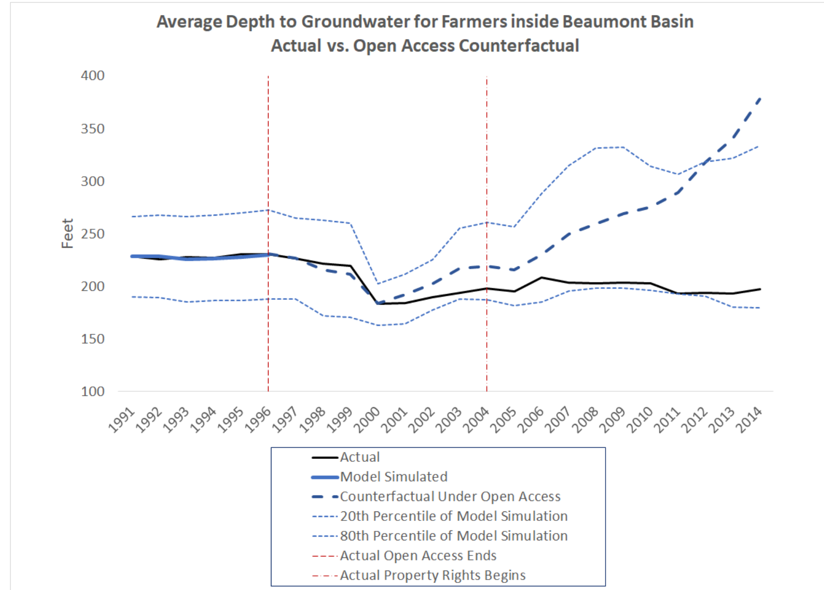


(d) Appropriator Depth to Groundwater outside Beaumont Basin

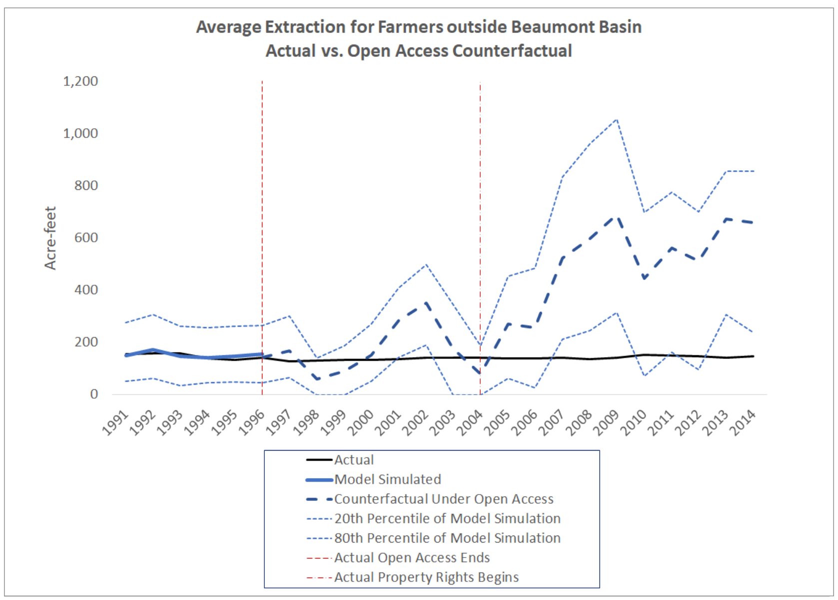
Figure B.9: Leave-One-Out Cross-Validation: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Appropriators, 1991-2014



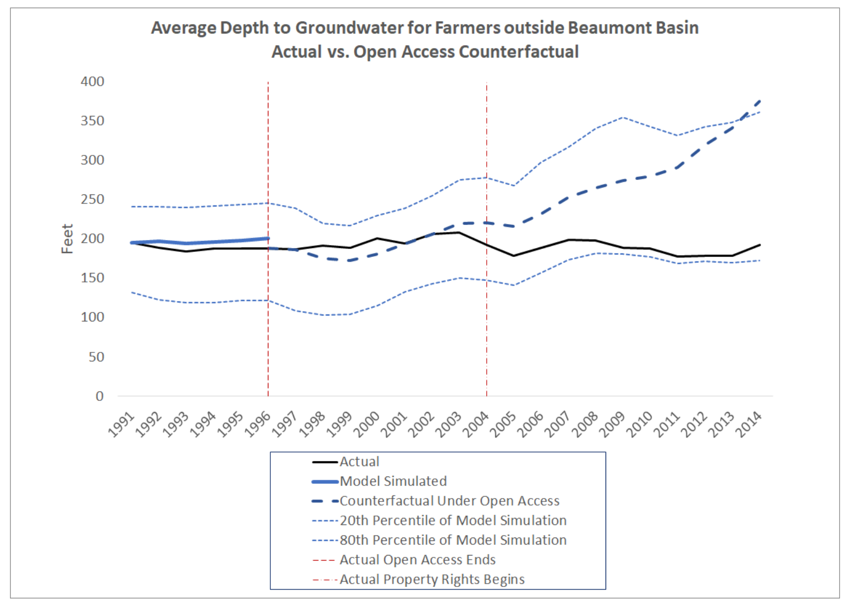
(a) Farmer Extraction in Beaumont Basin



(b) Farmer Depth to Groundwater in Beaumont Basin

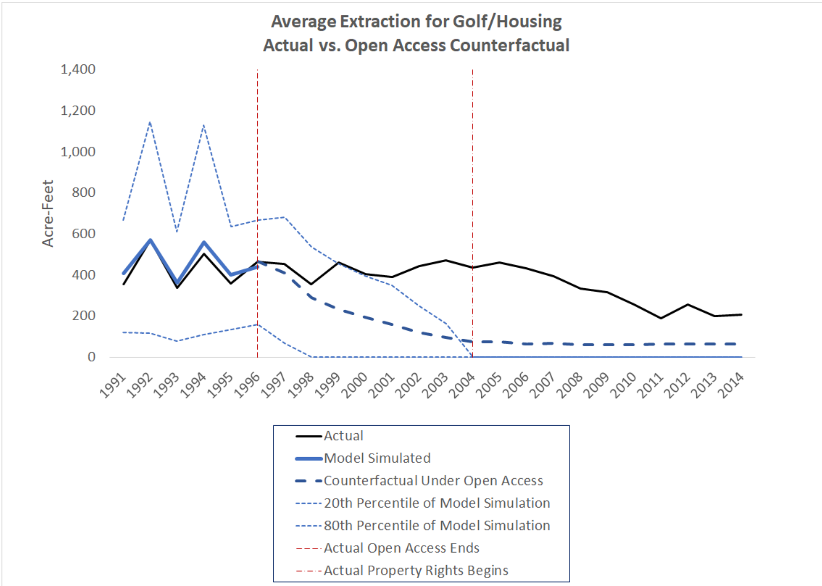


(c) Farmer Extraction outside Beaumont Basin

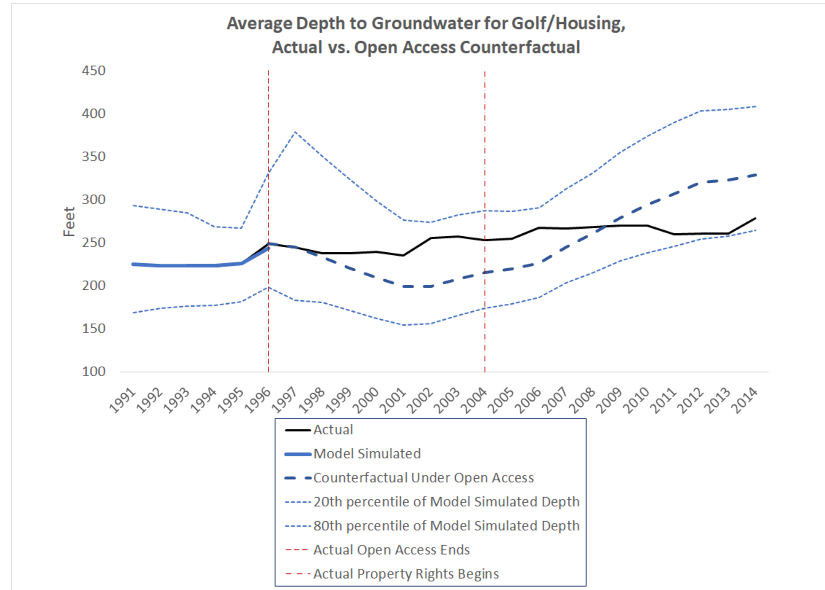


(d) Farmer Depth to Groundwater outside Beaumont Basin

Figure B.10: Leave-One-Out Cross-Validation: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Farmers, 1991-2014



(a) Golf Course / Housing Development Extraction



(b) Golf Course / Housing Development Depth to Groundwater

Figure B.11: Leave-One-Out Cross-Validation: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Golf/Housing, 1991-2014

Table B.6: Profitable Deviations

Player	Expected Profitable Deviations
Appropriators	
Beaumont-Cherry Valley Water District	0.00000913
City of Banning	0.0000153
South Mesa Water Company	0.0000443
Yucaipa Valley Water District	0.000052
Farmers in Beaumont Basin	
Murray	0.0010
Riedman	0.00017
Farmers outside Beaumont Basin	
Dowling	0.0037
Illy	0.0074
Summit Cemetery District	0.473
Golf Course / Housing Development	
California Oak Valley Golf and Resort LLC	0.0019
Coscan Stewart Partnership	0.0241
Oak Valley Partners LLP	0.000147
Plantation on the Lake	0.00084
Sharondale Mesa Owners Association	0.00822

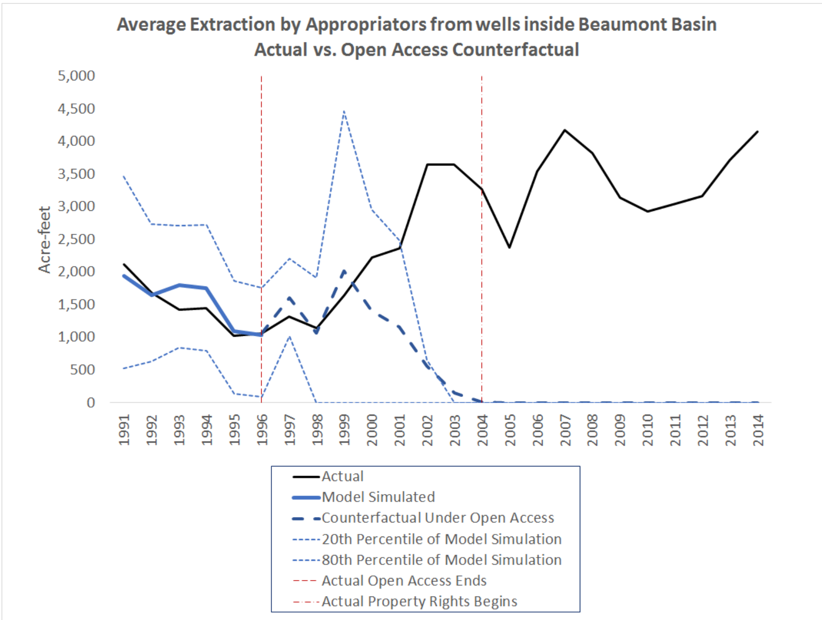
Note: Expected profitable deviations are expressed a percentage of welfare.

Appendix C. Robustness Checks

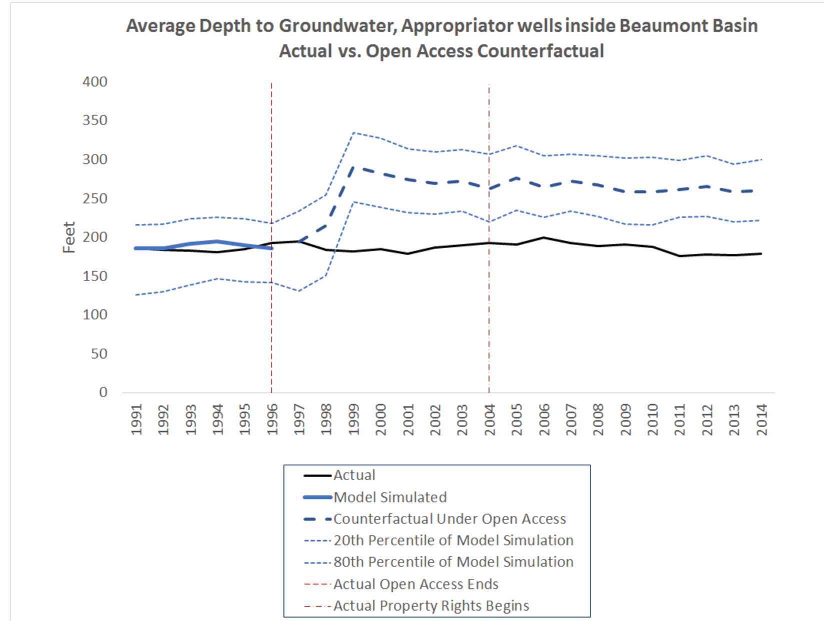
Table C.1: Robustness – Crop Price Variables: Structural Parameter Estimates

	Appropriators		Farmers	Golf Course /
	Inside Beaumont	Outside Beaumont		Housing Development
Coefficient in Farmer Marginal Revenue on:				
Average crop price (dollars per unit)			2.479***	
Precipitation, Apr-Oct (inches)			-52.622***	
Average crop price (dollars per unit) X High heat days			-0.025***	
Average crop price (dollars per unit) X Precipitation (inches)			-0.455***	
Average crop price (dollars per unit) X High heat days X Precipitation (inches)			0.011***	
Number of wells in Beaumont Basin, squared			11.182***	
Total wells owned before t			17.900***	
Has wells in Beaumont Basin (dummy)			11.198***	
Total Average Effect on Farmer Marginal Revenue:				
Average crop price (dollars per unit)			1.469	
Precipitation, Apr-Oct (inches)			-12.164	
Number of high heat days (> 90 F), Apr-Oct			0.098	
Coefficient in Golf Course / Housing Development Marginal Revenue on:				
Number of wells X Hydraulic conductivity (feet per day) X High heat days				-0.012**
Number of wells X Hydraulic conductivity (feet per day) X Precipitation (inches)				0.306***
Number of wells X Hydraulic conductivity (feet per day) X High heat days X Precipitation (inches)				0.003*
Number of wells X Log Population of Beaumont				3.946*
Number of wells X Real GDP per capita				0.909
Number of wells in Beaumont Basin, squared				-25.959***
Planned construction (dummy)				35.115
Total Average Effect on Golf Course / Housing Development Marginal Revenue:				
Number of wells in Beaumont Basin				66.906
Precipitation, Apr-Oct (inches)				235.323
Number of high heat days (> 90 F), Apr-Oct				-2.108
Saturated hydraulic conductivity (feet per day)				3.200
Coefficient in Appropriator Marginal Revenue on:				
Number of high heat days (> 90 F)	-2.860***			
Precipitation (inches)	5.345**			
Weight in Appropriator Per-Period Payoffs on:				
Consumer surplus	2.453***			
Consumer surplus squared	-5.44E-08***			
Profits from water sales	1.000 (normalization)			
Coefficient in Water Extraction Cost on:				
Extraction (acre-feet) squared	0.002	0.003**	0.019***	0.009

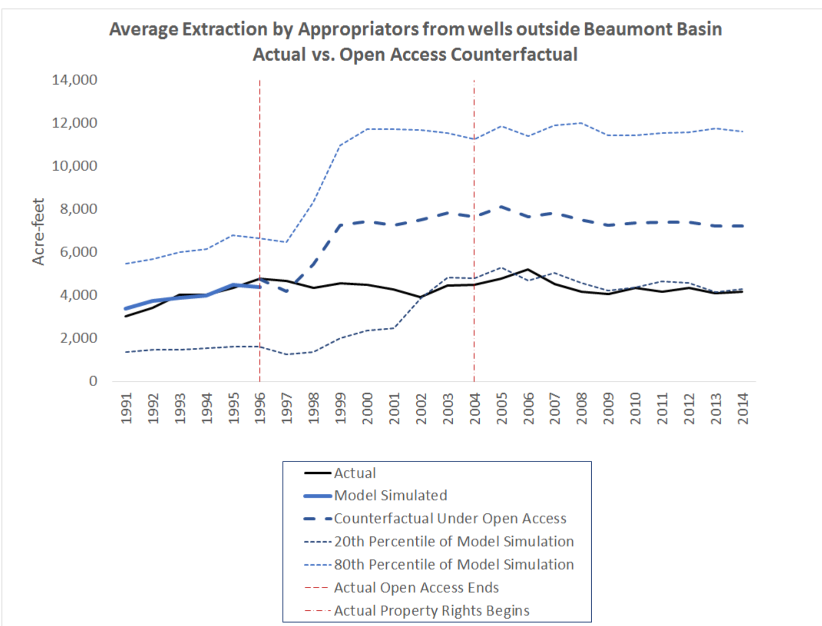
Notes: Per-period payoffs, revenue, marginal revenue, and costs are in dollars. Significance codes: *** p<0.001, ** p<0.01, * p<0.05



