Managing Common Pool Resources:
Lessons from Groundwater Resource Extraction in California*

Louis Sears   C.-Y. Cynthia Lin Lawell   Gerald Torres   M. Todd Walter

Abstract

The sustainable management of common pool resources has posed a challenge to natural resource management throughout history and around the world. Groundwater is a critical natural resource whose management is often considered a classic example of a "common pool resource" problem; in addition, its partially nonrenewable nature further confounds sustainable management. In this paper, we draw lessons from our spatial dynamic analyses of groundwater resource extraction in California, where groundwater resources have operated under a de-facto open access environment for much of the state's history. We examine how the institutional arrangements that commonly govern groundwater in California interact with the economic drivers of groundwater usage as well as the hydrology and climate of California to produce socially inefficient groundwater extraction in areas with both growing urban populations and existing agricultural interests. Our analyses use a combination of dynamic optimization, game theory, hydrology, agronomy, legal and institutional analysis, and reduced-form and structural models applied to detailed spatial panel data to examine the effects of these institutions on groundwater resources, agricultural profits, and welfare.

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*Sears: Cornell University; lss34@cornell.edu. Lin Lawell: Cornell University; clinlawell@cornell.edu. Torres: Yale University; gerald.torres@yale.edu. Walter: Cornell University; mtw5@cornell.edu. David Lim provided excellent research assistance. We thank Vic Adamowicz, Victor Aguirregabiria, Emmanuel Asinas, Andrew Ayres, Christina Babbitt, Lint Barrage, Chris Barrett, Panle Jia Barwick, Susanna Berkouwer, Marshall Burke, Cuicui Chen, Peter Christensen, Thom Covert, Sergio de Holanda Rocha, Tatyana Deryugina, Ariel Dinar, Joshua Duke, Levan Elbakidze, Bradley Ewing, Ram Fishman, Todd Gerarden, Matthew Gibson, Ken Gillingham, Todd Guilfoos, Catherine Hausman, Richard Howitt, Irene Jacqz, Gizem Kilic, Sonja Kolstoe, Gabe Lade, Andrea La Nauze, Kira Lancker, Ben Leyden, Shanjun Li, Robert Mendelsohn, Robert Metcalfe, Siwa Msangi, Ishan Nath, Martino Pelli, Ahad Pezeshkpoor, Mathias Reynaert, Timothy Richards, Mani Rouhi Rad, Ivan Rudik, Nick Sanders, Bill Schulze, Rich Sexton, Jeff Shrader, Steven Smith, John Spraggon, Katalin Springel, Garth Taylor, Itai Trilnick, Nick Tsivanidis, Arthur van Benthem, Roger von Haefen, Steve Wallander, Dennis Wesselbaum, Jim Wilen, Matt Woerman, and David Zilberman for detailed and helpful comments. We also benefited from comments from seminar participants at Cornell University; and conference participants at the Association of Environmental and Resource Economists (AERE) Summer Conference, the North American Meetings of the Regional Science Association International (NARSC), the Canadian Resource and Environmental Economics (CREE) Study Group Annual Conference, the Conference celebrating the 25th Anniversary of Douglass North's Nobel Prize in Economics at George Mason University, the Tenth Annual Meeting of the Society for Environmental Law and Economics, the Mid-Continent Regional Science Association (MCRSA) Annual Conference, the Agricultural and Applied Economics Association (AAEA) Annual Meeting, the Northeastern Agricultural and Resource Economics Association (NAREA) Annual Meeting, an Association of Environmental and Resource Economists (AERE) Session at the Western Economic Association International (WEAI) Annual Conference, the workshop on 'Water Pricing for a Dry Future: Policy Ideas from Abroad and their Relevance to California', and the Honorable Mention Bacon Lectureship at the University of California Center Sacramento. We are grateful to Emmanuel Asinas, Cayle Little, Morrie Orang, and Richard Snyder helping us acquire the data. We received funding for our research from Robert R. Dyson; a Cornell University Ching Endowment Summer Fellowship; a Cornell University Institute for the Social Sciences Small Grant; the U.S. Department of Agriculture (USDA) National Institute of Food and Agriculture (NIFA); a Cornell DEEP-GREEN-RADAR Research Grant; a Cornell TREESPEAR Research Grant; the Khaled H. Kheiravar Memorial Scholarship; the Giannini Foundation of Agricultural Economics; and the 2015-2016 Bacon Public Lectureship and White Paper Competition. Lin Lawell and Walter are Faculty Fellows and Torres is a former Faculty Fellow at the Cornell Atkinson Center for Sustainability. All errors are our own.

1 Introduction

Groundwater management is often considered a classic example of a ”common pool resource” problem (Gardner et al., 1990; Ostrom, 2008). 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. When there are multiple users of a common pool resource, 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. 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).

Groundwater has important spatial properties that must be accounted for in both the monitoring of the resource and the design of policies used to manage it. Groundwater aquifers can be hydraulically connected over a large geographical area, allowing the water across property lines in a manner determined by both the physical properties of the aquifer system, and the effects of groundwater pumping and other human activities. These properties then determine the geographic scope of the common pool resource problem (Dasgupta and Heal, 1979; Eswaran and 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; Pfeiffer and Lin, 2012; Lin and Pfeiffer, 2015; Lin Lawell, 2016; Sears et al., 2018; Merrill and Guilfoos, 2018; Sears and Lin Lawell, 2019; Sears et al., 2019, 2023a).

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., 2023a). 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).

Groundwater users extract water under an institutional setting that governs their property rights to the groundwater and affects the constraints they face and the choices they make. A variety of property rights doctrines and institutions governing groundwater have evolved in the western United States. Many more institutions, both formal and informal, are in place in other locations around the world (Sears et al., 2018; Sears and Lin Lawell, 2019; Bertone Oehninger and Lin Lawell, 2021; Smith, 2021).

California's groundwater resources have operated under a de-facto open access environment for much of the state's history. Despite hydraulic connections that explicitly link surface water supplies to groundwater aquifers, groundwater is subject to a different set of rules and regulations, which have over time lead to deterioration in stocks of groundwater in several of the state's most critical regions. In recent years this has created pressure the state's remaining groundwater supplies. A combination of recent public policy and innovations in water infrastructure make it necessary to better understand how groundwater extractors actually operate and react to changes in the institutions governing groundwater resources.

In this paper, we draw lessons from spatial dynamic analyses we have conducted of groundwater resource extraction in California, where groundwater resources have operated under a de-facto open access environment for much of the state's history. We consider groundwater management from a number of perspectives, including profit maximizing farmers and recreational businesses, as well as municipal water districts with mixed objectives, and finally regional regulators or water managers.

In our theoretical spatial dynamic analyses, we use a combination of dynamic optimization, game theory, hydrology, and legal and institutional analysis to provide theoretical predictions regarding the behavior of these different stakeholders, and to define differences in their objectives and how these differences generate variation in their behavior under different sets of governing institutions. In our empirical spatial dynamic analyses, we use empirical data on extraction and depth to groundwater in California under different sets of institutional rules and estimate a combination of structural and reduced-form models to pin down the signs and magnitudes of the effects of these rule changes on individual and social welfare. We make use of individual extraction data from two separate case studies of groundwater regional governance structures in Southern California: the Beaumont Basin Area and the Western Judgment Basins. Furthermore, we also draw on data gathered from groundwater depth monitoring, spatial soil hydrology data, regional economic data, and unique data related to the wells owned by individuals gathered from a set of administrative records.

We examine how the institutional arrangements that commonly govern groundwater in California interact with the economic drivers of groundwater usage as well as the hydrology and climate of California to produce socially inefficient groundwater extraction. We explain the factors that lead to the development of these particular institutions, by examining who these institutions have benefited in practice, and how they can be refined to better serve society as a whole.

2 Background

2.1 Groundwater resources in California

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. At the height of its recent sustained drought, the state declared 21 groundwater basins to be in a state of critical overdraft (California Department of Water Resources, 2016).

California recently experienced its third-worst drought in 106 years (Howitt and Lund, 2014), and in 2021 Northern California endured one of its driest Februarys, which is usually a wetter month, in more than 150 years (Calma, 2021). The hydrologic effects of the drought will take years to recover (U.S. Geological Survey, 2017). From 1960 to the present, there has been significant deterioration in the groundwater level of the Central Valley of California, making current levels of groundwater use unsustainable (Famiglietti, 2014). Figure 1 shows the decline in groundwater levels in California over the years 2011 to 2016.

Groundwater in California constitutes approximately 38 percent of the state's total water supply during an average year. During dry years, groundwater contributes up to 46 percent (or more) of the statewide annual supply, and serves as a critical buffer against the impacts of drought and climate change. Many municipal, agricultural, and disadvantaged communities rely on groundwater for up to 100 percent of their water supply needs. Groundwater extraction in excess of natural and managed recharge has caused historically low groundwater elevations in many regions of California (California Department of Water Resources, 2017a).

Figure 2 presents a map of the principal aquifer systems in California. Groundwater in California is contained in five major aquifers, four of which consist primarily of basin-fill deposits that occupy structural depressions caused by deformation of the Earth's crust. The four basin-fill aquifers are the Basin and Range aquifers, the Central Valley aquifer system, the Coastal Basins aquifers, and the northern California basin-fill aquifers. The fifth major aquifer is the northern California volcanic-rock aquifers (U.S. Geological Survey, 1995).

The Basin and Range aquifers are located in an area that comprises most of Nevada and the southern California desert. Many of these valleys and basins are internally drained; that is, water from precipitation that falls within the basin recharges the aquifer and ultimately discharges to the land surface and evaporates within the basin. Basins might be hydraulically connected in the subsurface by fractures or solution openings in the underlying bedrock, but this is rare. Several basins or valleys may develop surface-water drainage that hydraulically connects the basins, so that groundwater flows between the basins (U.S. Geological Survey, 1995).

The Central Valley aquifer system occupies most of a large basin in central California between the Sierra Nevada and the Coast Range Mountains. The Central Valley is the single most important source of agricultural products in the United States, and groundwater for irrigation has been essential in the development of that industry. The basin contains a single, large, basin-fill aquifer system, the largest such system in the United States (U.S. Geological Survey, 1995).

The Coastal Basins aquifers occupy a number of basins in coastal areas from northern to southern California. Nearly all the large population centers in California are located in these basins. In most of the basins, however, population has grown to such an extent that local groundwater supplies are no longer adequate, and surface water must be transported from distant sources to meet demand. In nearly all basins that contain more than one aquifer, the aquifers are hydraulically connected to some degree. Interior northern California is sparsely populated, and most groundwater demand there is for agricultural irrigation (U.S. Geological Survey, 1995).

The most productive and highly-utilized aquifers in the area are the northern California basin-fill aquifers. In some basins, wells drilled into underlying volcanic rocks might produce large quantities of water. The northern California volcanic-rock aquifers consist of volcanic rocks that yield water primarily from fractures and locally from intergranular spaces in porous tuffs. Because water-yielding zones in these rocks are unevenly distributed, there are more dry holes than wells that yield water; nevertheless, in some areas, wells completed in the volcanic-rock aquifers yield large volumes of water. The northern California volcanic-rock aquifers are relatively unexplored and undeveloped (U.S. Geological Survey, 1995).

2.2 Groundwater management institutions in California

Existing groundwater management in California has been primarily done at the local level. Local groundwater management agencies, special act districts, and court adjudications are the primary institutional arrangements to manage groundwater in the state (Landridge et al., 2016). While the state of California has the legal capacity to preempt local regulations, for the most part it has not done so (Torres, 2012).