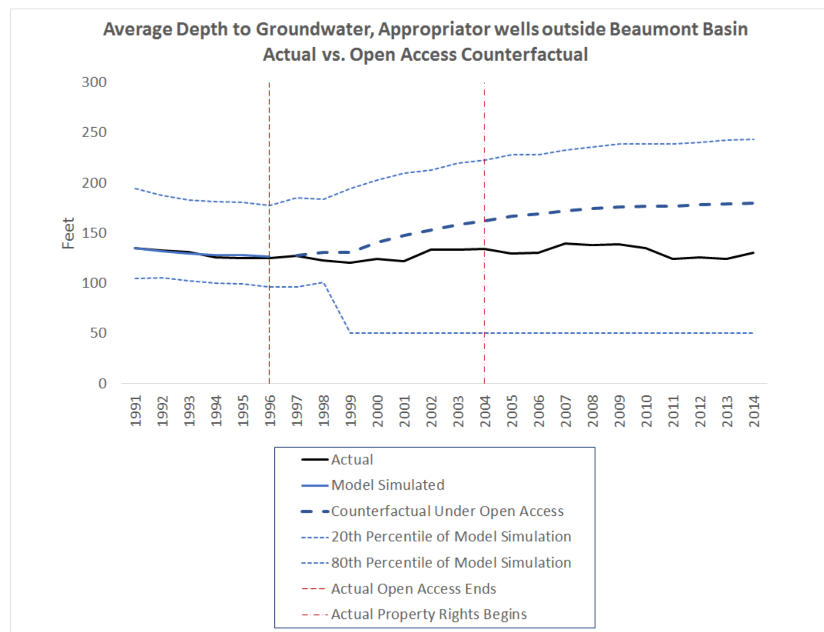
(a) Appropriator Extraction in Beaumont Basin



(b) Appropriator Depth to Groundwater in Beaumont Basin

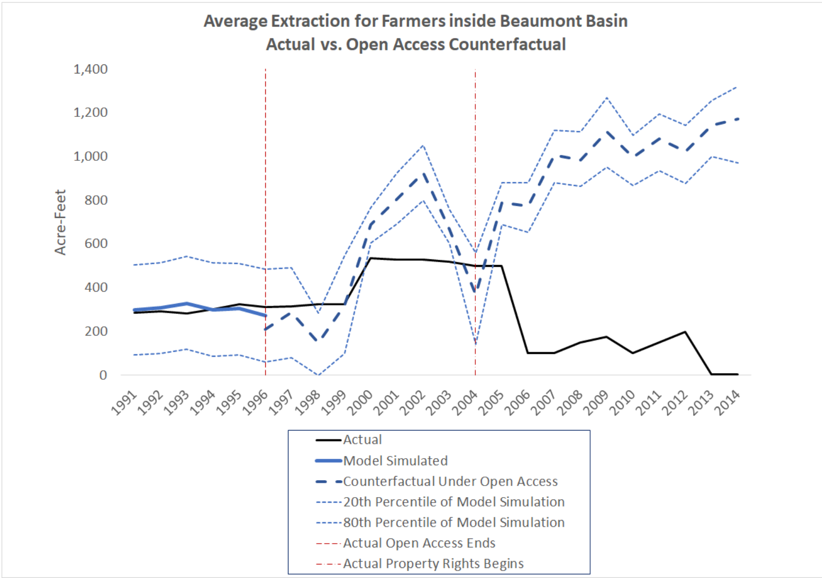


(c) Appropriator Extraction outside Beaumont Basin

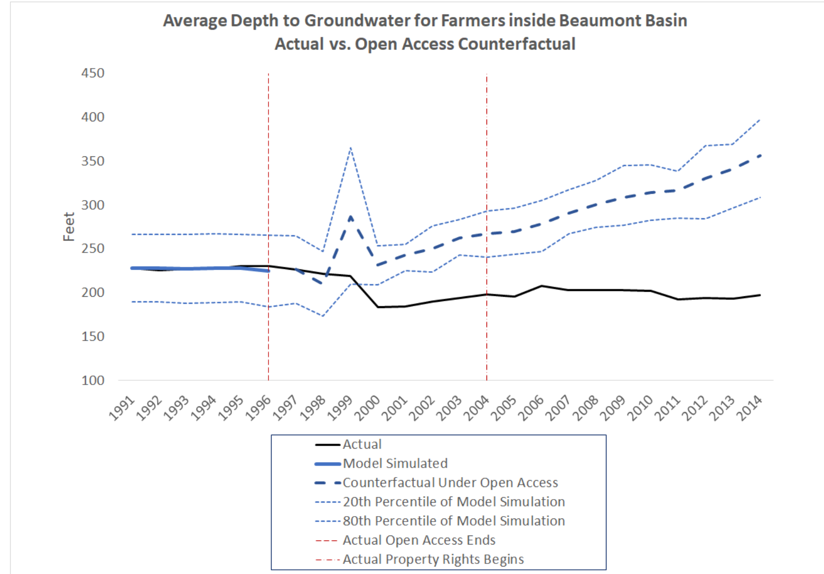


(d) Appropriator Depth to Groundwater outside Beaumont Basin

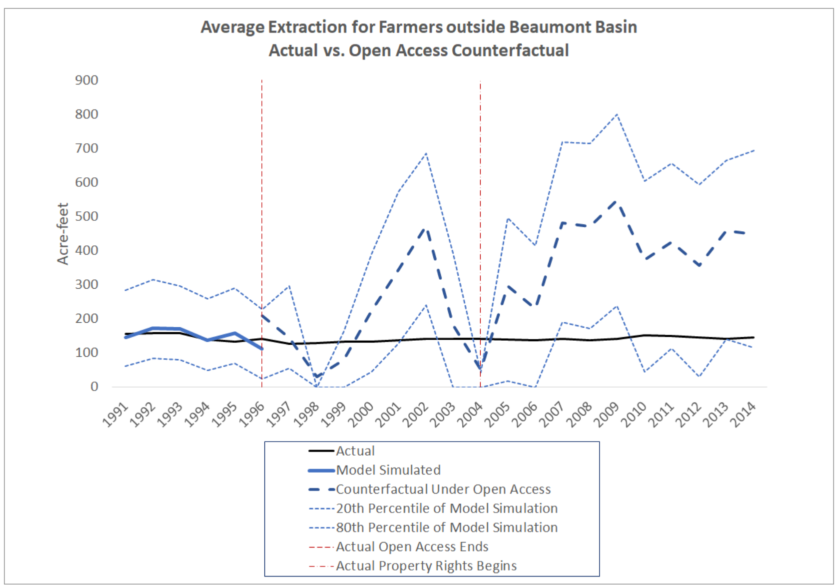
Figure C.1: Robustness – Crop Price Variables: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Appropriators, 1991-2014



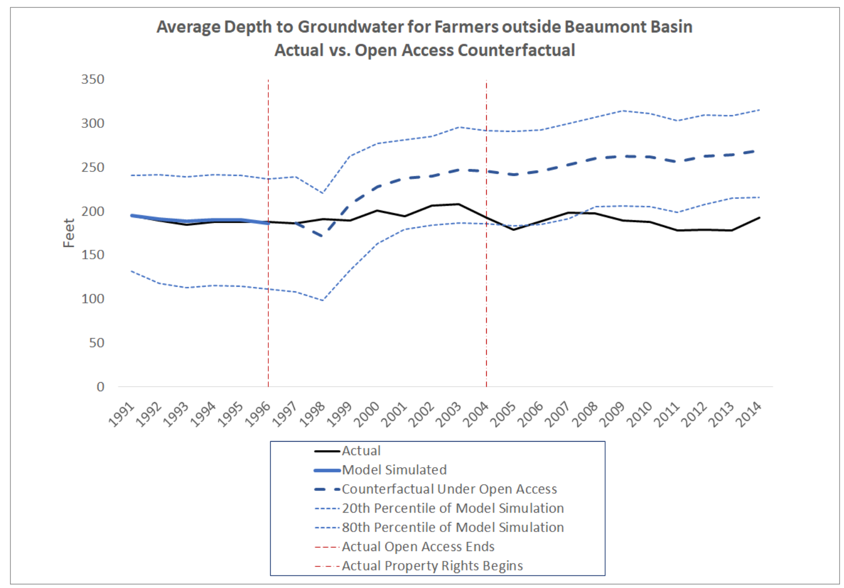
(a) Farmer Extraction in Beaumont Basin



(b) Farmer Depth to Groundwater in Beaumont Basin

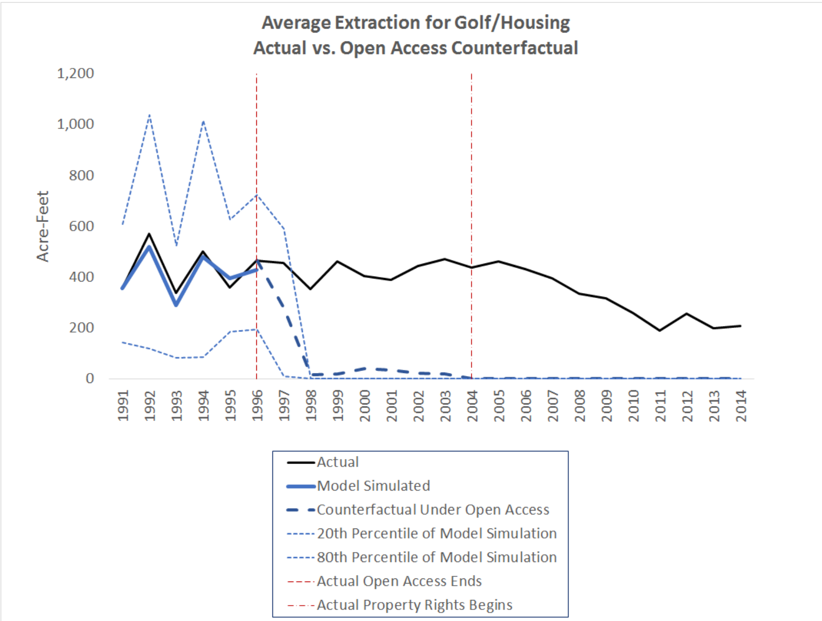


(c) Farmer Extraction outside Beaumont Basin

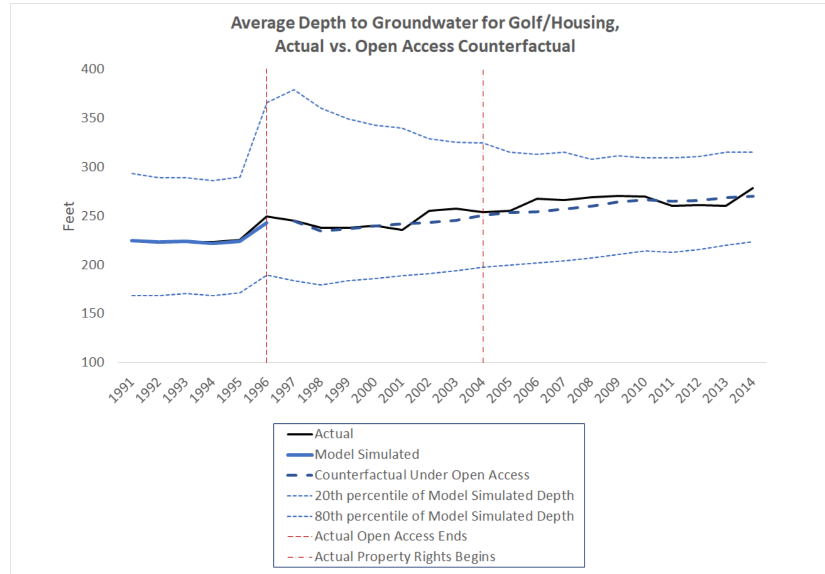


(d) Farmer Depth to Groundwater outside Beaumont Basin

Figure C.2: Robustness – Crop Price Variables: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Farmers, 1991-2014



(a) Golf Course / Housing Development Extraction



(b) Golf Course / Housing Development Depth to Groundwater

Figure C.3: Robustness – Crop Price Variables: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Golf/Housing, 1991-2014

Table C.2: Robustness – Crop Price Variables: Open Access Counterfactual vs. Actual Welfare After Institution of Property Rights, 1997-2014

	Average Annual Welfare (dollars)			
	Actual	Open Access Counterfactual	Open Access Counterfactual Minus Actual	Open Access Counterfactual Minus Actual, Bias Corrected
Appropriators				
Beaumont-Cherry Valley Water District	6.4 million	7.2 million	0.8 million	-5.7 thousand
City of Banning	8.1 million	8.8 million	0.6 million	-781.5 thousand
South Mesa Water Company	3.7 million	3.8 million	0.2 million	-344.5 thousand
Yucaipa Valley Water District	11.5 million	13.0 million	1.5 million	-467.2 thousand
Total appropriators	**29.7 million**	**32.8 million**	**3.1 million**	**-1.6 million**
Farmers in Beaumont Basin				
Murray, Cecil Merle	1.4 thousand	1.3 thousand	-0.2 thousand	-0.3 thousand
Riedman, Fred L. And Richard M.	3.2 thousand	-1.4 thousand	-4.6 thousand	-5.4 thousand*
Total farmers in Beaumont Basin	**4.6 thousand**	**-0.2 thousand**	**-4.8 thousand*** **	**-5.7 thousand*** **
Farmers outside Beaumont Basin				
Francis M Dowling Jr	0.8 thousand	1.1 thousand	0.4 thousand	0.2 thousand
Katharina Illy	0.0 thousand	2.6 thousand	2.6 thousand	2.7 thousand
Summit Cemetery District	0.0 thousand	-0.2 thousand	-0.1 thousand	-0.2 thousand
Total farmers outside Beaumont Basin	**0.8 thousand**	**3.6 thousand**	**2.8 thousand*** **	**2.8 thousand**
Golf Course / Housing Development				
California Oak Valley Golf and Resort LLC	15.2 thousand	3.5 thousand	-11.7 thousand***	-11.9 thousand***
Coscan Stewart Partnership	N/A	N/A	N/A	N/A
Oak Valley Partners	6.4 thousand	0.4 thousand	-6.0 thousand***	-7.4 thousand***
Plantation on the Lake	1.6 thousand	0.1 thousand	-1.5 thousand***	-1.6 thousand***
Sharondale Mesa Owners Association	4.8 thousand	0.0 thousand	-4.8 thousand***	-4.6 thousand***
Total golf course / housing development	**28.1 thousand**	**4.1 thousand**	**-24.0 thousand*** **	**-25.6 thousand*** **

Notes: Welfare is the present discounted value of the entire stream of per-period payoffs over the period 1997-2014. Average annual welfare is welfare divided by the number of years. 'Open Access Counterfactual Minus Actual' is the difference between counterfactual and actual welfare values. Both actual and open access counterfactual welfare are calculated using the parameter estimates from the structural model. Actual welfare is calculated using actual values of actions and states in the data. Open access counterfactual welfare is calculated using model predicted actions and states generated from 100 simulation runs. The standard errors for the open access counterfactual welfare values and for the difference between counterfactual and actual welfare values are calculated using the parameter estimates from each of 100 bootstrap samples. To adjust for the bias of our model relative to the actual data, we subtract the upward bias of the model relative to the actual data, as measured by the difference between our model prediction and the actual data for the respective welfare statistic over the open access period 1991-1996, from our difference between the open access counterfactual and the actual data over 1997-2014; this bias-corrected statistic is a measure of the difference between the open actual counterfactual and the actual data over 1997-2014 over and above any upward bias from the model relative to the actual data. Significance stars next to the difference between counterfactual and actual welfare values denote the significance level of the difference between counterfactual and actual average annual welfare. Significance codes: *** $p<0.001$, ** $p<0.01$, * $p<0.05$

Table C.3: Robustness – Crop Price Variables: Open Access Counterfactual vs. Actual Social Welfare After Institution of Property Rights, 1997-2014

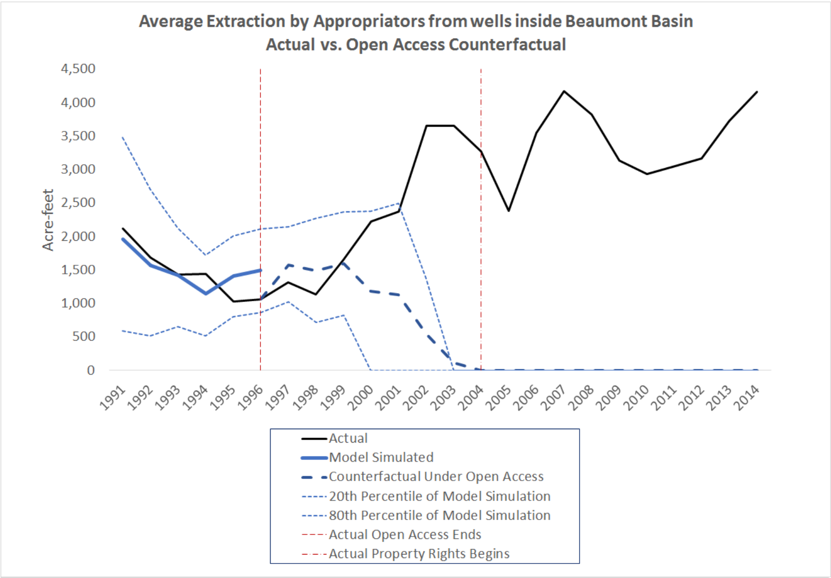
	Actual	Open Access Counterfactual	Open Access Counterfactual Minus Actual	Open Access Counterfactual Minus Actual, Bias Corrected
		Average Annual Producer Surplus (dollars)		
Appropriator profits	-256.5 thousand	-32.5 thousand	224.0 thousand	381.3 thousand
Farmer profits inside Beaumont Basin	4.6 thousand	-0.2 thousand	-4.8 thousand***	-5.7 thousand***
Farmer profits outside Beaumont Basin	0.8 thousand	3.6 thousand	2.8 thousand***	2.8 thousand
Golf course / housing development profits	28.1 thousand	4.1 thousand	-24.0 thousand***	-25.6 thousand***
Total Producer Surplus	**-0.2 million**	**0 million**	**0.2 million**	**0.4 million**
		Average Annual Consumer Surplus (dollars)		
Beaumont-Cherry Valley Water District	3.6 million	3.8 million	148.7 thousand***	-213.3 thousand***
City of Banning	4.7 million	5.3 million	592.5 thousand***	-148.8 thousand***
South Mesa Water Company	1.7 million	1.9 million	255.0 thousand***	0.8 thousand
Yucaipa Valley Water District	7.1 million	7.3 million	246.3 thousand***	-1.1 million***
Total Consumer Surplus	**17.0 million**	**18.3 million**	**1.2 million*** **	**-1.4 million*** **
		Average Annual Social Welfare (dollars)		
Social Welfare	**16.8 million**	**18.2 million**	**1.4 million** **	**-1.1 million***

Notes: Components of social welfare are the present discounted value of the entire stream of per-period payoffs related to each component over the period 1997-2014. Producer surplus is equal to the profits from groundwater extraction summed over all players. Consumer surplus is the consumer surplus faced by each appropriator, and is not weighted by parameters in the payoff function of the appropriator. Social welfare is equal to the sum of producer surplus and consumer surplus. Average annual values of these components are equal to the total value of the component divided by the number of years. 'Open Access Counterfactual Minus Actual' is the difference between counterfactual and actual component values. Both actual and open access counterfactual profits are calculated using the parameter estimates from the structural model. Both actual and open access counterfactual consumer surplus are calculated using the water demand parameter estimates. Actual values are calculated using actual values of actions and states in the data. Open access counterfactual values are calculated using model predicted actions and states generated from 100 simulation runs. The standard errors for the difference between open access counterfactual and actual welfare values are calculated using the parameter estimates from each of 100 bootstrap samples. To adjust for the bias of our model relative to the actual data, we subtract the upward bias of the model relative to the actual data, as measured by the difference between our model prediction and the actual data for the respective welfare statistic over the open access period 1991-1996, from our difference between the open access counterfactual and the actual data over 1997-2014; this bias-corrected statistic is a measure of the difference between the open actual counterfactual and the actual data over 1997-2014 over and above any upward bias from the model relative to the actual data. Significance stars next to the difference between counterfactual and actual values denote the significance level of the difference between counterfactual and actual average annual values. Significance codes: *** p<0.001, ** p<0.01, * p<0.05

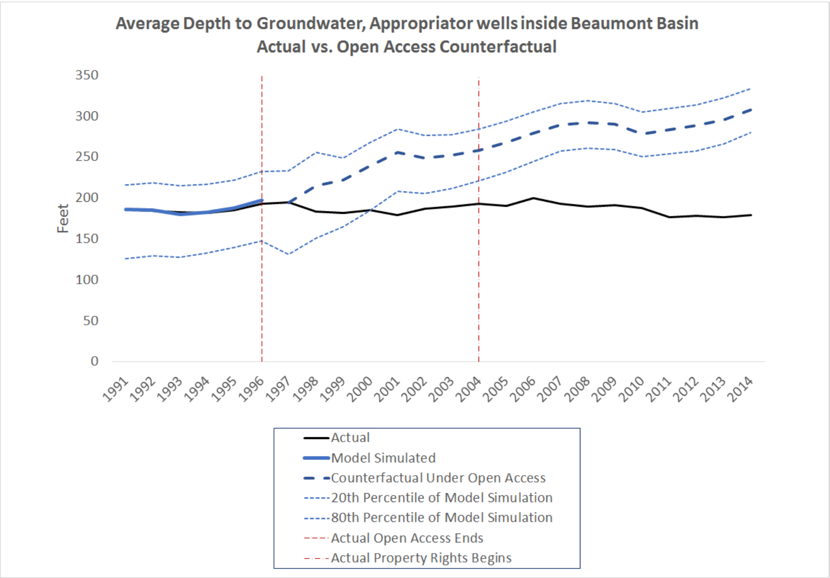
Table C.4: Robustness – Weather Variables: Structural Parameter Estimates

	Appropriators		Farmers	Golf Course /
	Inside Beaumont	Outside Beaumont		Housing Development
Coefficient in Farmer Marginal Revenue on:				
Average crop price (dollars per unit)			-1.744**	
Precipitation, Apr-Oct (inches)			-187.523***	
Average crop price (dollars per unit) X High heat days			0.025***	
Average crop price (dollars per unit) X Precipitation (inches)			2.558***	
Average crop price (dollars per unit) X High heat days X Precipitation (inches)			-0.007*	
Number of wells in Beaumont Basin, squared			11.019***	
Total wells owned before t			15.710***	
Has wells in Beaumont Basin (dummy)			11.001***	
Total Average Effect on Farmer Marginal Revenue:				
Average crop price (dollars per unit)			5.266***	
Precipitation, Apr-Oct (inches)			-10.070	
Number of high heat days (> 90 F), Apr-Oct			11.863	
Coefficient in Golf Course / Housing Development Marginal Revenue on:				
Number of wells X Hydraulic conductivity (feet per day) X High heat days				0.006
Number of wells X Hydraulic conductivity (feet per day) X Precipitation (inches)				0.647
Number of wells X Hydraulic conductivity (feet per day) X High heat days X Precipitation (inches)				-0.008
Number of wells X Log Population of Beaumont				259.897***
Number of wells X Real GDP per capita				-79.504***
Number of wells in Beaumont Basin, squared				-43.293**
Planned construction (dummy)				46.499
Total Average Effect on Golf Course / Housing Development Marginal Revenue:				
Number of wells in Beaumont Basin				118.627
Precipitation, Apr-Oct (inches)				-7.810
Number of high heat days (> 90 F), Apr-Oct				-4.531
Saturdated hydraulic conductivity (feet per day)				6.580
Coefficient in Appropriator Marginal Revenue on:				
Number of high heat days (> 90 F)	0.414			
Precipitation (inches)	0.782			
Weight in Appropriator Per-Period Payoffs on:				
Consumer surplus	2.221***			
Consumer surplus squared	-4.61E-08***			
Profits from water sales	1.000 (normalization)			
Coefficient in Water Extraction Cost on:				
Extraction (acre-feet) squared	0.015**	0.014***	0.030***	0.017

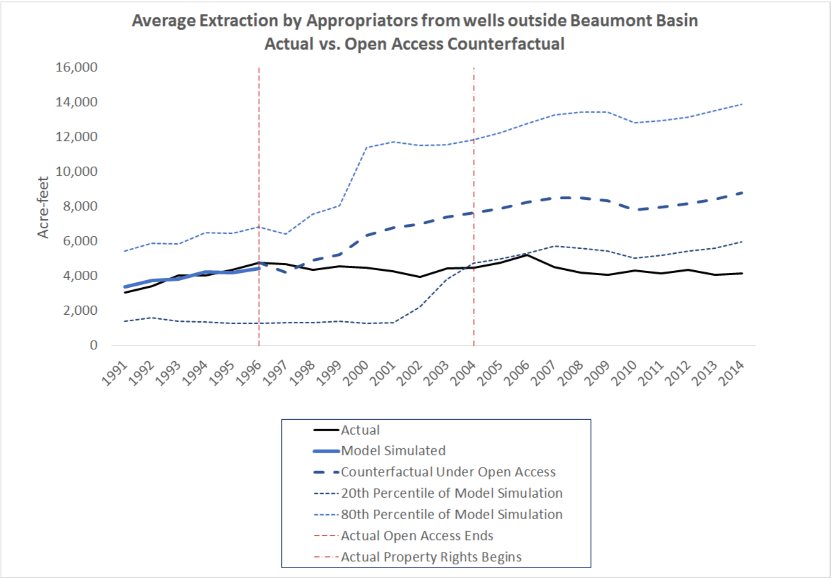
Notes: Per-period payoffs, revenue, marginal revenue, and costs are in dollars. Significance codes: *** p<0.001, ** p<0.01, * p<0.05



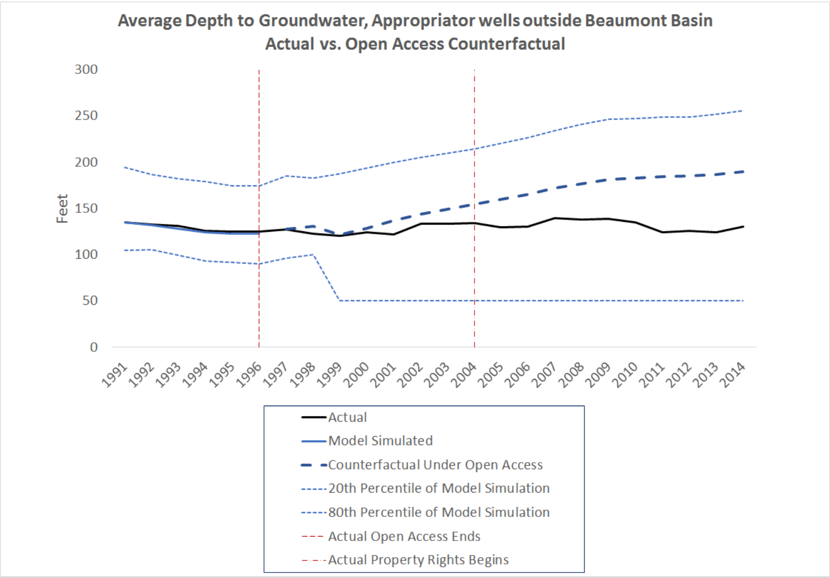
(a) Appropriator Extraction in Beaumont Basin



(b) Appropriator Depth to Groundwater in Beaumont Basin

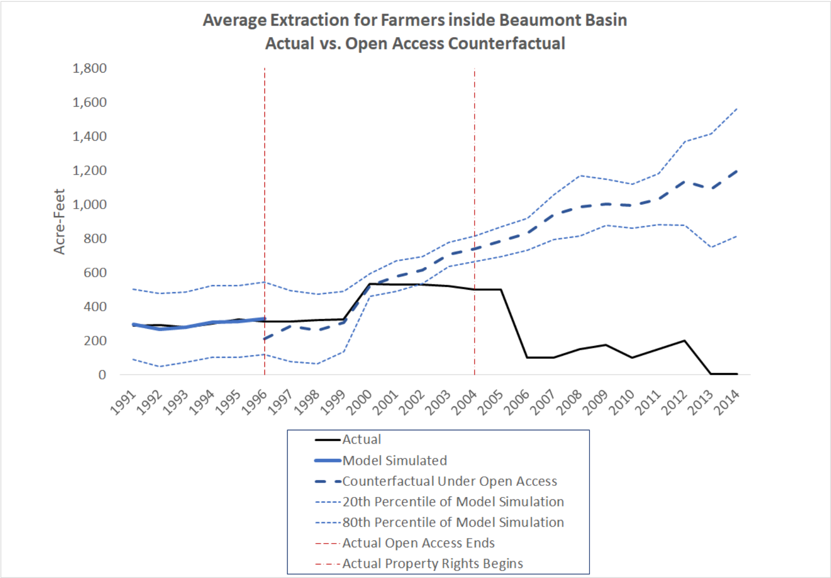


(c) Appropriator Extraction outside Beaumont Basin

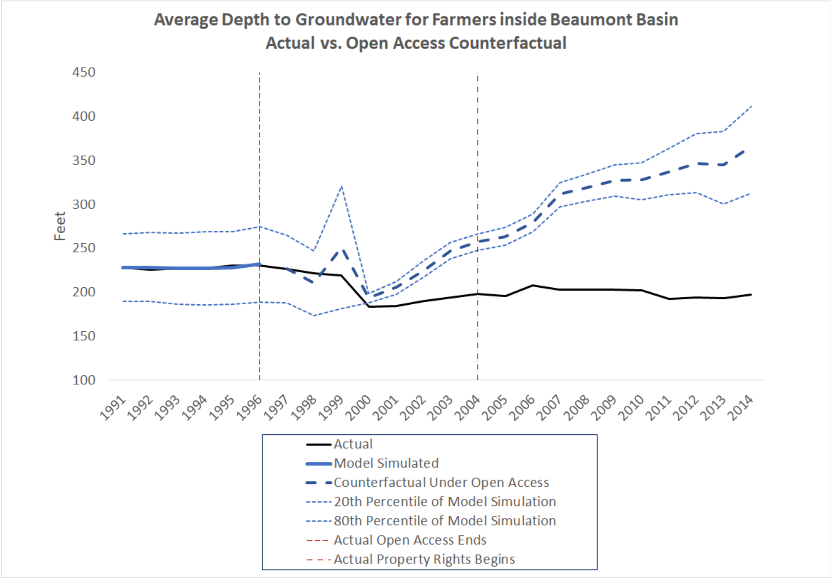


(d) Appropriator Depth to Groundwater outside Beaumont Basin

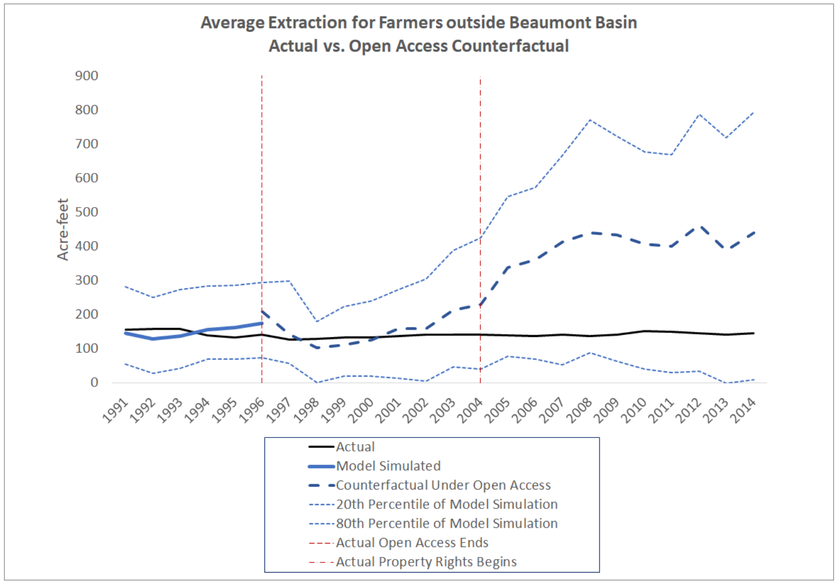
Figure C.4: Robustness – Weather Variables: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Appropriators, 1991-2014



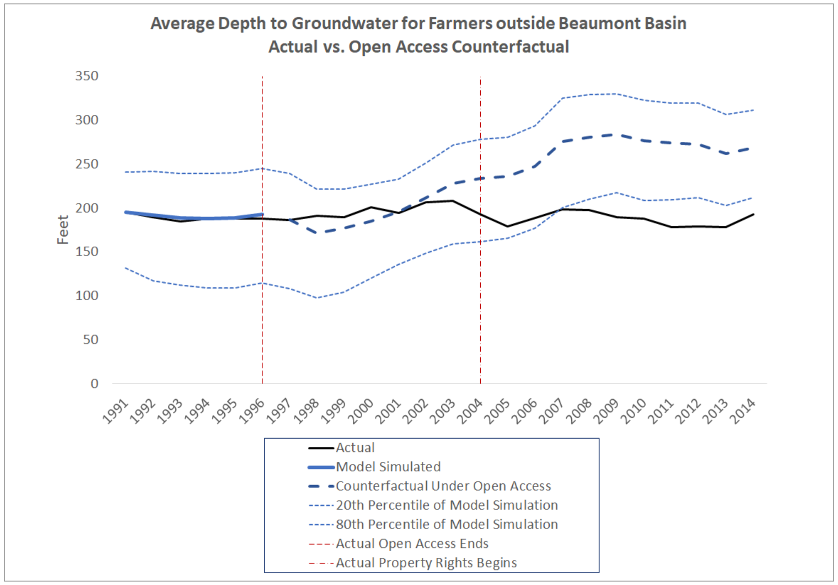
(a) Farmer Extraction in Beaumont Basin



(b) Farmer Depth to Groundwater in Beaumont Basin

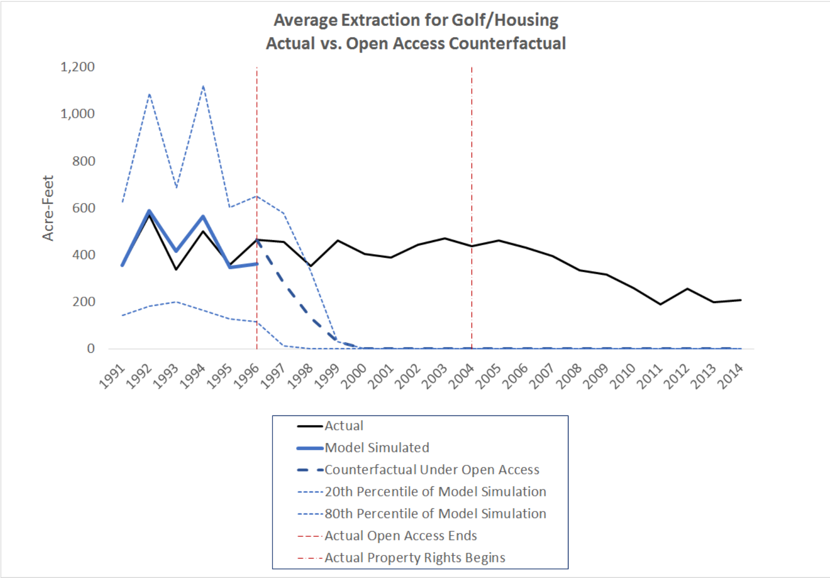


(c) Farmer Extraction outside Beaumont Basin

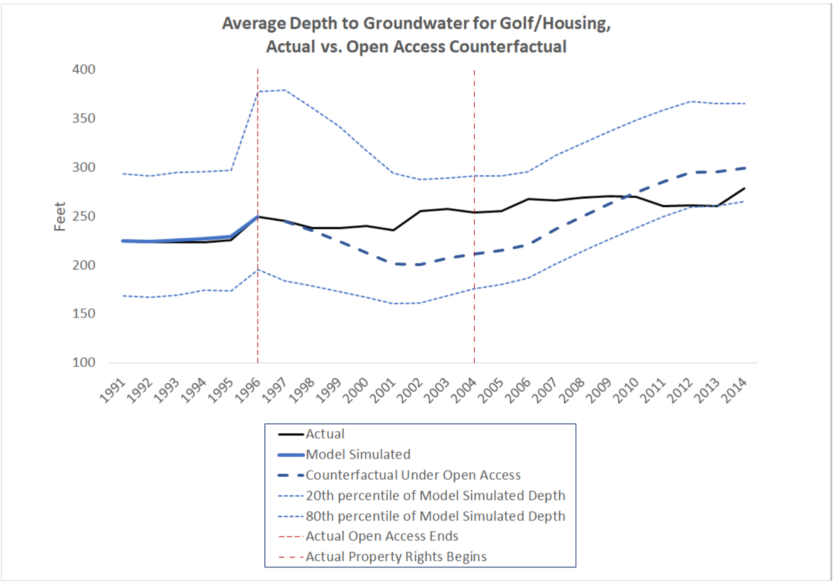


(d) Farmer Depth to Groundwater outside Beaumont Basin

Figure C.5: Robustness – Weather Variables: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Farmers, 1991-2014