Increasing declines in groundwater throughout much of the state and the associated negative impacts prompted the passage of the 2014 Sustainable Groundwater Management Act (SGMA) (Landridge et al., 2016). In 2015, the California Department of Water Resources developed a Strategic Plan to implement SGMA (California Department of Water Resources, 2015). While SGMA is noteworthy for its statewide scope, it leaves much of the regulatory power at the local and regional level. Each groundwater basin is to be managed at the local level by locally-controlled groundwater sustainability agencies (GSAs). Each groundwater sustainability agency is responsible for developing and implementing a groundwater sustainability plan. The California Department of Water Resources' primary role is to provide guidance and technical support to local agencies (California Department of Water Resources, 2015). SGMA empowers GSAs to allocate water among users, but does not alter the common law property rights system that has developed through California's history (Garner et al., 2020).

2.3 Groundwater property rights in California

Groundwater users in California can be divided broadly into individual users, like farmers, who extract water from beneath their own land; and water districts which combine rights to alternative sources (surface water) with appropriated water for use throughout the boundaries of their administrative zones.

Groundwater property rights in California are governed by a dual rights system, in which the primary right to groundwater is given to the owner of land “overlying” the resource, while appropriators may divert surplus supply of water that is unused by the overlying user to beneficial uses outside of the land. In most cases in California, overlying property right owners are farmers using groundwater for agricultural irrigation, and the appropriator is a municipal water district that sells its appropriated groundwater to residential household consumers in their administrative zones (California State Water Resources Control Board, 2017; Babbitt et al., 2018; Bartkiewicz et al., 2006). A third form of property rights, known as prescriptive rights, have evolved under common law through court adjudications in which appropriators show that they have openly and continuously pumped in excess of surplus for at least 5 years under a claim of right (Garner et al., 2020; Babbitt et al., 2018). Disputes involving claims to each of these rights are resolved through court adjudication.

The adjudication process has long been the primary process for defining groundwater rights in California. An adjudication comes about either as a result of disputes over water districts drawing beyond surplus water, or as a mechanism to plan additions to the local water supply, such as imports from outside the adjudicated area (Landridge et al., 2016). Adjudications have been primarily limited to Southern California, where groundwater resources have been historically more heavily used. They have also increased in number with the introduction of imported water from outside the region (Landridge et al., 2016).

Historically, the adjudication process has not followed a clear set of guidelines, and often produces results that do not promote great conservation of groundwater. For example, a key concept in adjudication is the determination of sustainable yield, or the quantity of groundwater that can be sustainably withdrawn in a year, and the existence of overdraft, whether or not current extraction exceeds inflow. In their survey of exisiting adjudication judgments, (Landridge et al., 2016) find that definitions used for each of these terms was not constant across judgments, nor were the methods used to measure them. Furthermore, adjudications do not always involve all users in the area, and may not define water rights for all users in their judgments (Landridge et al., 2016). For example, the Santa Paula Basin judgment in Ventura County defined water rights for some appropriators, but then left their rights junior to overlying users (Landridge et al., 2016).

Another issue is that, when the adjudication process results in a determination of groundwater rights, these rights are frequently based on an average of past production by users. Such an allocation of rights does not account for the possibility of different climate conditions in the future, the condition of the aquifer, or changes in each user’s demand over time (Landridge et al., 2016). While in some cases rights can be bought or sold, this is not always the case. The tendency to allocate rights based on historical use also creates an incentive structure in which users expecting adjudication have an incentive to withdraw more water in the periods leading up to the adjudication process. This is exacerbated by the institution of mutual prescription, which allows appropriators to gain secure rights in the event that they can demonstrate that they have withdrawn beyond the surplus of the overlyers for five years.

The adjudication process is often lengthy and costly for the parties involved. Water litigation is expensive, and some water disputes have lasted for decades (Babbitt, 2020). For example, the Raymond Basin near Los Angeles took seven years for its initial judgment, and then was appealed for an addition five years (Landridge et al., 2016). The West Coast Basin adjudication had a cost of over $5 million (Landridge et al., 2016). In many adjudications, this is not the end of the process either, as parties may re-enter adjudication, or appeal the court's ruling (Landridge et al., 2016). In order to streamline this process California passed regulations AB 1390 and SB 226 in 2015. The bills require that a stipulated judgment be accepted if it is supported by more than 50 percent of all named parties in the adjudication, and if the supporters include users who held title to at least 75 percent of production in the past 10 years. While this may expedite the process, it could also create an incentive to overpump, since it allocates bargaining power to those with a history of high production. It may also disincentivize the participation of a larger group of users, since this makes the process more onerous for the appropriator bringing suit.

As part of the 2014 Sustainable Groundwater Management Act (SGMA), the state has called for the creation of groundwater sustainability agencies (GSAs), which are in large part managed by either individual water districts, or groups of water districts operating in the basin. These groundwater sustainability agencies are empowered under SGMA to allocate groundwater supplies in the basin area, but are not empowered to alter groundwater property rights (Garner et al., 2020). This creates legal risk that allocations defined under SGMA may violate individual property rights claims and be disputed in court (Garner et al., 2020).

In California and the West more generally, initial determinations to assign water rights to landowners were more concerned with encouraging the settlement and productive use of arable land than with allocative or dynamic economic efficiency. Policy-makers only began to consider efficiency of how water was allocated after the surplus of unused land had disappeared (Zilberman et al., 2017).

Schlager and Ostrom (1992) differentiate property rights in common pool resources into operational and collective choice rights. Operational rights include the right to access and withdraw from the common pool. Collective action rights give users the rights to management (the right to regulate of the resource), exclusion (the right to determine who will have access), and alienation (the right to sell or lease the resource). Schlager and Ostrom (1992) argue that the rights to alienation and exclusion are necessary for undertaking long-term investment in the resource, since they guarantee that the owner will capture the benefits from investment.

In California, groundwater within a single basin is a common pool resource in which there are different property rights present. The groundwater sustainability agency has both exclusion and management power within their administrative zone, through its ability to set sustainable yield, and regulate the use of other participants. The water district that is not part of a GSA may lack some of the powers of regulation and exclusion, but due to their scale and the lowering of transaction costs, they have some right to alienation through water transfers. Transaction costs make the rights to exclusion, through adjudication and alienation through water transfer difficult for the individual farmer.

The second dimension through which property rights can be classified is between du jour and de-facto rights (Schlager and Ostrom, 1992). Du jour rights are given by the government, and can be expected to be upheld in court when they are challenged (Schlager and Ostrom, 1992). De-facto rights originate within the users, and can only be enforced by the users, not by the court (Schlager and Ostrom, 1992). Groundwater rights in California, and the inconsistency of their enforcement bears traits of both types of rights. Groundwater rights are state granted rights, and they can be challenged and defined more formally through the process of adjudication (Landridge et al., 2016). However, the process is lengthy, expensive, and perhaps most importantly, due to the inconsistency of rulings throughout history, the criteria that Schlager and Ostrom (1992) use to define du jour rights, that "Right-holder who have de jure rights can presume that if their rights were challenged in an administrative or judicial setting, their rights would most likely be sustained" does not hold (Landridge et al., 2016; Schlager and Ostrom, 1992). Thus, groundwater rights in California have historically lacked the formality of de jour rights.

If individual property rights are difficult to identify and keep track of, and are not economical to enforce, then this makes the right only profitable to exercise through extraction, which is equivalent to open access, where the only property right is extraction in the current period. Thus, even in the case of formal property rights, transaction costs related to the creation and monitoring of property rights may lead to open access management instead of dynamic efficiency (Sweeney et al., 1971).

There are several practical limits to reaching dynamically efficient behavior even with trading of groundwater rights. For example, rights that are transferred between users will shift the location of pumping within the basin, and can thus create spatial pumping externalities for nearby users (Nylen et al., 2017). Permit trading must also be set up with an eye to environmental externalities, as damages from seawater intrusion, or subsidence will not be borne only by the purchaser of a groundwater right, but also throughout the basin (Nylen et al., 2017). Finally, improvements in both reporting of groundwater extraction and basin wide conditions must be improved throughout the state. In order for permits to be sustainably allocated, basin managers must be able to understand the physical conditions governing their domains, and whether or not users are abiding by the basin's regulations (Nylen et al., 2017). Furthermore, in the absence of metering, Wallander (2017) notes that farmers may over-irrigate due to an incomplete understanding of how much water has been applied.

In the case of groundwater in California, the transaction costs related to efficient property right use may in some cases be too high to make them operational at the individual level. In the case of hydraulically connected aquifers spanning more than one user, groundwater flows between plots of land. In addition, there may hydraulic connection between the groundwater aquifer and surface water streams. In this case, identifying one's property right over time is costly at the individual level and prone to error. Making matters worse, once the water flows out of the land underlying the owner's property, the owner's right to use it vanishes. Asserting one's property right by catching an appropriator using beyond their share of surplus water is also difficult, given that monitoring use has not been a requirement for groundwater users. Thus, even in a system of secure property rights, the groundwater user has a strong incentive to use the property right through extraction today, rather than managing it dynamically.

Water trading has historically been viewed with suspicion in California, as smaller extractors fear negative equity effects, and water right holders object to the idea of the auctioning of rights (Zilberman et al., 2017). 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.

3 Lessons from Theoretical Spatial Dynamic Analyses

We first draw lessons from our theoretical spatial dynamic analyses, in which we use a combination of dynamic optimization, game theory, hydrology, and legal and institutional analysis to provide theoretical predictions regarding the behavior of these different stakeholders, and to define differences in their objectives and how these differences generate variation in their behavior under different sets of governing institutions.

Groundwater users face two types of spatial externalities that lead to non-cooperative behavior. The first is a pumping cost externality: withdrawal by one user lowers the water table and increases the pumping cost for all users. The second is a strategic externality: what a farmer does not withdraw today will be withdrawn by other farmers, which undermines the farmer's incentive to forgo current for future pumping. These spatial externalities lead to a divergence between the private trajectory of extraction by players and the socially optimal path (Dasgupta and Heal, 1979; Eswaran and 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; Sears et al., 2018; Merrill and Guilfoos, 2018; Sears and Lin Lawell, 2019; Sears et al., 2019, 2023a).

Policy-makers face a tension between tailoring the rules that govern groundwater management to local conditions, and coordinating management over hydraulically connected resources so as to limit the social cost of spatial externalities (Sears et al., 2019). The cost of uncoordinated management stems from the spatial externalities arising from groundwater resources that span across political boundaries (Dinar and Dinar, 2016). This tension between localized versus coordinated management is a central trade-off in debates over the optimal degree of decentralization in environmental and resource management (Sigman, 2005; Lin, 2010a; Lin Lawell, 2023b,a). Substantial anecdotal evidence suggests that political jurisdictions free ride in the allocation of shared water resources (Gleick, 1993). Olmstead and Sigman (2015) find empirical evidence that countries typically take advantage of opportunities to free ride on other countries in water impoundment and withdrawal decisions. To make optimal spatial management more politically feasible, Pitafi and Roumasset (2009) devise an intertemporal compensation plan that renders switching from the status quo to optimal spatial management Pareto-improving.

Common pool resources that span across jurisdictional boundaries have also been studied extensively in the context of international fisheries. For example, so-called "straddling" fisheries contain stocks of fish that migrate across political boundaries, including the border between two exclusive economic zones (EEZs) of individual countries, where fishing is regulated exclusively by individual coastal countries; and the border between an EEZ and the high seas, where fishing can be done by more remote participants. Much like groundwater, straddling fisheries have important dynamic and spatial dimensions that create tensions between the incentives of individual country regulators and the maximization of social welfare as a whole. The 1995 United Nations Fish Stock Agreement calls for management of straddling fisheries to be done at the regional level. While coastal states may set their own individual total allowable catch levels for the fishery within their EEZ, this level must be compatible with the total level deemed to be sustainable for the entire regional fishery (Henriksen and Hoel, 2011). Research on straddling fisheries has demonstrated the benefits of cooperative management strategies that internalize spatial externalities. Le and Flaaten (2011) compare and find that both the steady state rents and stock of a shared fishery are higher under a Stackelberg game in which a cooperative group of countries acts as a regulatory leader, than they are under a Cournot game in which the group and all other participants simultaneously set regulations. Bjørndal et al. (2004) simulate and compare several cooperative management strategies using a multi-agent dynamic model of the Norwegian spring-spawning herring stock, and find that stable cartel or monopolistic behavior with profit sharing to non-participant agents can provide significantly higher benefits relative to open access.

There is also extensive research on spatial externalities that span across jurisdictional boundaries. Transboundary pollution externalities have been studied in the context of international environmental agreements (Aldy and Stavins, 2010; Karp and Zhao, 2010; Stavins, 2015; Barrett, 2016; Chan et al., 2016; Chen and Zeckhauser, 2018; Zakerinia and Lin Lawell, 2023b,a), and include carbon leakage problems that arise when international climate agreements do not cover all countries of the world (van der Ploeg and Withagen, 2017). List and Mason (2001) use a dynamic model with asymmetric players to explore the whether environmental regulations for transboundary pollutants be carried out locally or centrally. Lin (2010b) develops a spatial econometric approach to measuring pollution externalities. Kakeu and Johnson (2018) analyze information exchange in a model of transnational pollution control in which countries use private information in independently determining their domestic environmental policies. Keiser et al. (2021) discuss environmental regulation for transboundary water pollution. Coria et al. (2021) study interjurisdictional externalities in the context of air pollution control policies. Research around cooperative natural resource and environmental regulations also demonstrates that regulations are most likely to succeed when private abatement and compliance costs are outweighed by the beneficial effects of limiting overproduction on revenues (Espínola-Arredondo and Muñoz García, 2012; Akhundjanov and Muñoz García, 2019).

Lesson 1: There are benefits from coordinated management, but the magnitudes of these benefits depend on a variety of factors, including crop characteristics, crop prices, climate, and hydrology.

In Sears et al. (2019), we present a dynamic game framework for analyzing spatial groundwater management. In particular, we characterize the Markov perfect equilibrium resulting from non-cooperative behavior, and compare it with the socially optimal coordinated solution. As seen in our dynamic game framework, farmers behaving non-cooperatively will overextract water relative to the socially optimal coordinated solution if there is spatial movement of water between patches owned by different farmers. In order to analyze the benefits from internalizing spatial externalities in California, we calibrate our dynamic game framework to California, and conduct a numerical analysis to compare the Markov perfect equilibrium arising from non-cooperative behavior with socially optimal coordinated management.

According to the results of our dynamic game in Sears et al. (2019), the inefficiencies arising from the spatial externality are driven by higher returns on crops, electricity input prices, whether the crop is an annual crop versus a perennial, the level of stock, the climate of the region, and the adjustment costs of fallowing production. As California is a state with diverse regional climates and crops, it faces substantially different groundwater management problems across contexts.[1]

Our results in Sears et al. (2019) indicate that the benefits from coordinated management in California are particularly high when crop prices are high. The benefits from coordinated management in California are also higher when there is an asymmetry between neighboring groundwater stocks and when stock levels are higher. Intuitively, we expect the degree of water extraction to be highest when water is relatively cheap to extract, and when it is likely to be lost to the neighboring plot.

We find in Sears et al. (2019) that years in which winter rainfall is high are also the years in which farmers use water least efficiently and deadweight loss is high, except in the case in which stocks are completely full and equal. Thus, policy-makers should be aware especially of wet years following

[1] This heterogeneity has led to heterogeneous results in the previous literature. For example, in their empirical analysis of how farmers respond to changes in groundwater costs in California using data heavily concentrated in California's Central Valley, Burlig et al. (2020) find that farmers are very price responsive and that their price elasticities of demand for electricity and for agricultural groundwater are large. In contrast, Bruno and Jessoe (2021) find that the price elasticity of demand for agricultural groundwater in the California's Coachella Valley is inelastic.

periods of drought. Our results also show that an extreme drought situation can increase the benefits from coordinated management in California. This is particularly salient for California, which has been experiencing its third-worst drought in 106 years (Howitt and Lund, 2014), and in light of the possibility of extreme drought as a result of climate change. However, we find that within our model, this can be reversed by a corresponding increase in wet years (Sears et al., 2019). Moreover, drought management practices like stumping avocado crops can play an import role in allowing farmers to temporarily halt production of perennials and conserve water in periods when water is most expensive Sears et al. (2019).

In the case of higher value specialty annual crops like strawberries, our results in Sears et al. (2019) show that deadweight loss becomes substantially larger, while in the case of a perennial crop like oranges, walnuts, and avocados, deadweight loss is limited to only a few cases, and behavior in the non-cooperative case aligns with the social optimum. We find that perennials are not invulnerable to strategic behavior though, as almonds, and especially table olives, grown in relatively arid regions induce substantial deadweight losses. Here deadweight loss appears to be dampened by the inability of perennial farmers to adjust seamlessly to changes in the size of the stock, as fallowing forgoes profits in both the present and the following period. We also see that high value crops have a higher marginal revenue of water, and thus can encourage over-extraction relative to the social optimum (Sears et al., 2019).

In addition, our results in Sears et al. (2019) show that fluctuations in commodity prices have an important role in determining the magnitude of these efficiency losses. The role of risk tolerance and price uncertainty has important implications in determining the dynamic behavior of farmers, and thus may affect the sensitivity of deadweight loss to changes in input and output prices.

Finally, we see in the context of the South Coastal region that the physical conditions governing the aquifer's ability to transmit water between users plays an important role in aligning private behavior with socially optimal practices. This result provides support generally for the idea that policies meant to induce sustainable groundwater management should tailored to reflect regional differences in economic and physical conditions. Nevertheless, the efficiency losses due to strategic and spatial considerations indicate that the policies governing management of the resource should be coordinated across regions in which water supplies are hydraulically connected Sears et al. (2019).

Lesson 2: Inefficiencies arise if the jurisdictions of local management agencies are not large enough to internalize spatial externalities.

Spatial externalities may arise not only among individual groundwater users sharing the same aquifer, but also among groundwater water managers whose separate jurisdictions do not each cover an entire aquifer. In Sears et al. (2023a), we develop a model of interjurisdictional spatial externalities in groundwater management. We find that groundwater managers each managing a subset of the plots of land that overlie an aquifer and each behaving non-cooperatively with respect to other groundwater managers will over-extract water relative to the socially optimal coordinated solution if there is spatial movement of water between patches that are managed by different groundwater managers. Thus, in order to achieve the socially optimal coordinated solution, the jurisdictions of local agencies should be large enough to internalize all spatial externalities, so that there are no transboundary issues between jurisdictions.

Our results in Sears et al. (2023a) have important implications for the policy framework created by California's 2014 Sustainable Groundwater Management Act (SGMA), wherein groundwater is managed by local agencies that do not each cover an entire groundwater basin. In particular, as stipulated in the Strategic Plan that the California Department of Water Resources developed in 2015 for the implementation of SGMA, each groundwater basin is to be managed at the local level by locally-controlled Groundwater Sustainability Agencies (California Department of Water Resources, 2015). These local agencies do not each cover an entire groundwater basin; on the contrary, there are many basins in which multiple Groundwater Sustainability Agencies operate. Thus, even if the local agencies under SGMA each internalize the spatial externalities within their jurisdiction, spatial externalities may still exist among local agencies that share the same groundwater basin.

In terms of the allocation of regulatory responsibility between the state and local agencies, the particular allocation for California delineated by 2014 Sustainable Groundwater Management Act (SGMA) and the 2015 Strategic Plan in which each local agency develops its own groundwater sustainability plan and policies, while the state agency provides guidance and technical support to the local agency, has features of reverse conjoint federalism. Under reverse conjoint federalism, the local governments each set their own regulatory standards while the central government aids the local governments in meeting the regulatory standards they each set on their own (Lin, 2010a; Lin Lawell, 2023b,a). Under certain circumstances, reverse conjoint federalism may be the most efficient distribution of regulatory power (Lin, 2010a; Lin Lawell, 2023b,a). Thus, in terms of the distribution of regulatory authority between central and local tiers of government, the 2014 Sustainable Groundwater Management Act may have it at least partially right (Sears et al., 2018).

Nevertheless, neither the 2014 Sustainable Groundwater Management Act (SGMA) nor its 2015 Strategic Plan for implementation may adequately address spatial externalities that may lead to non-cooperative behavior among groundwater users sharing the same aquifer. Local agencies do not each cover an entire groundwater basin; on the contrary, there are many basins in which multiple groundwater sustainability agencies operate. As seen in our model in Sears et al. (2023a), groundwater managers each managing a subset of the plots of land over an aquifer and each behaving non-cooperatively with respect to other groundwater managers will over-extract water relative to the socially optimal coordinated solution if there is spatial movement of water between patches that are managed by different groundwater managers. Thus, in order to achieve the socially optimal coordinated solution, the jurisdictions of local agencies should be large enough to internalize all externalities, so that there are no transboundary issues between jurisdictions. This means that local agencies should each cover an entire groundwater basin, and also that a groundwater basin should not be managed by multiple groundwater sustainability agencies.

Figure 3 presents a map of the jurisdictions of the Groundwater Sustainability Agencies in California. Regions managed by an exclusive Groundwater Sustainability Agency (GSA), which is a GSA that operates in an area in which no other local agency submitted a conflicting notice within 90 days, or in which previous GSA formation overlap has been resolved, are denoted in green. Exclusivity within a basin only applies to the area within a local agency's service area. Exclusive local agencies, which were created by statute to manage groundwater within their respective statutory boundaries, are denoted in yellow. Regions with a non-exclusive GSA or a non-exclusive GSA overlap are indicated in light blue and blue, respectively (California Department of Water Resources, 2017b).

When comparing the jurisdictions of the Groundwater Sustainability Agencies in Figure 3 with the map of the principal aquifer systems in California in Figure 2, it is apparent that local agencies do not each cover an entire groundwater basin; on the contrary, there are many basins in which multiple Groundwater Sustainability Agencies operate. Moreover, the prevalence of regions with a non-exclusive GSA or a non-exclusive GSA overlap, as indicated in light blue and blue, respectively, in Figure 3, show that there are many regions in which multiple local agencies operate.

SGMA stipulates that if a basin with multiple GSAs develops multiple Groundwater Sustainability Plans (GSPs), then a single Coordination Agreement must be submitted with the GSPs to the Department of Water Resources to ensure that GSPs are developed and implemented using consistent data, methodologies, and objectives (California Legal Code, 2019; California Code of Regulations, 2016). On the other hand, Interbasin Agreements, or agreements between adjacent basins, are not required under SGMA (Groundwater Exchange, 2023).

Our results in Sears et al. (2023a) show that interjurisdictional externalities emerged even in a regulated environment with legally binding rules addressing adverse impacts between users, and formalizing common tools and methods to reconcile water budgets, since the methods used to define the jurisdictions (political boundaries, rather than hydrological boundaries in some cases), define the water budgets (single year extraction rather than long term extraction), and adverse impacts (users were somewhat arbitrarily split into groups) limited the benefits delivered by the regulations. SGMA faces similar risks if inter- and intra-basin regulations are designed in this way.