(a) Golf Course / Housing Development Extraction



(b) Golf Course / Housing Development Depth to Groundwater

Figure C.6: Robustness – Weather Variables: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Golf/Housing, 1991-2014

Table C.5: Robustness – Weather Variables: Open Access Counterfactual vs. Actual Welfare After Institution of Property Rights, 1997-2014

	Average Annual Welfare (dollars)			
	Actual	Open Access Counterfactual	Open Access Counterfactual Minus Actual	Open Access Counterfactual Minus Actual, Bias Corrected
Appropriators				
Beaumont-Cherry Valley Water District	5.7 million	6.8 million	1.1 million**	328.7 thousand
City of Banning	8.1 million	8.7 million	0.7 million	-683.0 thousand
South Mesa Water Company	3.5 million	3.7 million	0.2 million	-326.2 thousand
Yucaipa Valley Water District	11.3 million	12.6 million	1.4 million**	-455.3 thousand
Total appropriators	**28.6 million**	**31.9 million**	**3.3 million**	**-1.1 million**
Farmers in Beaumont Basin				
Murray, Cecil Merle	7.1 thousand	7.1 thousand	0.0 thousand	-0.1 thousand
Riedman, Fred L. And Richard M.	15.2 thousand	26.9 thousand	11.7 thousand	10.7 thousand
Total farmers in Beaumont Basin	**22.3 thousand**	**34.0 thousand**	**11.7 thousand*** **	**10.5 thousand*** **
Farmers outside Beaumont Basin				
Francis M Dowling Jr	3.5 thousand	11.8 thousand	8.4 thousand***	8.3 thousand***
Katharina Illy	13.4 thousand	17.6 thousand	4.2 thousand	3.7 thousand
Summit Cemetery District	2.5 thousand	2.4 thousand	-0.1 thousand	-0.2 thousand
Total farmers outside Beaumont Basin	**19.4 thousand**	**31.8 thousand**	**12.5 thousand*** **	**11.9 thousand*** **
Golf Course / Housing Development				
California Oak Valley Golf and Resort LLC	-200.2 thousand	-15.6 thousand	184.6 thousand***	181.8 thousand***
Coscan Stewart Partnership	N/A	N/A	N/A	N/A
Oak Valley Partners	-134.7 thousand	-5.6 thousand	129.1 thousand***	124.4 thousand***
Plantation on the Lake	-59.6 thousand	-1.2 thousand	58.4 thousand***	56.5 thousand***
Sharondale Mesa Owners Association	-88.4 thousand	-0.4 thousand	88.0 thousand***	86.5 thousand***
Total golf course / housing development	**-482.9 thousand**	**-22.8 thousand**	**460.0 thousand*** **	**449.3 thousand*** **

Notes: Welfare is the present discounted value of the entire stream of per-period payoffs over the period 1997-2014. Average annual welfare is welfare divided by the number of years. 'Open Access Counterfactual Minus Actual' is the difference between counterfactual and actual welfare values. Both actual and open access counterfactual welfare are calculated using the parameter estimates from the structural model. Actual welfare is calculated using actual values of actions and states in the data. Open access counterfactual welfare is calculated using model predicted actions and states generated from 100 simulation runs. The standard errors for the open access counterfactual welfare values and for the difference between counterfactual and actual welfare values are calculated using the parameter estimates from each of 100 bootstrap samples. To adjust for the bias of our model relative to the actual data, we subtract the upward bias of the model relative to the actual data, as measured by the difference between our model prediction and the actual data for the respective welfare statistic over the open access period 1991-1996, from our difference between the open access counterfactual and the actual data over 1997-2014; this bias-corrected statistic is a measure of the difference between the open actual counterfactual and the actual data over 1997-2014 over and above any upward bias from the model relative to the actual data. Significance stars next to the difference between counterfactual and actual welfare values denote the significance level of the difference between counterfactual and actual average annual welfare. Significance codes: *** p<0.001, ** p<0.01, * p<0.05

Table C.6: Robustness – Weather Variables: Open Access Counterfactual vs. Actual Social Welfare After Institution of Property Rights, 1997-2014

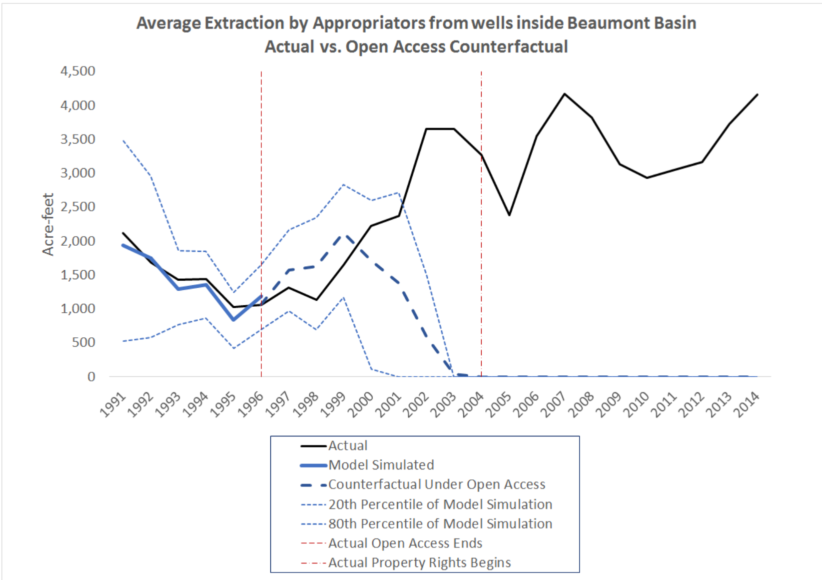
	Actual	Open Access Counterfactual	Open Access Counterfactual Minus Actual	Open Access Counterfactual Minus Actual, Bias Corrected
		Average Annual Producer Surplus (dollars)		
Appropriator profits	767.6 thousand	1.0 million	265.4 thousand	375.6 thousand
Farmer profits inside Beaumont Basin	22.3 thousand	34.0 thousand	11.7 thousand***	10.5 thousand***
Farmer profits outside Beaumont Basin	19.4 thousand	31.8 thousand	12.5 thousand***	11.9 thousand***
Golf course / housing development profits	-482.9 thousand	-22.8 thousand	460.0 thousand***	449.3 thousand***
Total Producer Surplus	**0.3 million**	**1.1 million**	**0.7 million**	**0.8 million**
		Average Annual Consumer Surplus (dollars)		
Beaumont-Cherry Valley Water District	3.6 million	3.9 million	268.8 thousand***	-93.7 thousand***
City of Banning	4.7 million	5.3 million	596.6 thousand***	-145.1 thousand***
South Mesa Water Company	1.7 million	2.0 million	271.5 thousand***	39.1 thousand
Yucaipa Valley Water District	7.1 million	7.5 million	419.0 thousand***	-925.7 thousand***
Total Consumer Surplus	**17.0 million**	**18.6 million**	**1.6 million*** **	**-1.1 million*** **
		Average Annual Social Welfare (dollars)		
Social Welfare	**17.4 million**	**19.7 million**	**2.3 million*** **	**-0.3 million**

Notes: Components of social welfare are the present discounted value of the entire stream of per-period payoffs related to each component over the period 1997-2014. Producer surplus is equal to the profits from groundwater extraction summed over all players. Consumer surplus is the consumer surplus faced by each appropriator, and is not weighted by parameters in the payoff function of the appropriator. Social welfare is equal to the sum of producer surplus and consumer surplus. Average annual values of these components are equal to the total value of the component divided by the number of years. 'Open Access Counterfactual Minus Actual' is the difference between counterfactual and actual component values. Both actual and open access counterfactual profits are calculated using the parameter estimates from the structural model. Both actual and open access counterfactual consumer surplus are calculated using the water demand parameter estimates. Actual values are calculated using actual values of actions and states in the data. Open access counterfactual values are calculated using model predicted actions and states generated from 100 simulation runs. The standard errors for the difference between open access counterfactual and actual welfare values are calculated using the parameter estimates from each of 100 bootstrap samples. To adjust for the bias of our model relative to the actual data, we subtract the upward bias of the model relative to the actual data, as measured by the difference between our model prediction and the actual data for the respective welfare statistic over the open access period 1991-1996, from our difference between the open access counterfactual and the actual data over 1997-2014; this bias-corrected statistic is a measure of the difference between the open actual counterfactual and the actual data over 1997-2014 over and above any upward bias from the model relative to the actual data. Significance stars next to the difference between counterfactual and actual values denote the significance level of the difference between counterfactual and actual average annual values. Significance codes: *** $p<0.001$, ** $p<0.01$, * $p<0.05$

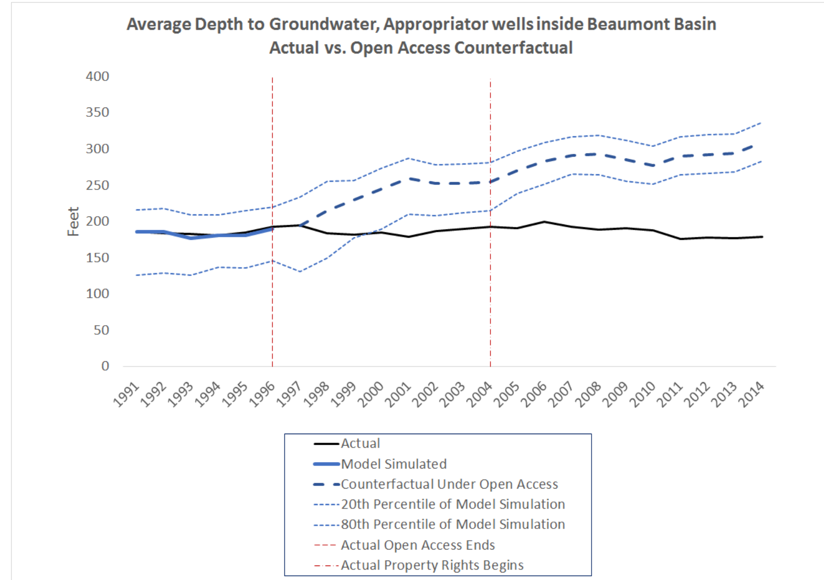
Table C.7: Robustness – Well Variables: Structural Parameter Estimates

	Appropriators Inside Beaumont	Appropriators Outside Beaumont	Farmers	Golf Course / Housing Development
Coefficient in Farmer Marginal Revenue on:				
Average crop price (dollars per unit)			-11.503***	
Precipitation, Apr-Oct (inches)			240.840***	
Average crop price (dollars per unit) X High heat days			0.165***	
Average crop price (dollars per unit) X Precipitation (inches)			1.538***	
Average crop price (dollars per unit) X High heat days X Precipitation (inches)			-0.062***	
Number of wells in Beaumont Basin, squared			-162475.483***	
Total wells owned before t			15.692*	
Has wells in Beaumont Basin (dummy)			162476.411***	
Average crop price (dollars per unit)			-6.522	
Precipitation, Apr-Oct (inches)			-78.808	
Number of high heat days (> 90 F), Apr-Oct			1.320	
Coefficient in Golf Course / Housing Development Marginal Revenue on:				
Number of wells X Hydraulic conductivity (feet per day) X High heat days				-0.014***
Number of wells X Hydraulic conductivity (feet per day) X Precipitation (inches)				0.382***
Number of wells X Hydraulic conductivity (feet per day) X High heat days X Precipitation (inches)				0.003***
Number of wells X Log Population of Beaumont				4.466***
Number of wells X Real GDP per capita				1.049***
Number of wells in Beaumont Basin, squared				-30.029***
Planned construction (dummy)				56.867
Total Average Effect on Golf Course / Housing Development Marginal Revenue:				
Number of wells in Beaumont Basin				77.239
Precipitation, Apr-Oct (inches)				283.325
Number of high heat days (> 90 F), Apr-Oct				-2.733
Saturated hydraulic conductivity (feet per day)				3.737
Coefficient in Appropriator Marginal Revenue on:				
Number of high heat days (> 90 F)	-1.763			
Precipitation (inches)	4.058			
Weight in Appropriator Per-Period Payoffs on:				
Consumer surplus	2.217			
Consumer surplus squared	-4.59E-08			
Profits from water sales	1.000 (normalization)			
Coefficient in Water Extraction Cost on:				
Extraction (acre-feet) squared	0.006***	0.006***	0.038***	0.015**

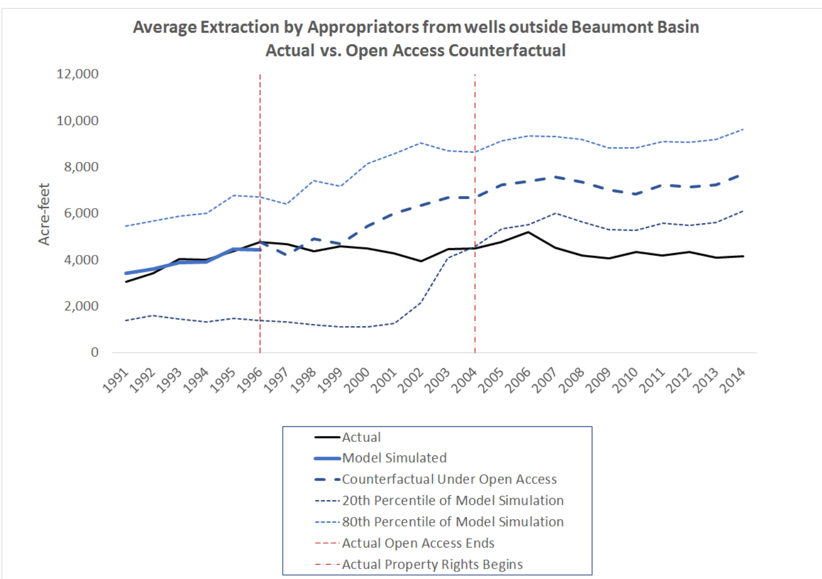
Notes: Per-period payoffs, revenue, marginal revenue, and costs are in dollars. Significance codes: *** p<0.001, ** p<0.01, * p<0.05



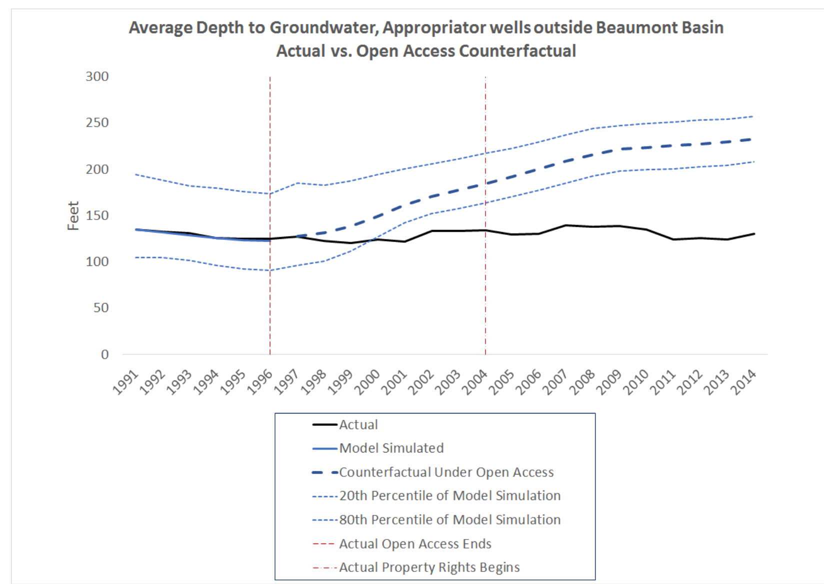
(a) Appropriator Extraction in Beaumont Basin