Another spatial externality that is not internalized by either the 2014 Sustainable Groundwater Management Act (SGMA) or its 2015 Strategic Plan for implementation are transboundary issues that may arise between California and Nevada. California's Basin and Range aquifers are located in an area that comprises most of Nevada and the southern California desert, and many of the basins are hydraulically connected. Thus, groundwater managers in California and Nevada may behave non-cooperatively with each other, leading to over-extraction relative to the socially optimal coordinated solution.

Lesson 3: Additional inefficiencies arise if municipal water utilities over-weight consumer surplus relative to water sale profits.

In addition to spatial externalities, a second source of inefficiency that may arise if groundwater users include agricultural, recreational, and municipal users because municipal water utility companies are not profit maximizing organizations, but instead optimize an objective function that considers the interests of consumers in addition to producer profits. If the municipal water utility's objectives do not align with society as a whole, either due to under-weighting, or over-weighting consumer surplus relative to water sale profits, then this too will lead to a divergence from the socially optimal extraction levels (Timmins, 2002).

In order to understand the inefficiencies arising from spatial externalities and the over-weighting of consumer surplus, consider a simple dynamic game model of extraction. In the model there are I players i who all share the same aquifer, and who each extract groundwater for agricultural, recreational, or municipal use. One of these players, denoted as player j, is a municipal water utility that extracts water for sale to its consumers.

A social planner would choose extraction for each of the players i so as to maximize the present discounted sum of producer surplus and consumer surplus over infinite horizon, where producer surplus for each player i is the profit player i receives from groundwater extraction, and consumer surplus is the consumer surplus of the customers of the municipal water utility. The social planner's value function is given by:

$$V_{SP}(x) = \max_{a} \left[\sum_{i \in I} \pi_i(a_i, x_i) + CS(a_j) + \beta E[V_{SP}(x')|a, x] \right],$$

where a represents the vector of extraction choices for each producer and x represents the vector of depth to groundwater for each player. Under the social optimum, the first-order condition for extraction by producer j is given by:

$$\frac{\partial \pi_j(a_j, x_j)}{\partial a_j} + \frac{\partial CS(a_j)}{\partial a_j} + \beta E \left[\sum_{i \in I} \left(\frac{\partial V_{SP}(x')}{\partial x_i'} \frac{\partial x_i'}{\partial a_j} \right) \right] = 0. \tag{1}$$

The social planner considers the marginal effect of extraction on the current period sum of the profits of all players and consumer surplus as well as on the continuation value of the future sum of the profits of all players and consumer surplus in future periods derived from extraction by each of the players. Assuming that extraction has non-negative effects on depth to groundwater across producers, and assuming that the social planner's value function is non-increasing in depth to groundwater for each player, this marginal effect on the continuation value can be assumed to be non-negative. In addition, the weighting of the effect on producer profits and consumer surplus in the present period is equalized. We show this marginal condition in Figure 4, which plots the social welfare frontier from extraction at well j, which is made up of present period payoffs and discounted future period continuation value. Thus the social planner trades off future benefit for current period profits by extracting groundwater, which is graphically represented as tracing the frontier from the bottom right to the top left. The social planner then chooses the point on the frontier that reaches the highest social welfare isoline. The social welfare isoline balances the present period payoffs, made up of the sum of j's producer surplus and consumer surplus equally with discounted future period continuation value.

In contrast to the social optimum, now consider the decision of agent j representing the water company in an open access dynamic game. To isolate the spatial externality, let's first assume that municipal water company j weighs consumer surplus equally with producer profits (so that there is no inefficiency from over- or under-weighting consumer surplus) but does not account for any spatial externalities. In other words, let's assume the municipal water company j weights consumer surplus and producer profits in the same way a social planner would, but, unlike a social planner, does not account for either the effect of other players on its own payoffs, nor the effect of its own decisions on the payoffs and actions of other players. Agent j's value function can then be written as:

$$V_j(x) = \max_{a_j} \left[\pi_j(a_j, x_j) + CS(a_j) + \beta E[V_j(x^{'})|a_j, \sigma_{-j}, x] \right], \tag{2}$$

where σ_{-j} is the strategy of all other players.

Then, assuming that there are no spatial externalities so that the value function is only directly affected through the player's own depth to groundwater state, the first-order condition can be written as:

$$\frac{\partial \pi_j(a_j, x_j)}{\partial a_j} + \frac{\partial CS(a_j)}{\partial a_j} + \beta E \left[\sum_{i \in I} \left(\frac{\partial V_j(x^{'})}{\partial x_i^{'}} \frac{\partial x_i^{'}}{\partial a_j} \right) \right] = 0. \tag{3}$$

We see that the term representing the marginal effect on continuation value now only contains the private continuation value for player j, and not the effect on the continuation value for all other players in the game. Thus the player now equates marginal present period payoffs with the marginal effect on future discounted private payoffs. Graphically, in Figure 5, we represent this by having the player now choose the point on the production frontier that reaches the highest private welfare isoline. The private welfare isolines are flatter than the social welfare line, representing the fact that the private welfare function only considers the impact of extraction on future private payoffs, and not the payoffs of all players. Thus we find that this point lies on a lower social welfare isoline and generates deadweight loss. The deadweight loss can be measured graphically as the difference in the intercepts of the social welfare isolines that cross the two points in the figure. We term this the spatial externality effect in our model.

Next, consider the agent j's decision when we allow consumer surplus to be weighted differently than profits. In theory, consumer surplus can be weighted above or below the value of producer profits. Let ω represent the weight of consumer surplus in j's payoff function. Then the first-order condition now becomes:

$$\frac{\partial \pi_j(a_j, x_j)}{\partial a_j} + \omega \frac{\partial CS(a_j)}{\partial a_j} + \beta E\left[\sum_{i \in I}\left(\frac{\partial V_j(x^{'})}{\partial x_i^{'}}\frac{\partial x_i^{'}}{\partial a_j}\right)\right] = 0. \tag{4}$$

In Figure 6, we show the case in which $\omega > 1$. Here the slope of the private welfare isoline is flatter still. This is due to the fact that losses in present period consumer surplus are weighted more highly in the private payoff function. The effect of current period extraction on future payoffs goes only through the channel of extraction costs, which affect producer profits. Therefore the weighting of this term does not change. We see then that when consumer surplus is over-weighted, the deadweight loss grows. This effect is then termed the consumer surplus weighting effect.

Property rights may indirectly remedy these inefficiencies. Consider the case in which each player is allocated S_i a stock of property rights which they can carry from period to period, but never exceed in extraction. Suppose further that these rights can be freely traded at a market price of P_S. Then the value function now becomes:

$$V_j(x, S_j) = \max_{a_j}\left[\pi_j(a_i, x_i) + \omega CS(a_j) - P_S z_j + \beta E[V_j(x^{'}, S_j^{'})|a_j, z_j, \sigma_{-j}, x, S]\right], \tag{5}$$

where z_j represents the number of rights purchased from other players. Thus:

$$S_j^{'} = S_j - a_j + z_j. \tag{6}$$

The first-order conditions are then:

$$\frac{\partial \pi_j(a_j, x_j)}{\partial a_j} + \omega \frac{\partial CS(a_j)}{\partial a_j} + \beta E\left[\sum_{i \in I}\left(\frac{\partial V_j(x^{'}, S_j^{'})}{\partial x_i^{'}}\frac{\partial x_i^{'}}{\partial a_j}\right) - \frac{\partial V_j(x^{'}, S_j^{'})}{\partial S_j^{'}}\right] = 0. \tag{7}$$

$$-P_S + \beta E\left[\frac{\partial V_j(x_j^{'}, S_j^{'})}{\partial S_j^{'}}\right] = 0. \tag{8}$$

Combining these gives us the single condition:

$$\frac{\partial \pi_j(a_j, x_j)}{\partial a_j} + \omega \frac{\partial CS(a_j)}{\partial a_j} + \beta E\left[\sum_{i \in I}\left(\frac{\partial V_j(x^{'}, S_j^{'})}{\partial x_i^{'}}\frac{\partial x_i^{'}}{\partial a_j}\right)\right] - P_S = 0. \tag{9}$$

This then counteracts the effect of the spatial externality. Nevertheless, if there is spatial heterogeneity, and the size of the spatial externality varies across players, then no single traded price can fully mitigate the spatial externality for all players. Neither does this directly correct for consumer surplus over-weighting. Thus, even in a functioning water market we should still expect to see the effect of these two sources of inefficiency.

4 Lessons from Structural Model of Dynamic Extraction Game

4.1 Empirical setting

We next draw lessons from structural empirical spatial dynamic analyses we have conducted in Sears et al. (2023d), Sears et al. (2023c), and Sears et al. (2023b) of groundwater resource extraction in the Beaumont Basin area of Southern California.

For much of its history, groundwater was the only source of water in the Beaumont Basin area, and during the 20th century the elevation of the water table declined by over 100 feet due to overdraft (Rewis et al., 2006). The Beaumont Basin provides groundwater to a mix of farmers, recreational users (golf courses and housing developments who use water for landscaping), and municipalities in the area, including the cities of Banning, Beaumont, Calimesa, and Yucaipa. We estimate our structural models using a large, detailed, and comprehensive spatial user-level panel data set we have collected and constructed from administrative 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.

In Sears et al. (2023d) and Sears et al. (2023c), 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. The parameters we estimate in Sears et al. (2023d) and Sears et al. (2023c) are structural parameters from the open access equilibrium under different equilibrium assumptions (Markov perfect equilibrium and moment-based Markov equilibrium, respectively). We use our parameter estimates in Sears et al. (2023d) 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 different groundwater extractors in our empirical setting. We use our parameter estimates in Sears et al. (2023c) analyze how players respond to counterfactual changes in the rules governing extraction, the incentives of players, the hydrology of the system, and the climate and economy of the region; and to measure long-run welfare implications of several of the factors affecting the efficiency of groundwater use in California.

In Sears et al. (2023b), we model a dynamic game among groundwater users under quantified 8property rights in which players extract groundwater and import outside water to a group of small groundwater basins. We estimate parameters in the payoff functions by taking advantage of variation in the extraction and water import decisions across a group of municipal water companies, farmers, and other users in the Beaumont Basin in Southern California over a 10-year period following the institution of quantified property rights. We use these parameters to simulate counterfactuals to evaluate the welfare impact of the property rights regime, and to understand the factors either amplified or diminished the impact of the program.

Our data set includes all the groundwater users in the Beaumont Basin over the years 1991-2014. 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.

Figure 7 shows the adjudicated boundaries of the Beaumont Basin following 2004. As is clear in the map, the adjudication 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 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 build on the literature on dynamic structural econometric models,[2] and in particular on the literature on structural econometric models of dynamic games. Most structural econometric models of dynamic games assume a Markov perfect equilibrium in which players maximize their present discounted value based on expectations about the evolution of the 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; Dearing and Blevins, 2021).[3] In Sears et al. (2023d), we apply the structural

[2]Dynamic structural econometric models have been applied to bus engine replacement (Rust, 1987), nuclear power plant shutdown decisions (Rothwell and Rust, 1997), retirement (Iskhakov, 2010), water management (Timmins, 2002), air conditioner purchase behavior (Rapson, 2014), wind turbine shutdowns and upgrades (Cook and Lin Lawell, 2020), copper mining decisions (Aguirregabiria and Luengo, 2016), long-term and short-term decision-making for disease control (Carroll et al., 2023a), the adoption of rooftop solar photovoltaics (Feger et al., 2020; Langer and Lemoine, 2018), supply chain externalities (Carroll et al., 2023b), vehicle scrappage programs (Li et al., 2022), urban travel demand (Donna, 2021), vehicle ownership and usage (Gillingham et al., 2021), agricultural productivity (Carroll et al., 2019), environmental regulations (Blundell et al., 2020), organ transplant decisions (Agarwal et al., 2021), hunting permits (Reeling et al., 2020), agroforestry trees (Oliva et al., 2020), the spraying of pesticides (Yeh et al., 2023; Sambucci et al., 2023), electric vehicles (Hu et al., 2022), forest management (Wu et al., 2023), the electricity industry (Cullen, 2015; Cullen et al., 2017; Weber, 2019), and deforestation (Araujo et al., 2020).