(b) Appropriator Depth to Groundwater in Beaumont Basin

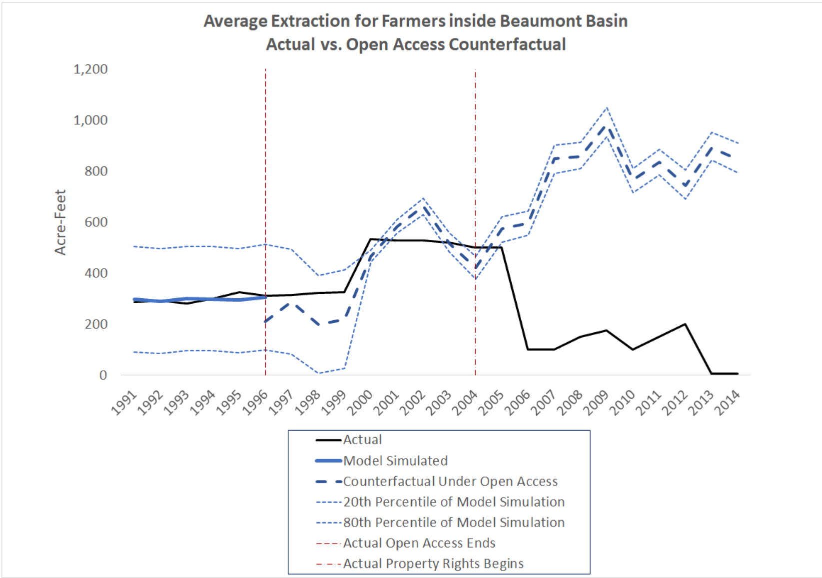


(c) Appropriator Extraction outside Beaumont Basin

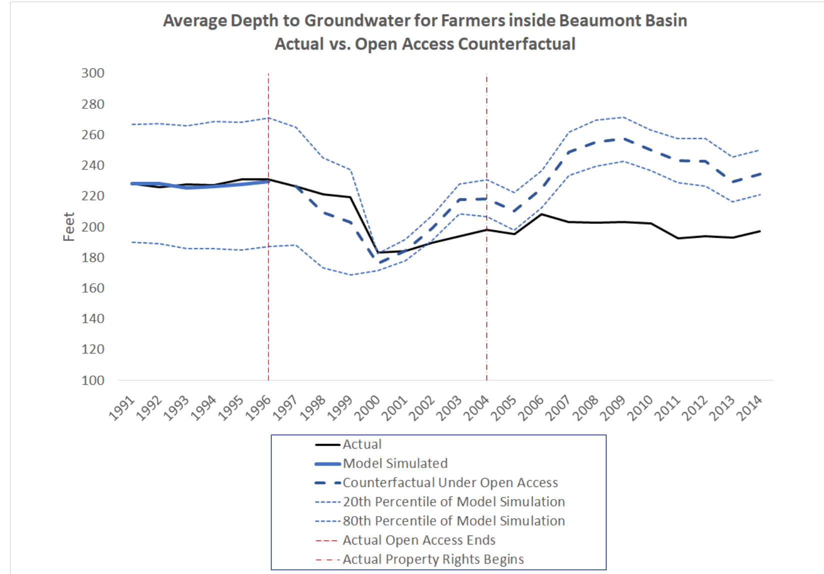


(d) Appropriator Depth to Groundwater outside Beaumont Basin

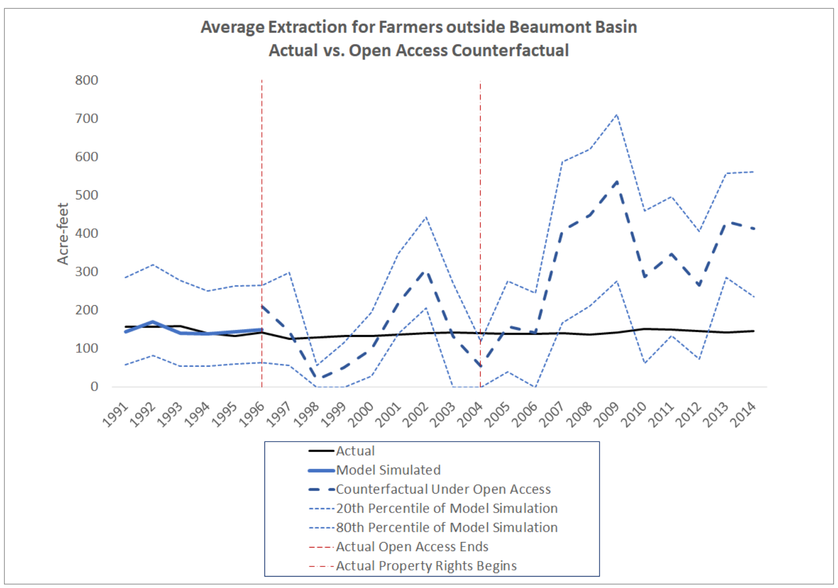
Figure C.7: Robustness – Well Variables: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Appropriators, 1991-2014



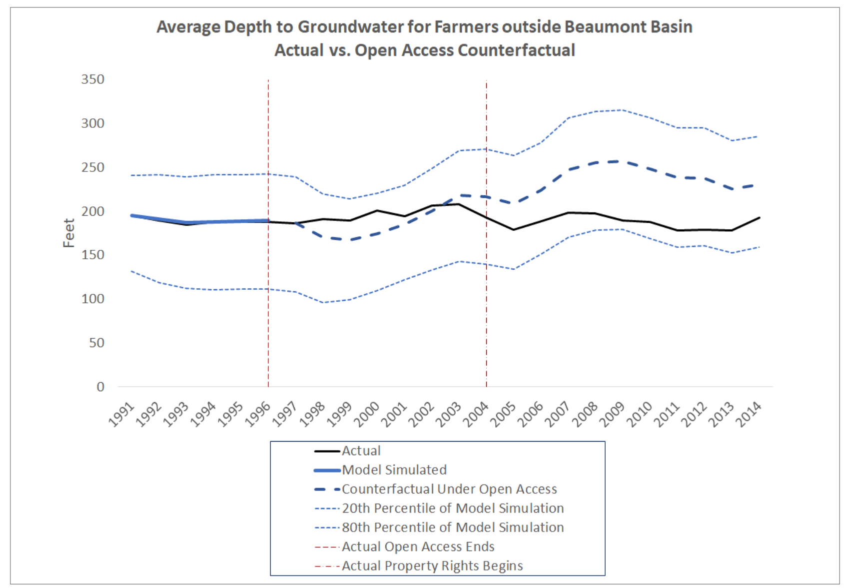
(a) Farmer Extraction in Beaumont Basin



(b) Farmer Depth to Groundwater in Beaumont Basin

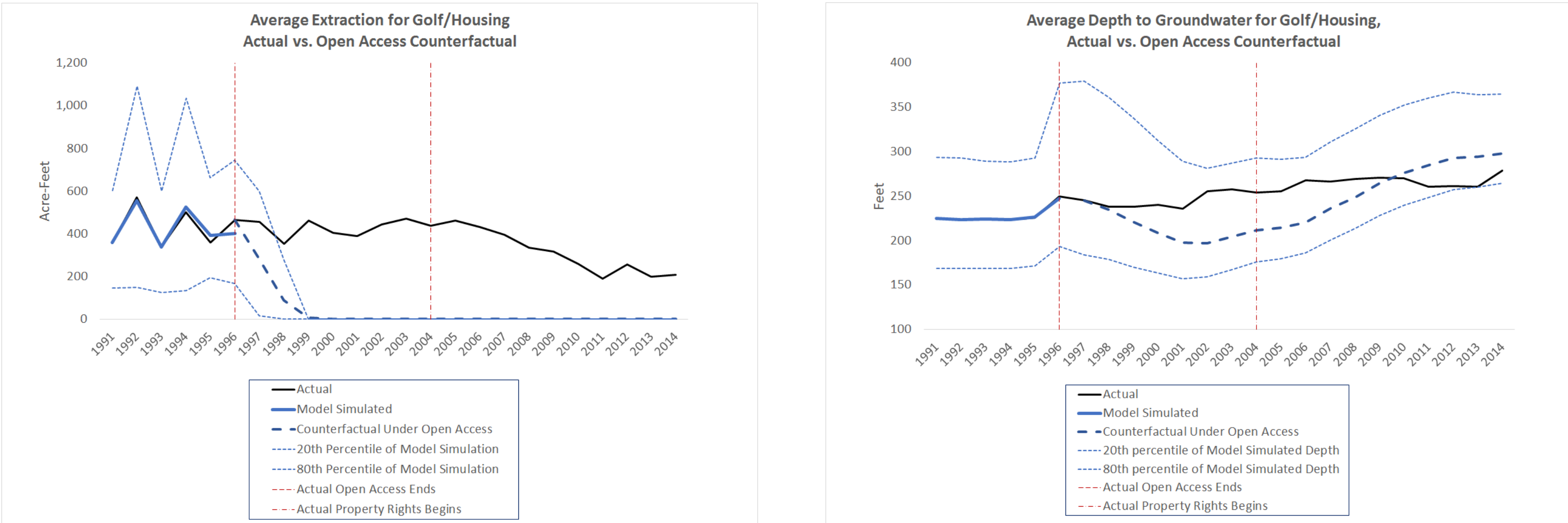


(c) Farmer Extraction outside Beaumont Basin



(d) Farmer Depth to Groundwater outside Beaumont Basin

Figure C.8: Robustness – Well Variables: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Farmers, 1991-2014



(a) Golf Course / Housing Development Extraction

(b) Golf Course / Housing Development Depth to Groundwater

Figure C.9: Robustness – Well Variables: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Golf/Housing, 1991-2014

Table C.8: Robustness – Well Variables: Open Access Counterfactual vs. Actual Welfare After Institution of Property Rights, 1997-2014

	Average Annual Welfare (dollars)			
	Actual	Open Access Counterfactual	Open Access Counterfactual Minus Actual	Open Access Counterfactual Minus Actual, Bias Corrected
Appropriators				
Beaumont-Cherry Valley Water District	5.9 million	6.7 million	0.8 million	106.8 thousand
City of Banning	7.7 million	8.4 million	0.7 million	-596.5 thousand
South Mesa Water Company	3.4 million	3.6 million	0.2 million	-285.4 thousand
Yucaipa Valley Water District	11.0 million	12.4 million	1.4 million	-447.5 thousand
Total appropriators	**28.0 million**	**31.1 million**	**3.2 million**	**-1.2 million**
Farmers in Beaumont Basin				
Murray, Cecil Merle	-18.7 thousand	-7.2 thousand	11.5 thousand*	11.1 thousand*
Riedman, Fred L. And Richard M.	-26.8 thousand	-14.7 thousand	12.1 thousand	10.5 thousand
Total farmers in Beaumont Basin	**-45.5 thousand**	**-21.9 thousand**	**23.5 thousand*** **	**21.6 thousand*** **
Farmers outside Beaumont Basin				
Francis M Dowling Jr	-5.0 thousand	4.7 thousand	9.7 thousand*	10.0 thousand*
Katharina Illy	-12.4 thousand	-11.9 thousand	0.5 thousand	0.0 thousand
Summit Cemetery District	-3.6 thousand	1.9 thousand	5.5 thousand***	5.2 thousand***
Total farmers outside Beaumont Basin	**-21.0 thousand**	**-5.3 thousand**	**15.7 thousand*** **	**15.3 thousand*** **
Golf Course / Housing Development				
California Oak Valley Golf and Resort LLC	19.9 thousand	8.1 thousand	-11.9 thousand***	-12.1 thousand***
Coscan Stewart Partnership	N/A	N/A	N/A	N/A
Oak Valley Partners	7.8 thousand	0.5 thousand	-7.4 thousand***	-9.3 thousand***
Plantation on the Lake	2.1 thousand	0.2 thousand	-2.0 thousand***	-2.1 thousand***
Sharondale Mesa Owners Association	5.8 thousand	0.1 thousand	-5.8 thousand***	-5.8 thousand***
Total golf course / housing development	**35.7 thousand**	**8.8 thousand**	**-27.0 thousand*** **	**-29.2 thousand*** **

Notes: Welfare is the present discounted value of the entire stream of per-period payoffs over the period 1997-2014. Average annual welfare is welfare divided by the number of years. 'Open Access Counterfactual Minus Actual' is the difference between counterfactual and actual welfare values. Both actual and open access counterfactual welfare are calculated using the parameter estimates from the structural model. Actual welfare is calculated using actual values of actions and states in the data. Open access counterfactual welfare is calculated using model predicted actions and states generated from 100 simulation runs. The standard errors for the open access counterfactual welfare values and for the difference between counterfactual and actual welfare values are calculated using the parameter estimates from each of 100 bootstrap samples. To adjust for the bias of our model relative to the actual data, we subtract the upward bias of the model relative to the actual data, as measured by the difference between our model prediction and the actual data for the respective welfare statistic over the open access period 1991-1996, from our difference between the open access counterfactual and the actual data over 1997-2014; this bias-corrected statistic is a measure of the difference between the open actual counterfactual and the actual data over 1997-2014 over and above any upward bias from the model relative to the actual data. Significance stars next to the difference between counterfactual and actual welfare values denote the significance level of the difference between counterfactual and actual average annual welfare. Significance codes: *** p<0.001, ** p<0.01, * p<0.05

Table C.9: Robustness – Well Variables: Open Access Counterfactual vs. Actual Social Welfare After Institution of Property Rights, 1997-2014

	Actual	Open Access Counterfactual	Open Access Counterfactual Minus Actual	Open Access Counterfactual Minus Actual, Bias Corrected
			Average Annual Producer Surplus (dollars)	
Appropriator profits	169.7 thousand	407.1 thousand	237.4 thousand	377.3 thousand
Farmer profits inside Beaumont Basin	-45.5 thousand	-21.9 thousand	23.5 thousand***	21.6 thousand***
Farmer profits outside Beaumont Basin	-21.0 thousand	-5.3 thousand	15.7 thousand***	15.3 thousand***
Golf course / housing development profits	35.7 thousand	8.8 thousand	-27.0 thousand****	-29.2 thousand***
Total Producer Surplus	**0.1 million**	**0.4 million**	**0.2 million**	**0.4 million**
			Average Annual Consumer Surplus (dollars)	
Beaumont-Cherry Valley Water District	3.6 million	3.9 million	268.0 thousand***	-94.9 thousand***
City of Banning	4.7 million	5.2 million	537.9 thousand***	-205.8 thousand***
South Mesa Water Company	1.7 million	2.0 million	275.9 thousand***	27.8 thousand
Yucaipa Valley Water District	7.1 million	7.5 million	399.2 thousand***	-929.6 thousand***
Total Consumer Surplus	**17.0 million**	**18.5 million**	**1.5 million*** **	**-1.2 million*** **
			Average Annual Social Welfare (dollars)	
Social Welfare	**17.2 million**	**18.9 million**	**1.7 million**	**-0.8 million**

Notes: Components of social welfare are the present discounted value of the entire stream of per-period payoffs related to each component over the period 1997-2014. Producer surplus is equal to the profits from groundwater extraction summed over all players. Consumer surplus is the consumer surplus faced by each appropriator, and is not weighted by parameters in the payoff function of the appropriator. Social welfare is equal to the sum of producer surplus and consumer surplus. Average annual values of these components are equal to the total value of the component divided by the number of years. 'Open Access Counterfactual Minus Actual' is the difference between counterfactual and actual component values. Both actual and open access counterfactual profits are calculated using the parameter estimates from the structural model. Both actual and open access counterfactual consumer surplus are calculated using the water demand parameter estimates. Actual values are calculated using actual values of actions and states in the data. Open access counterfactual values are calculated using model predicted actions and states generated from 100 simulation runs. The standard errors for the difference between open access counterfactual and actual welfare values are calculated using the parameter estimates from each of 100 bootstrap samples. To adjust for the bias of our model relative to the actual data, we subtract the upward bias of the model relative to the actual data, as measured by the difference between our model prediction and the actual data for the respective welfare statistic over the open access period 1991-1996, from our difference between the open access counterfactual and the actual data over 1997-2014; this bias-corrected statistic is a measure of the difference between the open actual counterfactual and the actual data over 1997-2014 over and above any upward bias from the model relative to the actual data. Significance stars next to the difference between counterfactual and actual values denote the significance level of the difference between counterfactual and actual average annual values. Significance codes: *** p<0.001, ** p<0.01, * p<0.05

Table C.10: Robustness – Lagged Depth to Groundwater: State Transition Results, 1991-1996