[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, 2023), and to the decision to wear and use glasses (Ma et al., 2023). 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, 2020), ethanol investment (Yi and Lin Lawell, 2023b,a), and preemption (Fang and Yang, 2023).

econometric model of a dynamic game that was developed by Bajari et al. (2007). This model has also been applied to the cement industry (Ryan, 2012; Fowlie et al., 2016), the world petroleum market (Kheiravar et al., 2023), the production decisions of ethanol producers (Yi et al., 2023), migration decisions (Rojas Valdés et al., 2018, 2023), the global market for solar panels (Gerarden, 2023), calorie consumption (Uetake and Yang, 2018), the digitization of consumer goods (Leyden, 2019), and climate change policy (Zakerinia and Lin Lawell, 2023b).

In our dynamic game, each player i chooses its action(s) a_i in each year t: in our open access dynamic games in Sears et al. (2023d) and Sears et al. (2023c), the action variable a_i is groundwater extraction; in our dynamic game following the institution of property rights in Sears et al. (2023b), the actions a_i include groundwater extraction, well drilling, artificial recharge, and imported filtered water sales. The per-period payoffs for each player i depend on the player's type (or use) j (i.e., farming, recreational, municipal), the player's action a_i, and the publicly observable state variables x_i. The state variables x_i include depth to groundwater, saturated hydraulic conductivity (which measures the ability of sediments or rocks to transmit water (Fryar and Mukherjee, 2021)), a vector of prices, and weather conditions. Each player i of type j chooses its action(s) a_i 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:

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

where 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.

To estimate the parameters for the open access dynamic game in Sears et al. (2023d) and for the dynamic game following the institution of property rights in Sears et al. (2023b), 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 a model of residential water demand, policy functions $\sigma_i(x)$ for each player type, and state transition densities for depth to groundwater. In the second step, we forward simulate estimates of the value function at a set of states under 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).

Finding a single 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. In Sears et al. (2023d), 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. The crucial mathematical assumption to be able to estimate the parameters in the payoff function is that, even when multiple equilibria are possible, the same equilibrium is always played.

Our estimation design in Sears et al. (2023c) assumes that observed behavior in the dynamic game is consistent with a moment-based Markov equilibrium, in which knowledge of the state space is limited to the private state and the distribution of the states of all other players. We then analyze how players respond to counterfactual changes in the rules governing extraction, the incentives of players, the hydrology of the system, and the climate and economy of the region. This allows us to measure long-run welfare implications of several of the factors affecting the efficiency of groundwater use in California.

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, degree 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.

<u>Lesson 3':</u> Municipal water utilities tend to over-weight the consumer surplus of their customers relative to a social planner problem in which consumer and producer surplus are weighted equally.

In Sears et al. (2023d), 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, our structural parameter estimates in Sears et al. (2023d) show that, for municipal water utilities, groundwater extraction decisions and the price they generate in our model are not strict profit maximizing decisions. Instead, a significant weight is placed the benefits generated for customers. Similar to Timmins (2002), we find water districts tend to over-weight 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 in Sears et al. (2023d) show that municipal water districts on average value \$1 in consumer surplus twice as much as they do \$1 in 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 (Sears et al., 2023d).

In Sears et al. (2023c), we similarly find that consumer surpus weighting created significant social welfare losses (around $7 million per year during our sample period) .

Lesson 4: Quantified property rights can prevent a significant decline in groundwater stock both in the regulated basin and in neighboring basins.

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 in Sears et al. (2023d). 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 and transition densities for depth to groundwater. 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. 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.

According to our results in Sears et al. (2023d), 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 Figures 8-9 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 in Sears et al. (2023d) 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 (Figures 8 and 9). 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 the 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 by golf courses and housing developments under the counterfactual scenario of continued open access. 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 (Sears et al., 2023d).

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. Under open access, farmers facing lower groundwater stocks may race to extract water before the groundwater stock run out (Sears et al., 2023d).

Thus, our results in Sears et al. (2023d) show that, in combination with the implementation of aqueducts carrying imported water used for artificial managed recharge of the Beaumont Basin, the property rights system helped to stabilize the stock of groundwater in the basin, and prevented a significant shift in extraction regionally.

The results of our counterfactual analysis in Sears et al. (2023d), which measure how groundwater pumping would have developed across space in the absence of the property rights regime, contrast 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, thereby preventing a shift in groundwater extraction to wells outside of Beaumont. These policies thus also had a positive spillover effect on the level of groundwater stocks at neighboring basins. Our work then shows the important role that these policies play in not only maintaining the stock inside the Beaumont Basin, but also at other basins in the region.

Lesson 5: Property rights induce changes in the behavior of groundwater extractors, but the initial welfare gains from quantified property rights can be relatively small.

Our welfare results in Sears et al. (2023d) show that the gains from instituting quantified property rights through adjudication were modest and statistically insignificant. For municipal water districts and farmers inside Beaumont Basin, welfare gains from the imposition of property rights and imported water, relative to a counterfactual of continued open access, were not statistically significantly different from 0. Moreover, social welfare gains from the imposition of property rights and imported water, relative to a counterfactual of continued open access, were not statistically significantly different from 0 either.

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 is important to note that the regulation we consider in Sears et al. (2023d) 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 weaken, 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. Subsequent research has suggested that these results may not incorporate important factors which 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.

Lesson 6: Property rights design affects groundwater extraction and other behavior, but is constrained by California's legal institutions.

Our results in Sears et al. (2023b) suggest that there are important practical limitations on the effectiveness of property rights systems that derive from differences in how California treats the water rights of appropriators and overlying rights holders. In Sears et al. (2023b), we examine behavior in the Beaumont Basin in the years following the institution of property rights and estimate a structural model of extraction, well drilling, and water importing. Under the adjudication groundwater extractors could trade, and store water rights. They could also add to their water rights by purchasing imported water and using it for artificial recharge of the basin.

A key advantage of tradable permit schemes is the idea that under transaction costless trading, initial allocation does not matter for efficiency, and water rights can be grandfathered to players to induce their cooperation (Montgomery, 1972; Stavins, 1995, 1998). As is clear from the limited amount of water rights trading, there appear to have been significant transaction costs, and thus we would expect for initial allocation to impact efficiency. Our counterfactual analysis of a scenario in which trading is curtailed showed little impact on social welfare, an unsurprising result given the volume of trading observed. When we alter the initial allocation of water rights, so that they are allocated equally among players, we find that there is a substantial impact on behavior of players. Appropriators extract more on average and social welfare decreased slightly compared to the baseline. This suggests that the allocation based on historical extraction was a slight improvement over an equal allocation regime in the context of limited trading. Thus, there was indeed heterogeneity in the profitability of extraction in the Beaumont Basin region among these players. Avoiding grandfathering then, and auctioning water rights, would be expected to induce additional social benefits. Importantly avoiding using historical extraction as a basis for determining the allocation of water rights also would prevent players from raising their extraction under open access in the hope of gaining additional water rights in the future under an adjudication. If grandfathering is indeed necessary for a property rights regime to be accepted, then watermasters must work to limit transaction costs to trading. This can happend through expanding the scope of the market to include a larger number of participants, and acting as a broker between players.

A key finding of Sears et al. (2023e) was that the Beaumont Basin adjudication influenced the extraction behavior of players but had only a modest impact on social welfare. A key question from that analysis was whether the market for water pumping rights was what influenced extraction, or whether the advent of imported water in the region was the true cause. Our results in Sears et al. (2023b) provide substantial evidence that the property rights regime did influence the actions of players in the region, even after accounting for the impact of imports on the stock of groundwater. However, the evidence from our paper points to the limitations that market based mechanisms face in confronting groundwater management in California, in particular legal, spatial, and technological constraints.

Market mechanisms rely upon the transferability of permits for a resource to promote trading and allocate extraction of the resource to the use that is most beneficial (Blomquist, 2020). However, our case study Our in Sears et al. (2023b) shows that trading was not prevalent between users, and that marginal payoffs from extraction varied widely across users. This points to the legal constraints placed on transferability across players with different types of water rights. While such transfers were allowed in Beaumont, they required appropriators to extend service connections to overlying users. Beyond the legal constraints, the relatively small geographic scope of the adjudication and the water rights system also likely limited the amount of water rights trading between appropriators. Groundwater regulation under SGMA is done at the local level, and will also likely face this obstacle.

The significant amount of artificial recharge and water importing done by players in the dynamic game suggests that the water rights system did create a market signal for the value of groundwater. We see for example that when water rights allocation was taken away for recharge, that players adjusted their extraction in the Beaumont Basin in order to conserve water rights for future years, suggesting that the water rights were indeed scarce. This indicates that players did expect to be able to capture their water rights in future years, and thus that they were dynamically optimizing. However, the large gap between the price players were willing to pay for imports, and the relatively low value of current groundwater extraction point to the expectations players have about the rising cost of imports in the future, and the political and legal constraints they may face in the present. While it may indeed be efficient to continue paying for any available water imports in the present, it would also be more efficient to raise prices and signal to consumers the high long term cost of water, which would help to better balance out consumption over the long term. Raising prices should be done with an eye to equity so that rising prices do not place an undue burden on low income households (Cardoso and Wichman, 2021).

Lesson 7: Under open access there is little incentive for dynamic optimization, and extractors care little for the level of groundwater stock outside their own land.

In Sears et al. (2023c) we estimate a structural model of open access groundwater extraction in the Beaumont Basin using an alternative concept for equilibrium taken from (Ifrach and Weintraub, 2017). Using this so called, "Moment-based Markov Equilibrium (MME)" approach allows us to re-solve full versions of the dynamic game and perform long-run counterfactual simulations. This means that we can measure the full value of changes to assumptions including any adjustments that players make to their strategies in response. In this paper we look at several measures of how players value the level of groundwater stock both near their own well, and in the area in general. We do this by allowing players to track levels of depth to groundwater at their well, and as an average of all wells in the game.

We then simulate counterfactuals in which we eliminate consumer surplus weighting, spatial flows of groundwater, and dynamic optimization. While we once again find that consumer surpus weighting created significant social welfare losses (around \$7 million per year during our sample period) we do not find large effects from spatial externalities or dynamic optimization. This suggests that players do not alter their behavior dramatically to account for different expectations about the level of stock throughout the system. Further, they act in a way that is difficult to distinguish from simple profit or payoff maximization in the current period. This is consistent with a model of open access in which players do not perceive present period actions as having a large impact on future payoffs.

This is further buttressed when we examine the full value functions of players over their state space. We estimate a fixed effects model in which we control for time invariant differences across players, and regress the value function as a dependent variable on depth to groundwater both at wells owned by the player and on the average across all wells in the game. We first estimate separate models for each year in our finite period sample, and then pool data within each group of players and include player-year dummy variables. Looking first at appropriators that the sign for own depth to groundwater is negative and significant across basins. The effect decreases over time in each case and is significantly larger at wells outside the Beaumont Basin, averaging around \$12.6 thousand per foot at wells outside Beaumont and \$1.6 thousand per foot at wells inside Beaumont. Individual year results suggest a positive but insignificant sign for average depth. Pooling all observations produces a significant results of around \$205 per foot. For farmers we find that own depth has a negative and significant sign, and produces an average of only \$63 dollars. average depth again has no effect as results show a precisely estimated 0 value. For golf courses and housing developments we find an own well depth effect that is consistently negative and averages just under \$200 per foot. For average depth we find generally positive results that diminish over time before reaching a value of 0 in the final year of the model. This suggests that for these players the primary effect on welfare for this variable comes through its effect on expected future payoffs.

Finally, we leverage our MME modeling approach to capure a measure of the value of information to players. We simulate an alternate version of the MME dynamic game while providing individual players with access to the full state vector over which they can form their expectations of the state transition. We can then compare our welfare results for players with those obtained values under a Markov Perfect Equilibrium from Sears et al. (2023d), and with the welfare values under our baseline MME for different types of players.

Our results in Sears et al. (2023c) suggest that players would not benefit from additional information in this case. Welfare values were very close to what we obtained in our baseline, as were the values we found in our open access model. This is consistent with our finding that players cared little for the future value of the stock, and thus would do little to change their behavior in response to more information. It suggests that information provision in cases like open access groundwater basins may not be particularly valuable, unless it is wedded with policies that help to internalize social damages from groundwater extraction.

5 Lessons from Empirical Model of Interjurisdictional Externalities

We also draw lessons from our reduced-form empirical spatial dynamic analysis in Sears et al. (2023a).

In Sears et al. (2023a), we use a detailed spatial data set to analyze and estimate interjurisdictional spatial externalities in groundwater management in California under the policy framework created by the 2014 Sustainable Groundwater Management Act (SGMA). In particular, we use data gathered as part of the 1969 Western Judgment in San Bernardino and Riverside counties to estimate the share of externalities internalized when a common pool of groundwater is managed under multiple regulatory frameworks. We then estimate the effects of policy and spatial dynamics on extraction using a panel dataset covering the years 1960-2016 that we constructed from handwritten hard-copy historical records.

We focus our empirical analysis in Sears et al. (2023a) on three basins that were adjudicated under the 1969 Western Judgment due to the interdependency of groundwater flows: San Bernardino Basin, Riverside Basin, and Colton Basin. Figure 10 maps these 3 basins. San Bernardino Basin is upstream, while Riverside Basin and Colton Basin are downstream.

San Bernardino Basin, Riverside Basin, and Colton Basin are part of the Coastal Basins aquifers, which occupy a number of basins in coastal areas from northern to southern California. Nearly all the large population centers in California are located in the Coastal Basins aquifers. In most of the basins, however, population has grown to such an extent that local groundwater supplies are no longer adequate, and surface water must be transported from distant sources to meet demand. In nearly all basins that contain more than one aquifer, the aquifers are hydraulically connected to some degree. Interior northern California is sparsely populated, and most groundwater demand there is for agricultural irrigation (U.S. Geological Survey, 1995; Sears et al., 2018).

The 1969 Western Judgment set up separate upstream and downstream systems of governance. Upstream in the San Bernardino Basin, groundwater users are divided into two groups: plaintiffs and non-plaintiffs. Each plaintiff faces an individual limit to their groundwater extraction, while non-plaintiffs as a group face an aggregate limit. In particular, each plaintiff is given an individual annual adjusted right based on extraction levels measured between 1960 and 1963, and its groundwater extraction is limited to a 5-year total extraction of 5 times its adjusted right. Non-plaintiffs as a group are limited to a 5-year total extraction of 5 times the average annual base period extraction of 165,407 acre-feet per year, which is based on group extraction between 1960 and 1963 (Landridge et al., 2016).

Users in the downstream Colton Basin are divided into groundwater users who put the water to use in the San Bernardino Valley, and those who put it to use outside of the San Bernardino Valley. Users inside the San Bernardino Valley do not face any groundwater extraction limits, except in the case that average groundwater stock measurements at three reference wells falls below 1963 groundwater levels. Then replenishment must be provided. Users outside the San Bernardino Valley as a group are limited to 5-year totals of 5 times average annual totals of 3,349 acre-feet, and to annual limits of 120 percent of this total (Landridge et al., 2016).

Users in the downstream Riverside Basin within San Bernardino County (Riverside North) are also divided into users who use the water in the San Bernardino Valley, and those who use it outside of the San Bernardino Valley. Users inside the San Bernardino Valley do not face any groundwater extraction limits, except in the case that average groundwater stock measurements at three reference wells falls below 1963 groundwater levels. Then replenishment must be provided. Users outside the San Bernardino Valley as a group are limited to 5-year totals of 5 times average annual totals of 20,191 acre-feet, and to annual limits of 120 percent of this total (Landridge et al., 2016).

Users in the Riverside Basin within Riverside County (Riverside South) as a group are limited to 5-year totals of 5 times the average annual totals of 30,044 acre-feet, and to annual limits of 120 percent of this total (Landridge et al., 2016).

The split regulation under the 1969 Western Judgment is broadly analogous to policies implemented under the 2014 Sustainable Groundwater Management Act (SGMA) by multiple sustainability agencies in a single basin. The regulations under the 1969 Western Judgment were coordinated as part of a single judgment, but allowed users to operate under different regulations based on their location and the function of their extraction. The fact that groups of extractors in Colton and Riverside North were effectively left unregulated also provides an example of a basin in which some extractors internalize only their own extraction (Sears et al., 2023a).

<u>Lesson 2':</u> Fragmented regulation may lead to inefficient pumping.

Our empirical results in Sears et al. (2023a) indicate that when a single hydraulically connected groundwater system is managed under several different sets of regulations, there are statistically significant differences between groundwater extractors in terms of the share of spatial externalities that are internalized under fragmented regulation. We also find significant differences across space and between regulatory zones, implying that the effectiveness of these groundwater management plans depends on the degree to which management is fractured across space. Using a set of panel instrumental variable regression models to examine several of our theoretical results against the data, we see that the split-groundwater management mandated under the Western Judgment did little to correct the effects of these interjurisdictional spatial externalities on groundwater pumping behavior. While there appear to be changes in pumping behavior caused by the judgment, these changes appear to support a story in which the judgment caused groundwater extractors to shift their pumping spatially to avoid violating the terms of the judgment but did not mitigate the strategic response described in our theoretical model.

Our results in Sears et al. (2023a) suggest that laws governing extraction may lead to greater cooperation within regulatory boundaries, but that fragmented regulation may not ameliorate the effects of competition for the resource across boundaries. Further, these boundaries influence the spatial pattern of extraction.

Our results in Sears et al. (2023a) therefore provide empirical evidence that split regulation of a common pool resource can lead to heterogeneity in the degree to which well owners internalize spatial extraction externalities. We also find that fragmented regulation can also lead to changes in how extractors respond to nearby pumping. Pumpers in more fragmented areas reduce their pumping more in response to nearby pumping by others, and cluster their own extraction less than pumpers who are in a more concentrated regulation group. Our results suggest that fragmented regulation may lead to inefficient pumping in the face of uninternalized externalities, and provide empirical evidence for the presence of interjurisdictional spatial externalities that should be accounted for in the optimal design of groundwater management in California. These results suggest that further research should be done on similar policies designed to prevent groundwater overdraft in California, Texas (Torres, 2012), and other parts of the Western United States and the world where groundwater is managed at the local level.

More generally, our results suggest that policies like those used in the Western Judgment that split regulation of a common pool resource across non-physical boundaries such as political borders may not be effective in mitigating the undesirable effects of interjurisdictional spatial externalities.

Our analysis of partial coordination, wherein a groundwater manager only manages a subset of all the patches that constitute an aquifer, builds on the work of Costello et al. (2015), who examine the efficiency, distributional, and environmental consequences of assigning spatial property rights to part of a spatially-connected natural resource while the remainder is competed for by an open access fringe. Ayres et al. (2021) analyze a market for groundwater rights that does not cover the entire aquifer. Drysdale and Hendricks (2018) analyze the impact of a water restriction imposed through local governance.

Our analysis both builds on existing research and suggests possible extensions for future analysis of other common pool resources that span across jurisdictional boundaries. For example, in the realm of tuna fisheries, regional fishing agreements frequently may only allocate catch limits for a subset of fish, and often rely on factors like historical catch share to determine these allocations (Seto et al., 2021). This is broadly analogous to groundwater management institutions that suffer from not covering the full extent of connected groundwater and surface water resources, and whose allocated extraction limits are often based on historical extraction levels. Future research can harness an approach similar to ours to examine fishing effort across allocated and unallocated parts of the fishery, and the response to changes in allocation over time and across space in the fishery.

6 Conclusion

The sustainable management of common pool resources has posed a challenge to natural resource management throughout history and around the world. Groundwater is a critical natural resource whose management is often considered a classic example of a ”common pool resource” problem; in addition, its partially nonrenewable nature further confounds sustainable management.

Sustainable agricultural groundwater management would account for both the spatial and dynamic properties of the resource. Components of sustainable agricultural groundwater management include complete, measured, enforceable, and enforced property rights that consider the physical properties of the resource; as well as carefully designed policies that internalize any externalities, whether they are caused by the physical movement of water, by environmental damages or benefits, or by other causes (Lin Lawell, 2016; Sears and Lin Lawell, 2019).

In this paper, we draw lessons from our spatial dynamic analyses of groundwater resource extraction in California, where groundwater resources have operated under a de-facto open access environment for much of the state's history. We consider groundwater management from a number of perspectives, including profit maximizing farmers and recreational businesses, as well as municipal water districts with mixed objectives, and finally regional regulators or water managers. We examine how the institutional arrangements that commonly govern groundwater in California interact with the economic drivers of groundwater usage as well as the hydrology and climate of California to produce socially inefficient groundwater extraction. We explain the factors that lead to the development of these particular institutions, by examining who these institutions have benefited in practice, and how they can be refined to better serve society as a whole.

The lessons we glean from our spatial dynamic analyses of groundwater resource extraction in California are as follows.

First, there are benefits from coordinated management, but the magnitudes of these benefits depend on a variety of factors, including crop characteristics, crop prices, climate, and hydrology (Lesson 1). Our results in Sears et al. (2019) show that California, a state with diverse regional climates, and crops, faces substantially different groundwater management problems across contexts.

Second, owing to transboundary issues between jurisdictions, inefficiencies arise if the jurisdictions of local management agencies are not large enough to internalize spatial externalities (Lesson 2). Fragmented regulation may lead to inefficient pumping (Lesson 2'). Thus, even if groundwater extraction is managed or coordinated among users within a local manager's jurisdiction, inefficiencies can still remain if there are transboundary issues between jurisdictions. Our results in Sears et al. (2023a) provide empirical evidence for the presence of interjurisdictional spatial externalities that should be accounted for in the optimal design of groundwater management in California.

Third, in addition to spatial externalities, further inefficiencies arise if municipal water utilities over-weight consumer surplus relative to water sale profits (Lesson 3), which is what municipal water utilities tend to do (Lesson 3'). In Sears et al. (2023d), 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, our empirical results in Sears et al. (2023d) show that appropriators in the Beaumont Basin area of Southern California place a significant weight on the benefits generated for customers and that the appropriator's payoff function is concave with respect to consumer surplus. When consumer surplus is over-valued by appropriators, this leads to inefficient underpricing of water, inefficient over-extraction of groundwater, and the consequent deterioration of the stock for nearby users.

Fourth, quantified property rights can prevent a significant decline in groundwater stock both in the regulated basin and in neighboring basins (Lesson 4). According to our results in Sears et al. (2023d), the institution of quantified property rights in Beaumont Basin through adjudication, in combination with the implementation of aqueducts carrying imported water used for artificial managed recharge, helped to stabilize the stock of groundwater in the basin, and prevented a significant shift in extraction regionally. In contrast with a traditional spatial leakage story, 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. This reliance on imported water may be unsustainable in the long term, however, if surface water supplies become less predictable. Our work in Sears et al. (2023d) shows the important role that these policies play in not only maintaining the stock inside the Beaumont Basin, but also at other basins in the region.