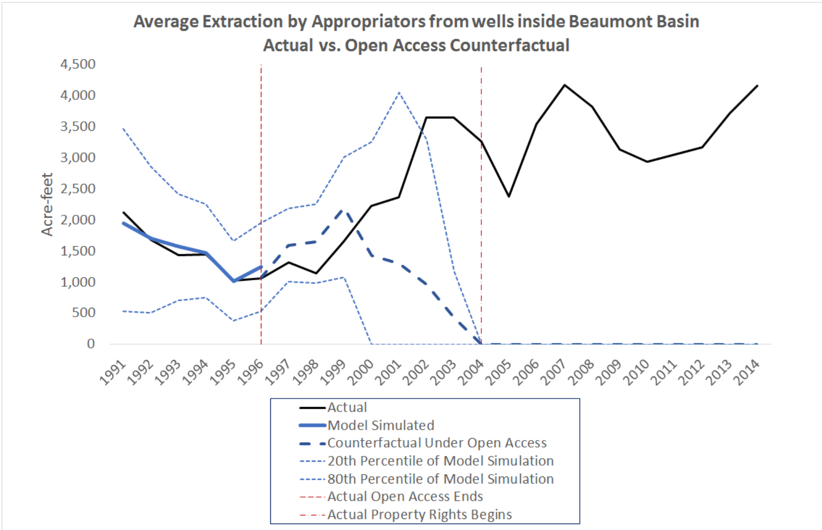
	Dependent variable is depth to groundwater (ft) for:			
	Farmer	Golf/ Housing	Appropriator inside Beaumont	Appropriator outside Beaumont
	(1)	(2)	(3)	(4)
Lagged values of:				
Depth to groundwater (ft)		0.808***		
		(0.0480)		
Depth to groundwater inside management zone (ft)			0.635*	
			(0.272)	
Depth to groundwater outside management zone (ft)				0.806***
				(0.0764)
Depth to groundwater (ft) X Electricity price (dollars/kwh)	1.879***	1.381**		
	(0.558)	(0.481)		
Own extraction (acre-ft) X Saturated hydraulic conductivity (ft/day)	0.00304	0.000185*		
	(0.00383)	(0.000074)		
Own extraction in Beaumont (acre-ft) X Saturated hydraulic conductivity (ft/day)			0.0000717	
			(0.000079)	
Own extraction outside Beaumont (acre-ft) X Saturated hydraulic conductivity (ft/day)				-0.000005
				(0.000004)
Neighbor extraction in Beaumont (acre-ft), 0.5 to 1 miles X Saturated hydraulic conductivity (ft/day)			0.000223	
			(7.02E-05)	
Neighbor extraction in Beaumont (acre-ft), 1 to 2 miles X Saturated hydraulic conductivity (ft/day)				0.000046
				(0.000054)
Neighbor extraction (acre-ft), 2 to 3 miles X Saturated hydraulic conductivity (ft/day)	0.000108**			
	(0.000034)			
Neighbor extraction (acre-ft), 3 to 4 miles X Saturated hydraulic conductivity (ft/day)	0.0000763*			
	(0.000033)			
Neighbor extraction in Beaumont (acre-ft), 3 to 4 miles X Saturated hydraulic conductivity (ft/day)				-0.000369**
				(0.000135)
Average pump strength outside management zone (gallons per minute)				-0.00758*
				(0.00355)
Precipitation, Apr-Oct (inches)	-1.705*		-0.101	
	(0.809)		(1.350)	
Number of high heat days (> 90 F), Apr-Oct		0.0982*	-0.277*	
		(0.0482)	(0.119)	
CA real GDP per capita (1997 chained dollars)	0.00241*		0.00767***	0.00125*
	(0.00103)		(0.00180)	(0.000521)
Retail price of untreated water (dollars/acre-foot)			0.103***	
			(0.0201)	
# Observations	30	25	20	20
# Players	5	5	4	4
p-value (Prob>F)	0.000	0.000	0.000	0.000
RMSE	4.047	2.715	4.364	4.166

Notes: Standard errors in parentheses. Significance codes: *** p<0.001, ** p<0.01, * p<0.05

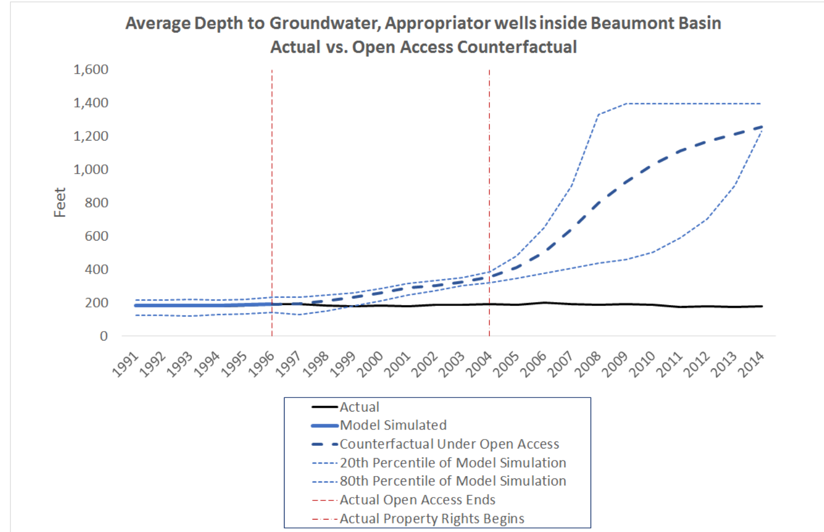
Table C.11: Robustness – Lagged Depth to Groundwater: Structural Parameter Estimates

	Appropriators		Farmers	Golf Course /
	Inside Beaumont	Outside Beaumont		Housing Development
Coefficient in Farmer Marginal Revenue on:				
Average crop price (dollars per unit)			-11.410***	
Precipitation, Apr-Oct (inches)			133.605***	
Average crop price (dollars per unit) X High heat days			0.167***	
Average crop price (dollars per unit) X Precipitation (inches)			2.847***	
Average crop price (dollars per unit) X High heat days X Precipitation (inches)			-0.064***	
Number of wells in Beaumont Basin, squared			1.71E05***	
Total wells owned before t			14.427	
Has wells in Beaumont Basin (dummy)			-1.71E05***	
Total Average Effect on Farmer Marginal Revenue:				
Average crop price (dollars per unit)			3.521	
Precipitation, Apr-Oct (inches)			-85.670	
Number of high heat days (> 90 F), Apr-Oct			1.042	
Coefficient in Golf Course / Housing Development Marginal Revenue on:				
Number of wells X Hydraulic conductivity (feet per day) X High heat days				-0.017***
Number of wells X Hydraulic conductivity (feet per day) X Precipitation (inches)				0.449***
Number of wells X Hydraulic conductivity (feet per day) X High heat days X Precipitation (inches)				0.004***
Number of wells X Log Population of Beaumont				4.046***
Number of wells X Real GDP per capita				0.847***
Number of wells in Beaumont Basin, squared				-25.357***
Planned construction (dummy)				63.249
Total Average Effect on Golf Course / Housing Development Marginal Revenue:				
Number of wells in Beaumont Basin				83.626
Precipitation, Apr-Oct (inches)				331.311
Number of high heat days (> 90 F), Apr-Oct				-3.397
Saturated hydraulic conductivity (feet per day)				3.876
Coefficient in Appropriator Marginal Revenue on:				
Number of high heat days (> 90 F)	-1.801			
Precipitation (inches)	5.223			
Weight in Appropriator Per-Period Payoffs on:				
Consumer surplus	2.009***			
Consumer surplus squared	-3.89E-08			
Profits from water sales	1.000 (normalization)			
Coefficient in Water Extraction Cost on:				
Extraction (acre-feet) squared	0.016***	0.011**	0.039***	0.014

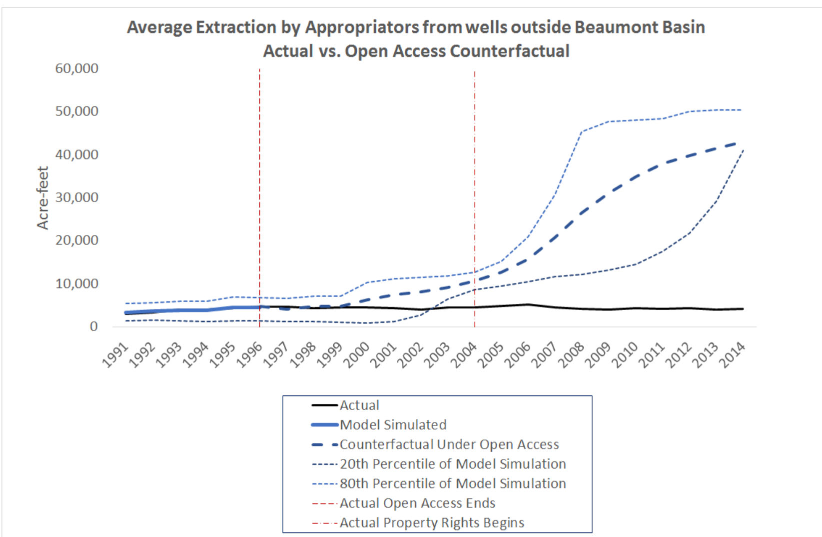
Notes: Per-period payoffs, revenue, marginal revenue, and costs are in dollars. Significance codes: *** p<0.001, ** p<0.01, * p<0.05



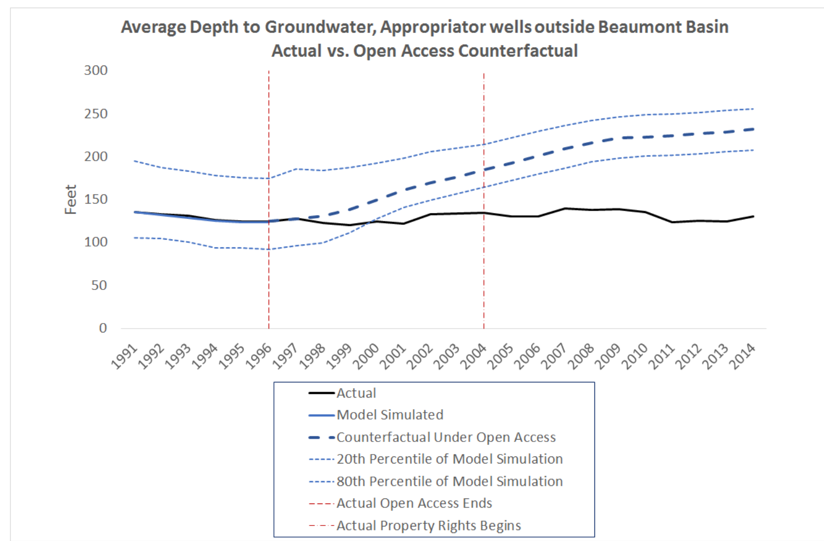
(a) Appropriator Extraction in Beaumont Basin



(b) Appropriator Depth to Groundwater in Beaumont Basin

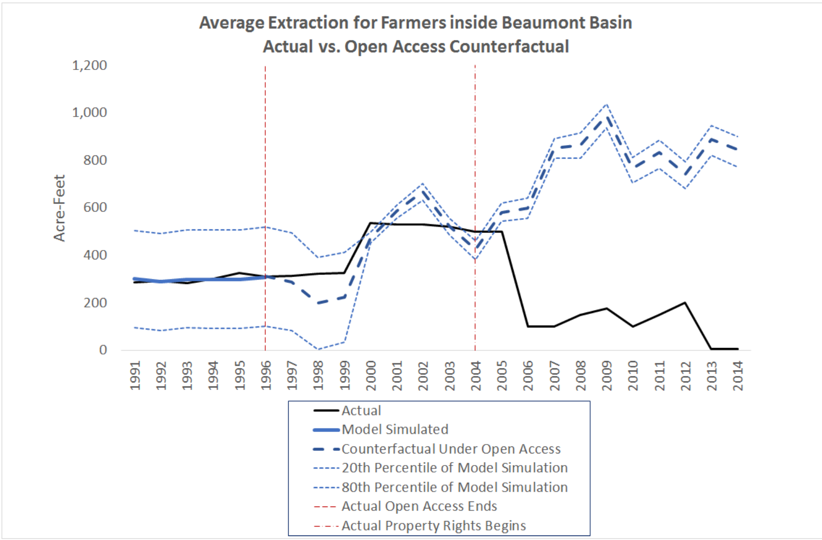


(c) Appropriator Extraction outside Beaumont Basin

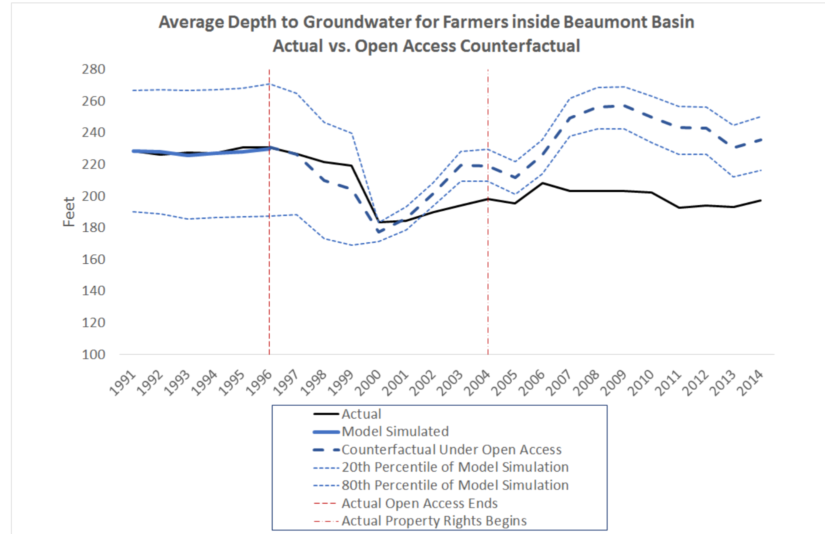


(d) Appropriator Depth to Groundwater outside Beaumont Basin

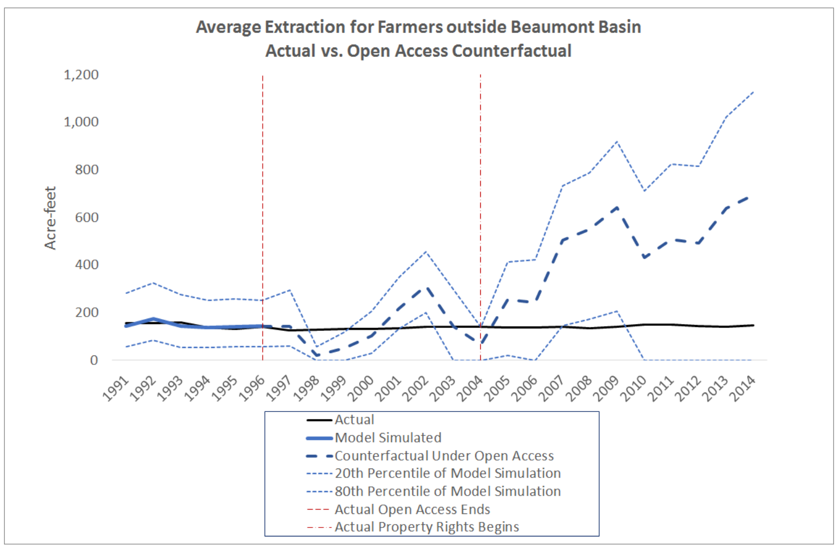
Figure C.10: Robustness – Lagged Depth to Groundwater: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Appropriators, 1991-2014



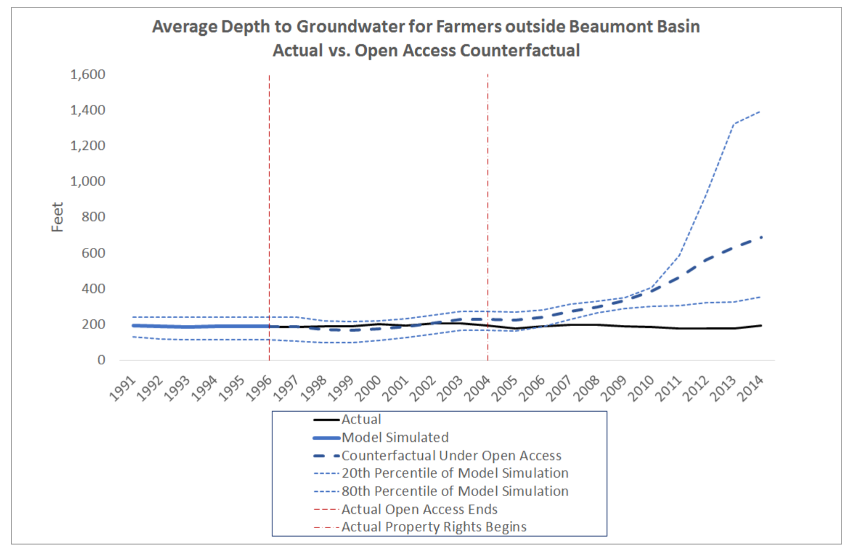
(a) Farmer Extraction in Beaumont Basin



(b) Farmer Depth to Groundwater in Beaumont Basin

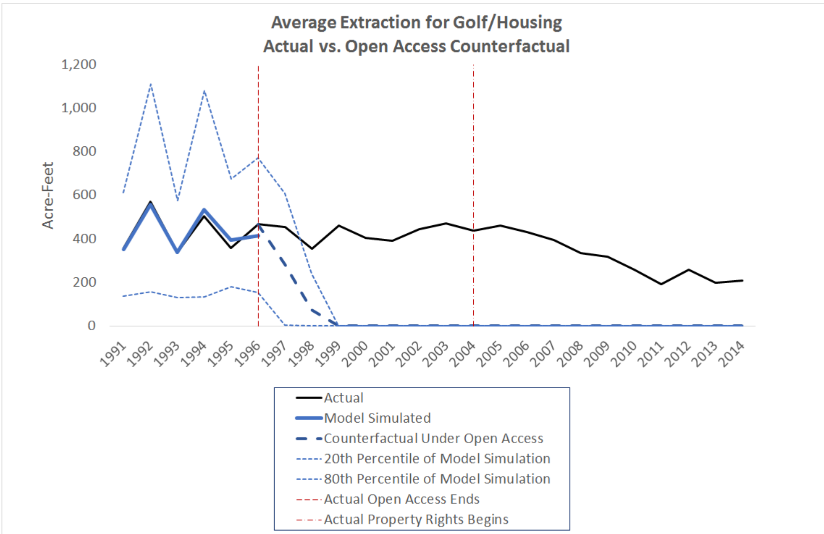


(c) Farmer Extraction outside Beaumont Basin

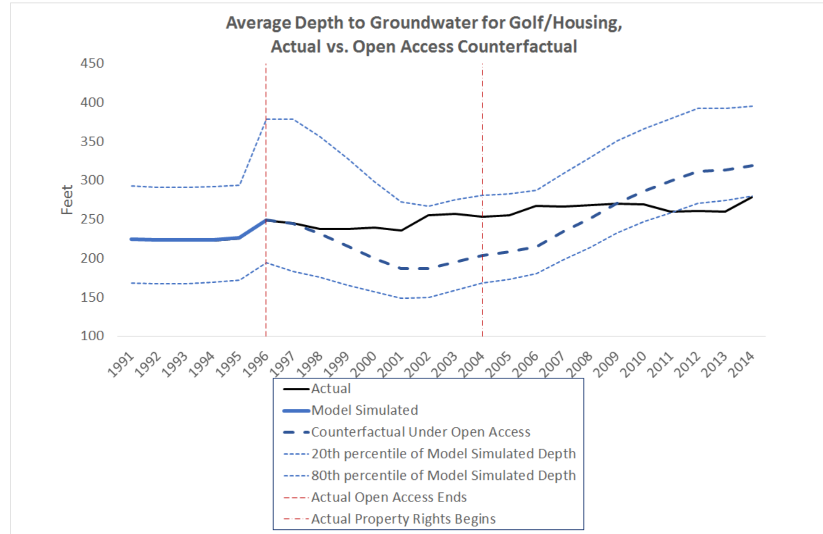


(d) Farmer Depth to Groundwater outside Beaumont Basin

Figure C.11: Robustness – Lagged Depth to Groundwater: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Farmers, 1991-2014



(a) Golf Course / Housing Development Extraction



(b) Golf Course / Housing Development Depth to Groundwater

Figure C.12: Robustness – Lagged Depth to Groundwater: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Golf/Housing, 1991-2014

Table C.12: Robustness – Lagged Depth to Groundwater: Open Access Counterfactual vs. Actual Welfare After Institution of Property Rights, 1997-2014

	Average Annual Welfare (dollars)			
	Actual	Open Access Counterfactual	Open Access Counterfactual Minus Actual	Open Access Counterfactual Minus Actual, Bias Corrected
Appropriators				
Beaumont-Cherry Valley Water District	5.1 million	4.1 million	-0.9 million	-1.6 million
City of Banning	7.0 million	6.2 million	-0.9 million	-2.1 million
South Mesa Water Company	3.1 million	-10.2 million	-13.3 million**	-13.6 million**
Yucaipa Valley Water District	10.4 million	11.3 million	0.9 million	-857.2 thousand
Total appropriators	**25.6 million**	**11.4 million**	**-14.2 million**	**-18.2 million***
Farmers in Beaumont Basin				
Murray, Cecil Merle	-16.4 thousand	-6.4 thousand	9.9 thousand*	9.6 thousand*
Riedman, Fred L. And Richard M.	-21.6 thousand	-4.5 thousand	17.1 thousand	15.6 thousand
Total farmers in Beaumont Basin	**-38.0 thousand**	**-10.9 thousand**	**27.1 thousand*** **	**25.1 thousand*** **
Farmers outside Beaumont Basin				
Francis M Dowling Jr	-3.7 thousand	8.6 thousand	12.3 thousand	12.6 thousand
Katharina Illy	-6.1 thousand	-8.2 thousand	-2.1 thousand	-2.5 thousand
Summit Cemetery District	-2.3 thousand	4.0 thousand	6.2 thousand***	6.0 thousand***
Total farmers outside Beaumont Basin	**-12.1 thousand**	**4.3 thousand**	**16.4 thousand*** **	**16.2 thousand*** **
Golf Course / Housing Development				
California Oak Valley Golf and Resort LLC	21.2 thousand	7.9 thousand	-13.3 thousand***	-13.2 thousand***
Coscan Stewart Partnership	N/A	N/A	N/A	N/A
Oak Valley Partners	7.6 thousand	0.3 thousand	-7.2 thousand***	-9.2 thousand***
Plantation on the Lake	1.5 thousand	0.1 thousand	-1.4 thousand***	-1.4 thousand***
Sharondale Mesa Owners Association	6.0 thousand	0.1 thousand	-5.9 thousand***	-6.0 thousand***
Total golf course / housing developments	**36.3 thousand**	**8.4 thousand**	**-27.8 thousand*** **	**-29.8 thousand*** **

Notes: Welfare is the present discounted value of the entire stream of per-period payoffs over the period 1997-2014. Average annual welfare is welfare divided by the number of years. 'Open Access Counterfactual Minus Actual' is the difference between counterfactual and actual welfare values. Both actual and open access counterfactual welfare are calculated using the parameter estimates from the structural model. Actual welfare is calculated using actual values of actions and states in the data. Open access counterfactual welfare is calculated using model predicted actions and states generated from 100 simulation runs. The standard errors for the open access counterfactual welfare values and for the difference between counterfactual and actual welfare values are calculated using the parameter estimates from each of 100 bootstrap samples. To adjust for the bias of our model relative to the actual data, we subtract the upward bias of the model relative to the actual data, as measured by the difference between our model prediction and the actual data for the respective welfare statistic over the open access period 1991-1996, from our difference between the open access counterfactual and the actual data over 1997-2014; this bias-corrected statistic is a measure of the difference between the open actual counterfactual and the actual data over 1997-2014 over and above any upward bias from the model relative to the actual data. Significance stars next to the difference between counterfactual and actual welfare values denote the significance level of the difference between counterfactual and actual average annual welfare. Significance codes: *** p<0.001, ** p<0.01, * p<0.05

Table C.13: Robustness – Lagged Depth to Groundwater: Open Access Counterfactual vs. Actual Social Welfare After Institution of Property Rights, 1997-2014

	Actual	Open Access Counterfactual	Open Access Counterfactual Minus Actual	Open Access Counterfactual Minus Actual, Bias Corrected
		Average Annual Producer Surplus (dollars)		
Appropriator profits	-179.0 thousand	-17.7 million	-17.5 million	-17.4 million***
Farmer profits inside Beaumont Basin	-38.0 thousand	-10.9 thousand	27.1 thousand***	25.1 thousand***
Farmer profits outside Beaumont Basin	-12.1 thousand	4.3 thousand	16.4 thousand***	16.2 thousand***
Golf course / housing development profits	36.3 thousand	8.4 thousand	-27.8 thousand***	-29.8 thousand***
Total Producer Surplus	**-0.2 million**	**-17.6 million**	**-17.5 million*** **	**-17.4 million*** **
		Average Annual Consumer Surplus (dollars)		
Beaumont-Cherry Valley Water District	3.6 million	4.0 million	418.1 thousand***	55.7 thousand***
City of Banning	4.7 million	5.3 million	595.1 thousand***	-159.2 thousand***
South Mesa Water Company	1.7 million	2.0 million	281.2 thousand***	121.2 thousand***
Yucaipa Valley Water District	7.1 million	8.1 million	1.1 million***	-237.5 thousand
Total Consumer Surplus	**17.0 million**	**19.4 million**	**2.4 million*** **	**-219.8 thousand**
		Average Annual Social Welfare (dollars)		
Social Welfare	**16.8 million**	**1.8 million**	**-15.1 million*** **	**-17.6 million*** **

Notes: Components of social welfare are the present discounted value of the entire stream of per-period payoffs related to each component over the period 1997-2014. Producer surplus is equal to the profits from groundwater extraction summed over all players. Consumer surplus is the consumer surplus faced by each appropriator, and is not weighted by parameters in the payoff function of the appropriator. Social welfare is equal to the sum of producer surplus and consumer surplus. Average annual values of these components are equal to the total value of the component divided by the number of years. 'Open Access Counterfactual Minus Actual' is the difference between counterfactual and actual component values. Both actual and open access counterfactual profits are calculated using the parameter estimates from the structural model. Both actual and open access counterfactual consumer surplus are calculated using the water demand parameter estimates. Actual values are calculated using actual values of actions and states in the data. Open access counterfactual values are calculated using model predicted actions and states generated from 100 simulation runs. The standard errors for the difference between open access counterfactual and actual welfare values are calculated using the parameter estimates from each of 100 bootstrap samples. To adjust for the bias of our model relative to the actual data, we subtract the upward bias of the model relative to the actual data, as measured by the difference between our model prediction and the actual data for the respective welfare statistic over the open access period 1991-1996, from our difference between the open access counterfactual and the actual data over 1997-2014; this bias-corrected statistic is a measure of the difference between the open actual counterfactual and the actual data over 1997-2014 over and above any upward bias from the model relative to the actual data. Significance stars next to the difference between counterfactual and actual values denote the significance level of the difference between counterfactual and actual average annual values. Significance codes: *** $p<0.001$, ** $p<0.01$, * $p<0.05$

Table C.14: Robustness – Hydrological Groundwater Transition Density: State Transition Results, 1991-1996

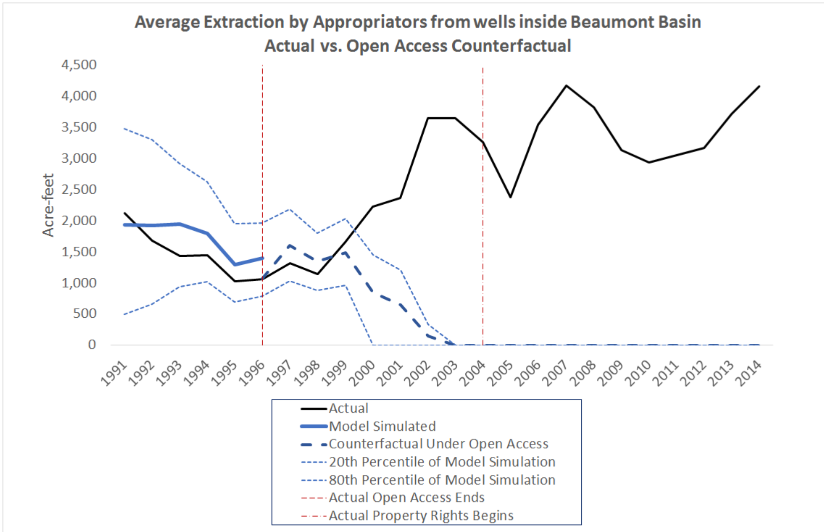
	Dependent variable is depth to groundwater (ft) for:			
	Farmer	Golf/ Housing	Appropriator inside Beaumont	Appropriator outside Beaumont
	(1)	(2)	(3)	(4)
Lagged values of:				
Depth to groundwater (ft)	0.278*	0.930***		
	(0.116)	(0.0228)		
Depth to groundwater inside management zone (ft)			0.480	
			(0.376)	
Depth to groundwater outside management zone (ft)				0.988***
				(0.0115)
Own extraction (acre-ft) X Saturated hydraulic conductivity (ft/day)	0.00352	0.000248***		
	(0.00355)	(0.000073)		
Own extraction in Beaumont (acre-ft) X Saturated hydraulic conductivity (ft/day)			0.0000262	
			(0.000119)	
Own extraction outside Beaumont (acre-ft) X Saturated hydraulic conductivity (ft/day)				0.000000651
				(0.000004)
Neighbor extraction in Beaumont (acre-ft), 0.5 to 1 miles X Saturated hydraulic conductivity (ft/day)			0.000151	
			(0.000104)	
Neighbor extraction in Beaumont (acre-ft), 1 to 2 miles X Saturated hydraulic conductivity (ft/day)				0.0000287
				(0.0000654)
Neighbor extraction (acre-ft), 2 to 3 miles X Saturated hydraulic conductivity (ft/day)	0.000122**			
	(0.0000375)			
Neighbor extraction (acre-ft), 3 to 4 miles X Saturated hydraulic conductivity (ft/day)	0.0000903*			
	(0.0000372)			
Neighbor extraction in Beaumont (acre-ft), 3 to 4 miles X Saturated hydraulic conductivity (ft/day)				-0.000109
				(0.0000986)
Average pump strength outside management zone (gallons per minute)				0.000476
				(0.00144)
Precipitation, Apr-Oct (inches)	-0.00321		3.135	
	(0.692)		(1.787)	
Number of high heat days (> 90 F), Apr-Oct		0.145**	-0.0422	
		(0.0469)	(0.150)	
# Observations	30	25	20	20
# Players	5	5	4	4
p-value (Prob>F)	0.000	0.000	0.017	0.000
RMSE	4.212	3.063	6.173	4.382

Notes: Standard errors in parentheses. Significance codes: *** p<0.001, ** p<0.01, * p<0.05

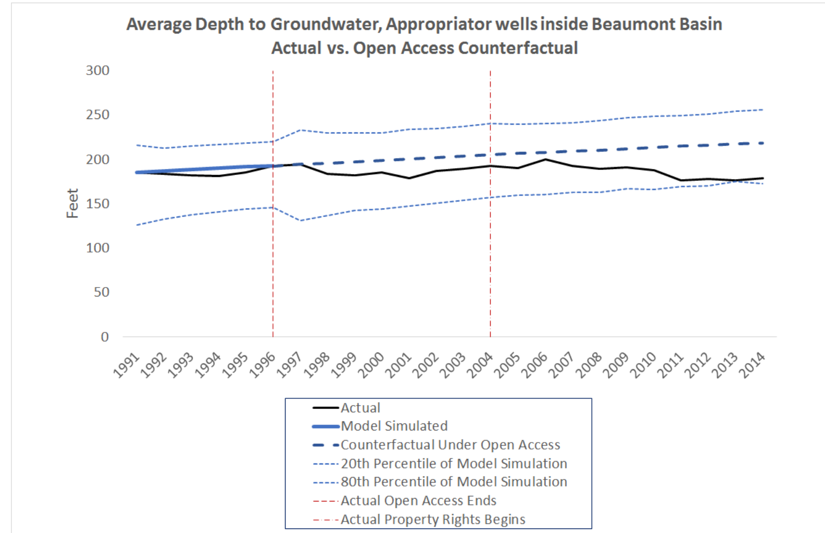
Table C.15: Robustness – Hydrological Groundwater Transition Density: Structural Parameter Estimates

	Appropriators		Farmers	Golf Course /
	Inside Beaumont	Outside Beaumont		Housing Development
Coefficient in Farmer Marginal Revenue on:				
Average crop price (dollars per unit)			-12.093***	
Precipitation, Apr-Oct (inches)			424.750***	
Average crop price (dollars per unit) X High heat days			0.169***	
Average crop price (dollars per unit) X Precipitation (inches)			-0.489***	
Average crop price (dollars per unit) X High heat days X Precipitation (inches)			-0.062***	
Number of wells in Beaumont Basin, squared			-1.59E05***	
Total wells owned before t			16.787*	
Has wells in Beaumont Basin (dummy)			1.59E05***	
Total Average Effect on Farmer Marginal Revenue:				
Average crop price (dollars per unit)			-11.648*	
Precipitation, Apr-Oct (inches)			-71.467	
Number of high heat days (> 90 F), Apr-Oct			1.719	
Coefficient in Golf Course / Housing Development Marginal Revenue on:				
Number of wells X Hydraulic conductivity (feet per day) X High heat days				-0.015***
Number of wells X Hydraulic conductivity (feet per day) X Precipitation (inches)				0.398***
Number of wells X Hydraulic conductivity (feet per day) X High heat days X Precipitation (inches)				0.004***
Number of wells X Log Population of Beaumont				5.266***
Number of wells X Real GDP per capita				1.251***
Number of wells in Beaumont Basin, squared				-35.991***
Planned construction (dummy)				82.311
Total Average Effect on Golf Course / Housing Development Marginal Revenue:				
Number of wells in Beaumont Basin				89.311
Precipitation, Apr-Oct (inches)				297.693
Number of high heat days (> 90 F), Apr-Oct				-2.664
Saturated hydraulic conductivity (feet per day)				4.382
Coefficient in Appropriator Marginal Revenue on:				
Number of high heat days (> 90 F)	-1.118***			
Precipitation (inches)	2.413**			
Weight in Appropriator Per-Period Payoffs on:				
Consumer surplus	1.937***			
Consumer surplus squared	-3.57E-08			
Profits from water sales	1.000 (normalization)			
Coefficient in Water Extraction Cost on:				
Extraction (acre-feet) squared	0.004***	0.005**	0.039***	0.026***

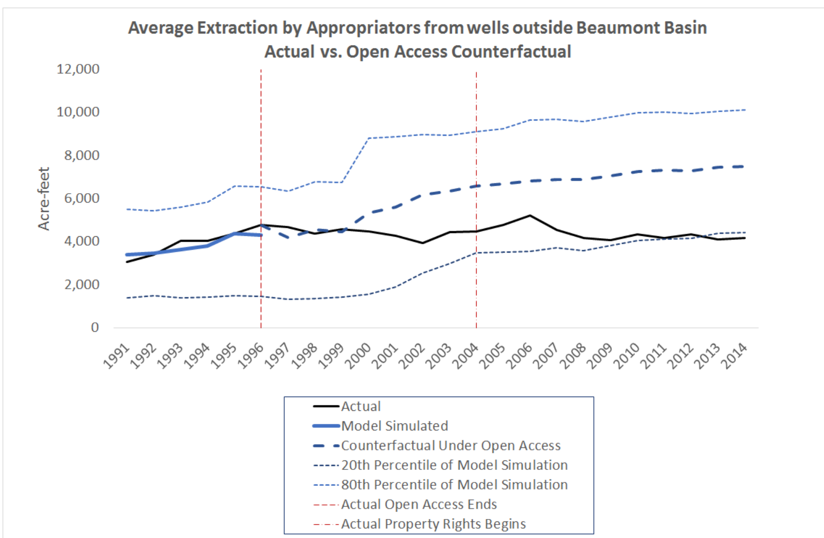
Notes: Per-period payoffs, revenue, marginal revenue, and costs are in dollars. Significance codes: *** p<0.001, ** p<0.01, * p<0.05