Fifth, the short-term welfare gains from quantified property rights can be relatively small (Lesson 5). We find in Sears et al. (2023d) that the gains from instituting quantified property rights through adjudication in Beaumont Basin were modest and statistically insignificant. Since water districts were able to still pump at high levels outside of the Beaumont Basin in our counterfactual, they were able to still maintain a cheap water supply for their customers, and generate high levels of consumer surplus. Nevertheless, over the longer term these stocks may be depleted to the point at which they are no longer economicaly feasible to continue extraction, meaning that water districts might have to rely solely on more expensive, and potentially unreliable imported water supplies. This would potentially require increases in prices and diminished consumer welfare in order to remain in business.

Sixth, property rights design affects groundwater extraction and other behavior, but is constrained by California's legal institutions. Our results in Sears et al. (2023b) suggest that, while the property rights regime did influence the actions of players in the region, even after accounting for the impact of imports on the stock of groundwater, there are important practical limitations on the effectiveness of property rights systems that derive from differences in how California treats the water rights of appropriators and overlying rights holders. In particular, the evidence from Sears et al. (2023b) points to the limitations that market based mechanisms face in confronting groundwater management in California, in particular legal, spatial, and technological constraints.

Seventh, under open access there is little incentive for dynamic optimization, and extractors care little for the level of groundwater stock outside their own land. Our results in Sears et al. (2023c) suggest that players do not alter their behavior dramatically to account for different expectations about the level of stock throughout the system. Further, they act in a way that is difficult to distinguish from simple profit or payoff maximization in the current period. This is consistent with a model of open access in which players do not perceive present period actions as having a large impact on future payoffs. We also find in Sears et al. (2023c) that players would not benefit from additional information. This is consistent with our finding that players cared little for the future value of the stock, and thus would do little to change their behavior in response to more information. It suggests that information provision in cases like open access groundwater basins may not be particularly valuable, unless it is combined with policies that help to internalize social damages from groundwater extraction.

Our research has important implications for sustainable agricultural groundwater management in California and globally. The lessons we draw from our research are important lessons for policy makers to consider when designing policies and institutions for groundwater and other common pool resources.

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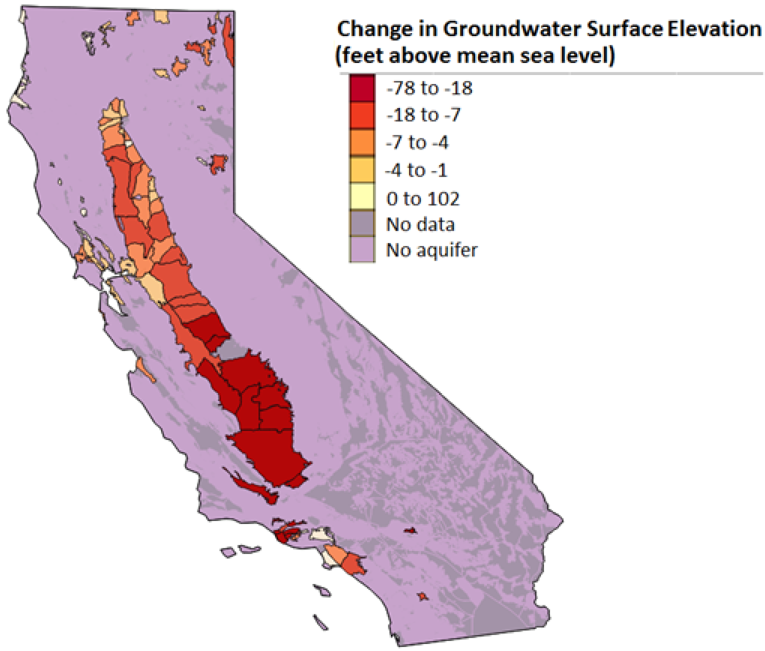


Figure 1: Decline in Groundwater Levels in California, 2011-2016
Data source: California Department of Water Resources

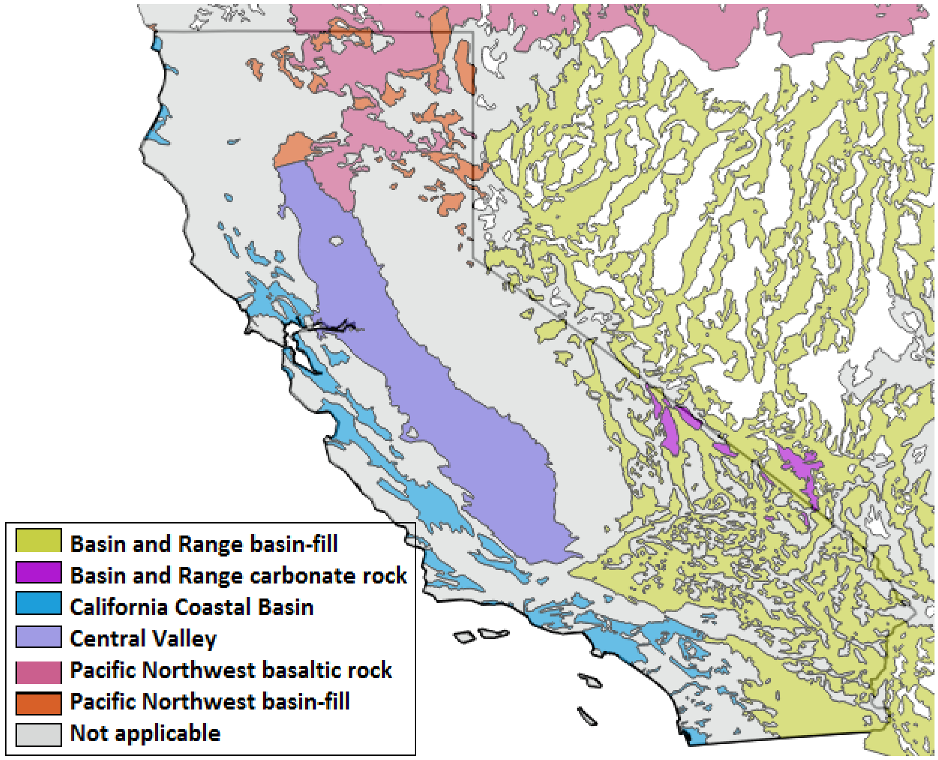


Figure 2: Aquifer Systems in California
Data source: U. S. Geological Survey (2003)

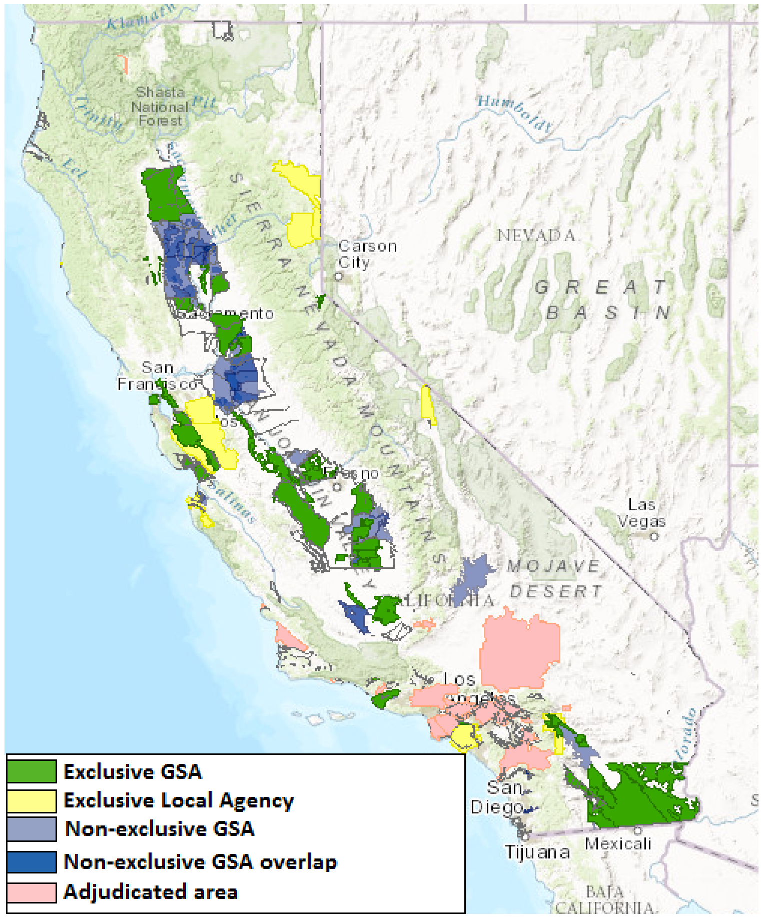


Figure 3: California Groundwater Sustainability Agencies (GSAs)
Data source: California Department of Water Resources (2017b)