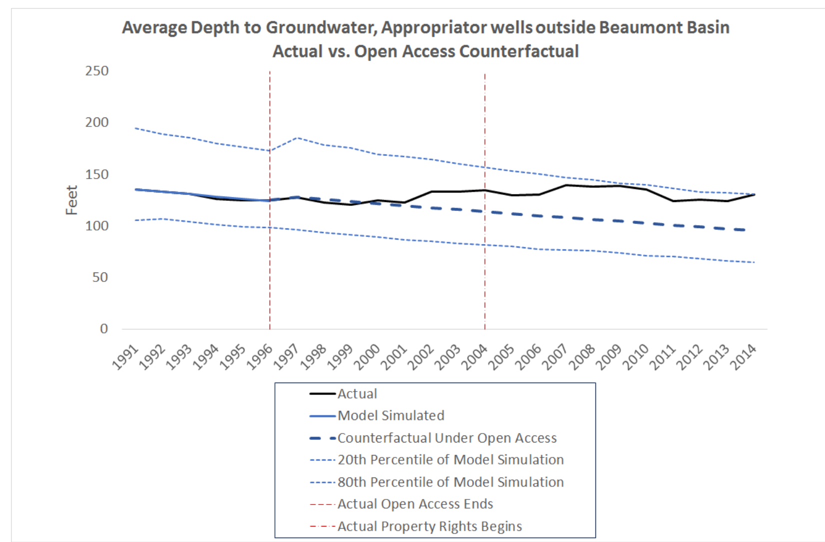
(a) Appropriator Extraction in Beaumont Basin



(b) Appropriator Depth to Groundwater in Beaumont Basin

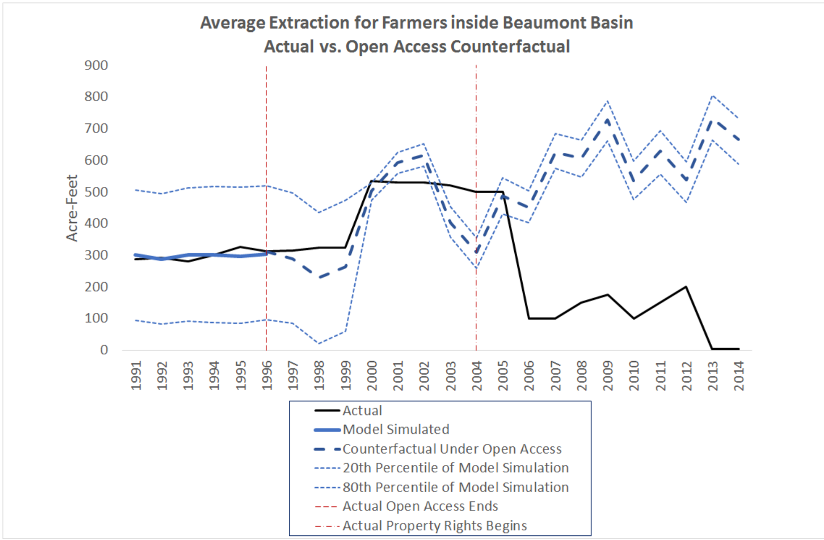


(c) Appropriator Extraction outside Beaumont Basin

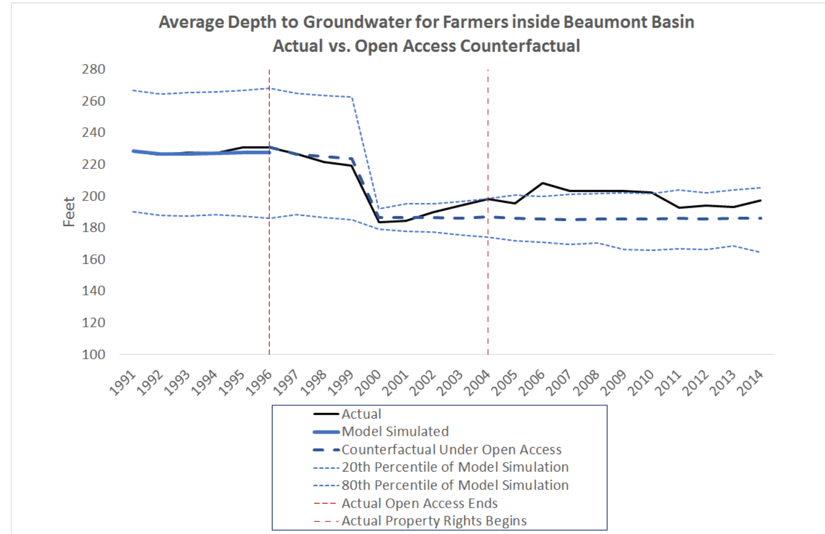


(d) Appropriator Depth to Groundwater outside Beaumont Basin

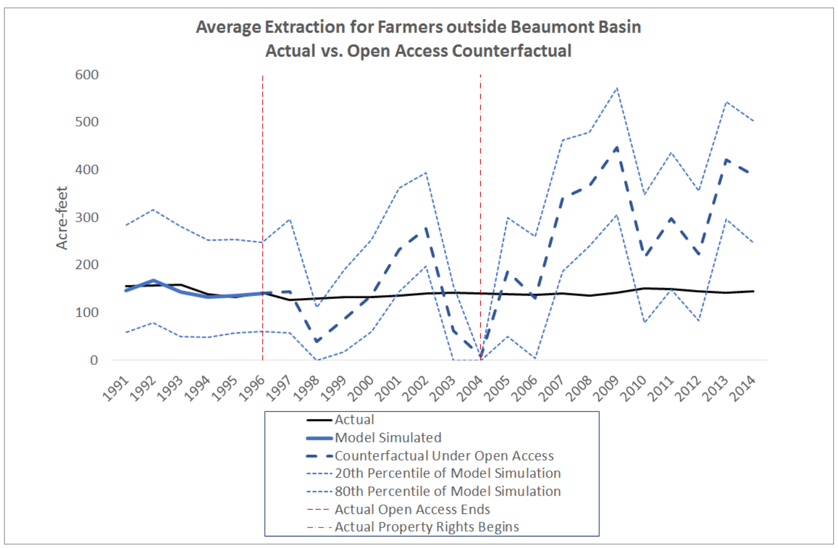
Figure C.13: Robustness – Hydrological Groundwater Transition Density: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Appropriators, 1991-2014



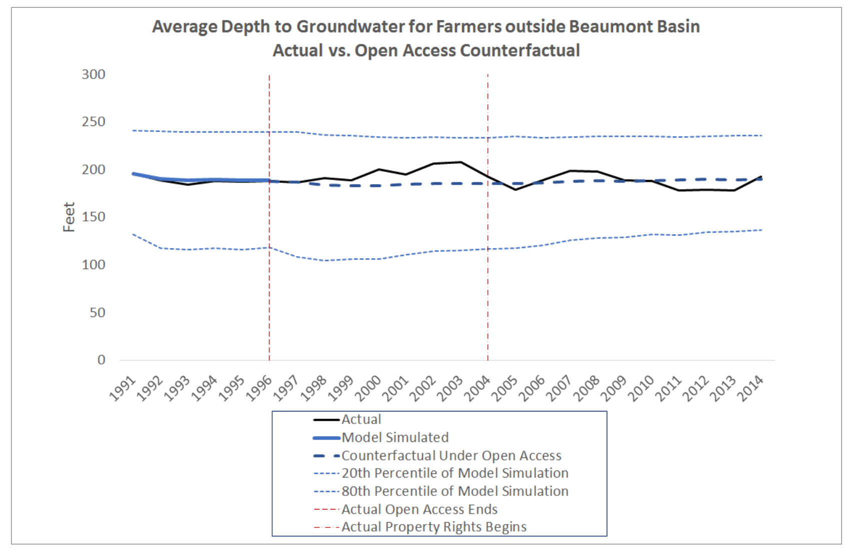
(a) Farmer Extraction in Beaumont Basin



(b) Farmer Depth to Groundwater in Beaumont Basin

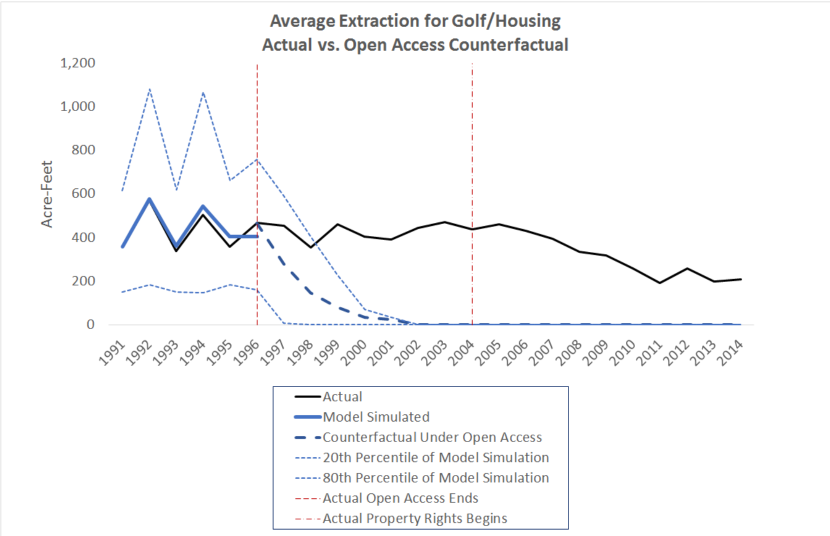


(c) Farmer Extraction outside Beaumont Basin

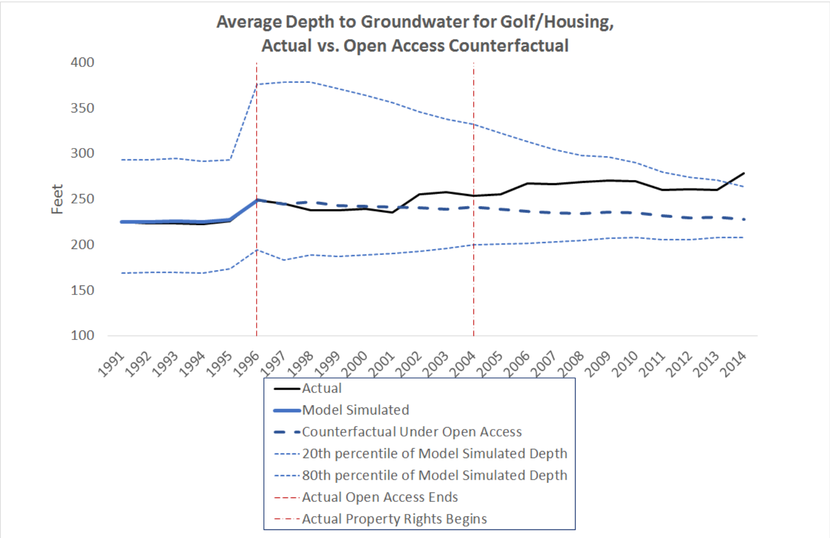


(d) Farmer Depth to Groundwater outside Beaumont Basin

Figure C.14: Robustness – Hydrological Groundwater Transition Density: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Farmers, 1991-2014



(a) Golf Course / Housing Development Extraction



(b) Golf Course / Housing Development Depth to Groundwater

Figure C.15: Robustness – Hydrological Groundwater Transition Density: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights, Golf/Housing, 1991-2014

Table C.16: Robustness – Hydrological Groundwater Transition Density: Open Access Counterfactual vs. Actual Welfare After Institution of Property Rights, 1997-2014

	Average Annual Welfare (dollars)			
	Actual	Open Access Counterfactual	Open Access Counterfactual Minus Actual	Open Access Counterfactual Minus Actual, Bias Corrected
Appropriators				
Beaumont-Cherry Valley Water District	5.3 million	6.1 million	0.8 million***	145.6 thousand
City of Banning	7.0 million	7.8 million	0.8 million***	-431.1 thousand
South Mesa Water Company	3.0 million	3.3 million	0.3 million**	-169.9 thousand
Yucaipa Valley Water District	10.3 million	11.5 million	1.2 million***	-458.4 thousand
Total appropriators	**25.7 million**	**28.8 million**	**3.1 million*** **	**-913.8 thousand**
Farmers in Beaumont Basin				
Murray, Cecil Merle	-23.6 thousand	-13.6 thousand	10.0 thousand	9.7 thousand
Riedman, Fred L. And Richard M.	-37.1 thousand	-27.4 thousand	9.7 thousand	8.3 thousand
Total farmers in Beaumont Basin	**-60.7 thousand**	**-41.0 thousand**	**19.7 thousand*** **	**18.0 thousand*** **
Farmers outside Beaumont Basin				
Francis M Dowling Jr	-7.5 thousand	-2.8 thousand	4.8 thousand	5.2 thousand
Katharina Illy	-23.2 thousand	-16.2 thousand	7.1 thousand	6.6 thousand
Summit Cemetery District	-5.9 thousand	-1.2 thousand	4.7 thousand**	4.4 thousand**
Total farmers outside Beaumont Basin	**-36.7 thousand**	**-20.2 thousand**	**16.6 thousand*** **	**16.1 thousand*** **
Golf Course / Housing Development				
California Oak Valley Golf and Resort LLC	23.0 thousand	13.8 thousand	-9.2 thousand*	-9.6 thousand*
Coscan Stewart Partnership	N/A	N/A	N/A	N/A
Oak Valley Partners	9.1 thousand	0.8 thousand	-8.3 thousand***	-11.0 thousand***
Plantation on the Lake	2.8 thousand	0.2 thousand	-2.6 thousand***	-2.8 thousand***
Sharondale Mesa Owners Association	6.8 thousand	0.1 thousand	-6.7 thousand***	-7.0 thousand***
Total golf course / housing development	**41.7 thousand**	**14.9 thousand**	**-26.8 thousand*** **	**-30.2 thousand*** **

Notes: Welfare is the present discounted value of the entire stream of per-period payoffs over the period 1997-2014. Average annual welfare is welfare divided by the number of years. 'Open Access Counterfactual Minus Actual' is the difference between counterfactual and actual welfare values. Both actual and open access counterfactual welfare are calculated using the parameter estimates from the structural model. Actual welfare is calculated using actual values of actions and states in the data. Open access counterfactual welfare is calculated using model predicted actions and states generated from 100 simulation runs. The standard errors for the open access counterfactual welfare values and for the difference between counterfactual and actual welfare values are calculated using the parameter estimates from each of 100 bootstrap samples. To adjust for the bias of our model relative to the actual data, we subtract the upward bias of the model relative to the actual data, as measured by the difference between our model prediction and the actual data for the respective welfare statistic over the open access period 1991-1996, from our difference between the open access counterfactual and the actual data over 1997-2014; this bias-corrected statistic is a measure of the difference between the open actual counterfactual and the actual data over 1997-2014 over and above any upward bias from the model relative to the actual data. Significance stars next to the difference between counterfactual and actual welfare values denote the significance level of the difference between counterfactual and actual average annual welfare. Significance codes: *** $p<0.001$, ** $p<0.01$, * $p<0.05$

Table C.17: Robustness – Hydrological Groundwater Transition Density: Open Access Counterfactual vs. Actual Social Welfare After Institution of Property Rights, 1997-2014

	Actual	Open Access Counterfactual	Open Access Counterfactual Minus Actual	Open Access Counterfactual Minus Actual, Bias Corrected
	Average Annual Producer Surplus (dollars)			
Appropriator profits	496.1 thousand	1.1 million	570.0 thousand	469.0 thousand**
Farmer profits inside Beaumont Basin	-60.7 thousand	-41.0 thousand	19.7 thousand***	18.0 thousand***
Farmer profits outside Beaumont Basin	-36.7 thousand	-20.2 thousand	16.6 thousand***	16.1 thousand***
Golf course / housing development profits	41.7 thousand	14.9 thousand	-26.8 thousand***	-30.2 thousand***
Total Producer Surplus	**0.4 million**	**1 million**	**0.6 million*** **	**0.5 million** **
	Average Annual Consumer Surplus (dollars)			
Beaumont-Cherry Valley Water District	3.6 million	3.8 million	210.9 thousand***	-152.3 thousand***
City of Banning	4.7 million	5.2 million	539.4 thousand***	-230.0 thousand***
South Mesa Water Company	1.7 million	1.9 million	183.0 thousand***	-102.7 thousand**
Yucaipa Valley Water District	7.1 million	7.6 million	579.7 thousand***	-442.1 thousand*
Total Consumer Surplus	**17.0 million**	**18.5 million**	**1.5 million*** **	**-927.1 thousand*** **
	Average Annual Social Welfare (dollars)			
Social Welfare	**17.5 million**	**19.6 million**	**2.1 million*** **	**-0.5 million**

Notes: Components of social welfare are the present discounted value of the entire stream of per-period payoffs related to each component over the period 1997-2014. Producer surplus is equal to the profits from groundwater extraction summed over all players. Consumer surplus is the consumer surplus faced by each appropriator, and is not weighted by parameters in the payoff function of the appropriator. Social welfare is equal to the sum of producer surplus and consumer surplus. Average annual values of these components are equal to the total value of the component divided by the number of years. 'Open Access Counterfactual Minus Actual' is the difference between counterfactual and actual component values. Both actual and open access counterfactual profits are calculated using the parameter estimates from the structural model. Both actual and open access counterfactual consumer surplus are calculated using the water demand parameter estimates. Actual values are calculated using actual values of actions and states in the data. Open access counterfactual values are calculated using model predicted actions and states generated from 100 simulation runs. The standard errors for the difference between open access counterfactual and actual welfare values are calculated using the parameter estimates from each of 100 bootstrap samples. To adjust for the bias of our model relative to the actual data, we subtract the upward bias of the model relative to the actual data, as measured by the difference between our model prediction and the actual data for the respective welfare statistic over the open access period 1991-1996, from our difference between the open access counterfactual and the actual data over 1997-2014; this bias-corrected statistic is a measure of the difference between the open actual counterfactual and the actual data over 1997-2014 over and above any upward bias from the model relative to the actual data. Significance stars next to the difference between counterfactual and actual values denote the significance level of the difference between counterfactual and actual average annual values. Significance codes: *** p<0.001, ** p<0.01, * p<0.05