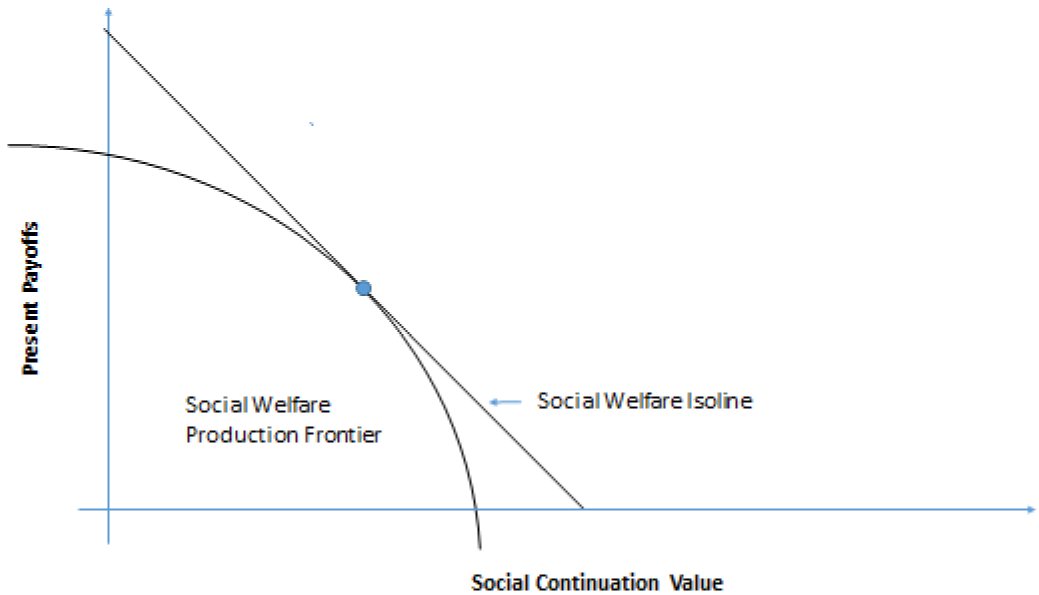


Figure 4: Appropriator Extraction Decision: Social Planner's Problem

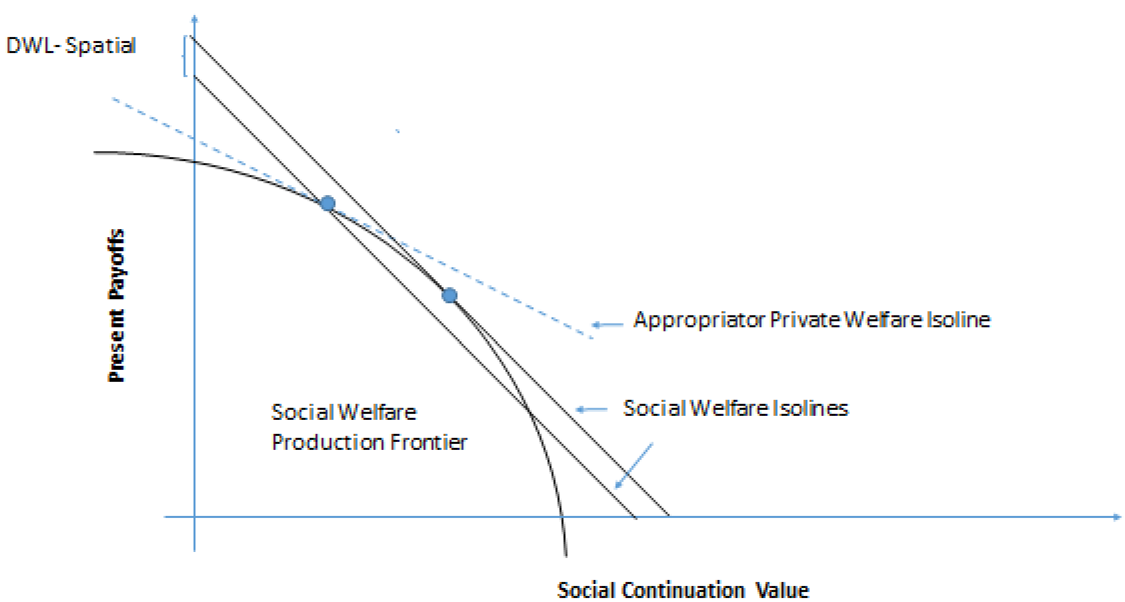


Figure 5: Appropriator Extraction Decision: Spatial Externality Effect

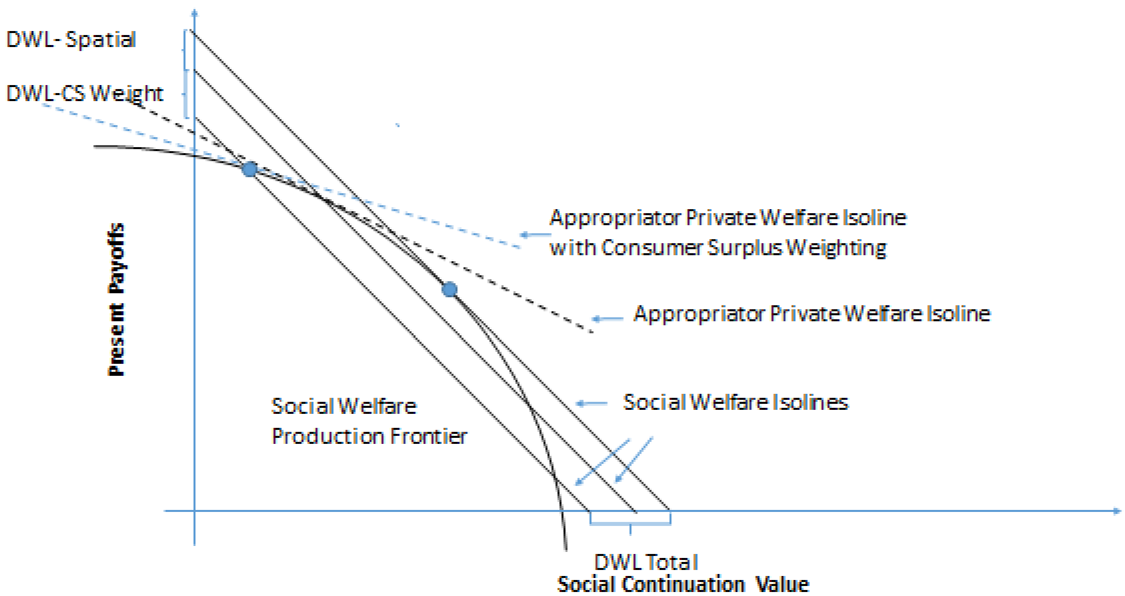


Figure 6: Appropriator Extraction Decision: Consumer Surplus Weighting Effect

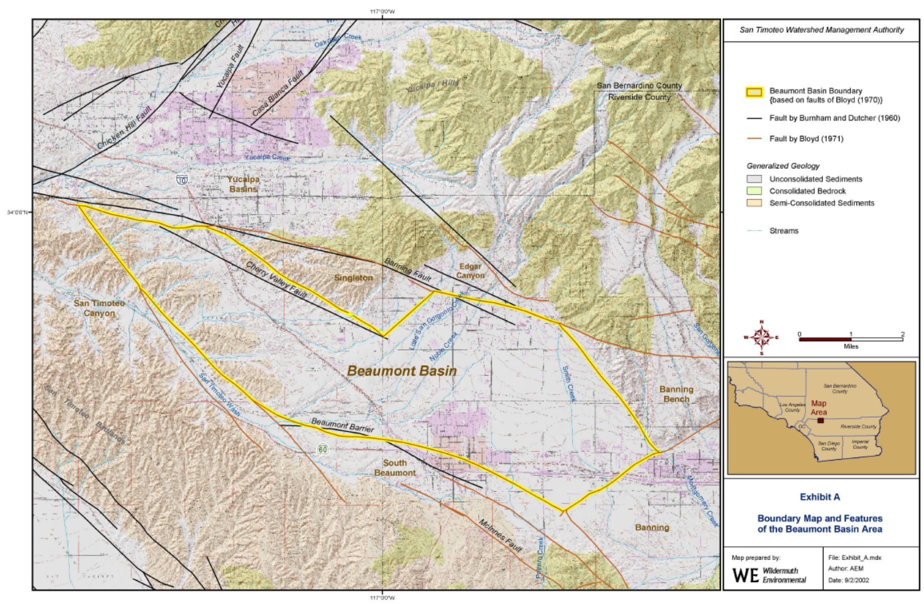
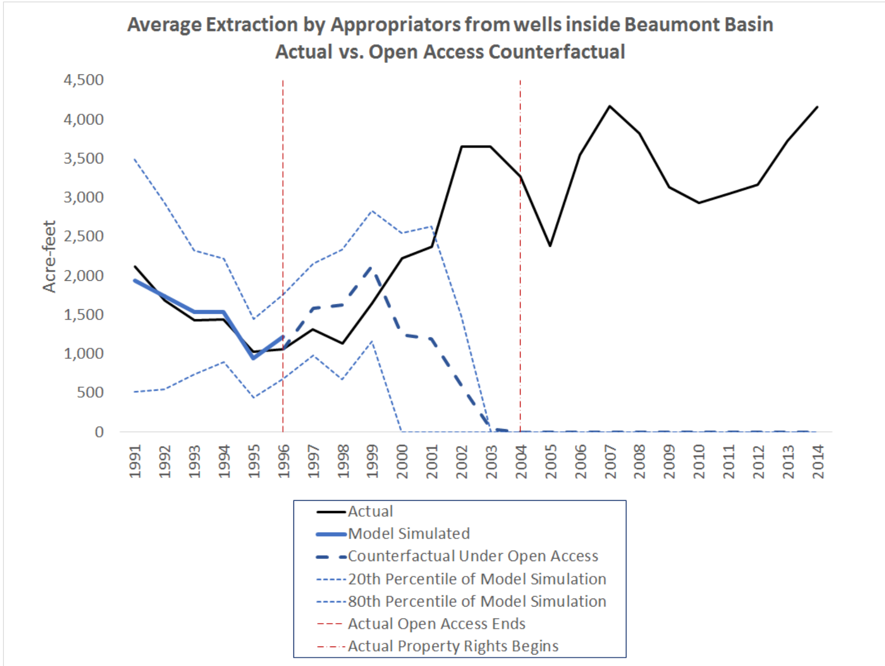
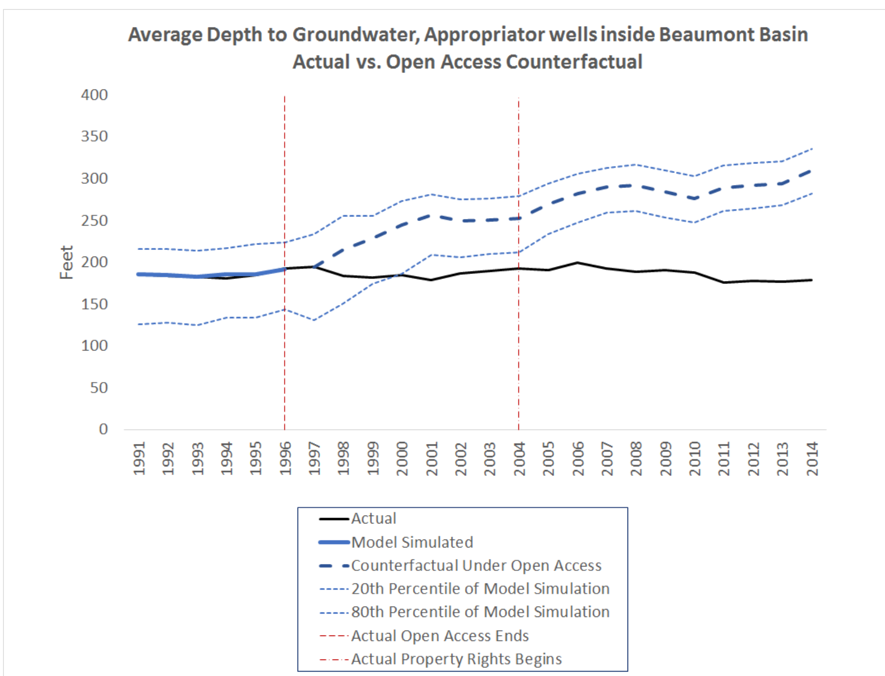


Figure 7: Adjudicated Boundaries of the Beaumont Basin
Source: Exhibit A of Beaumont Basin Adjudication Judgment

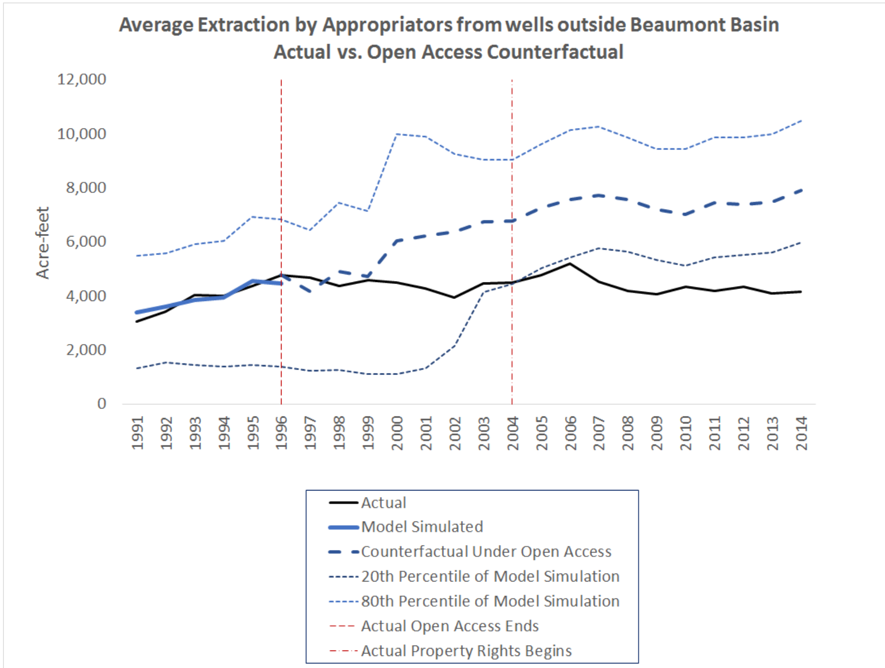


(a) Appropriator Extraction in Beaumont Basin

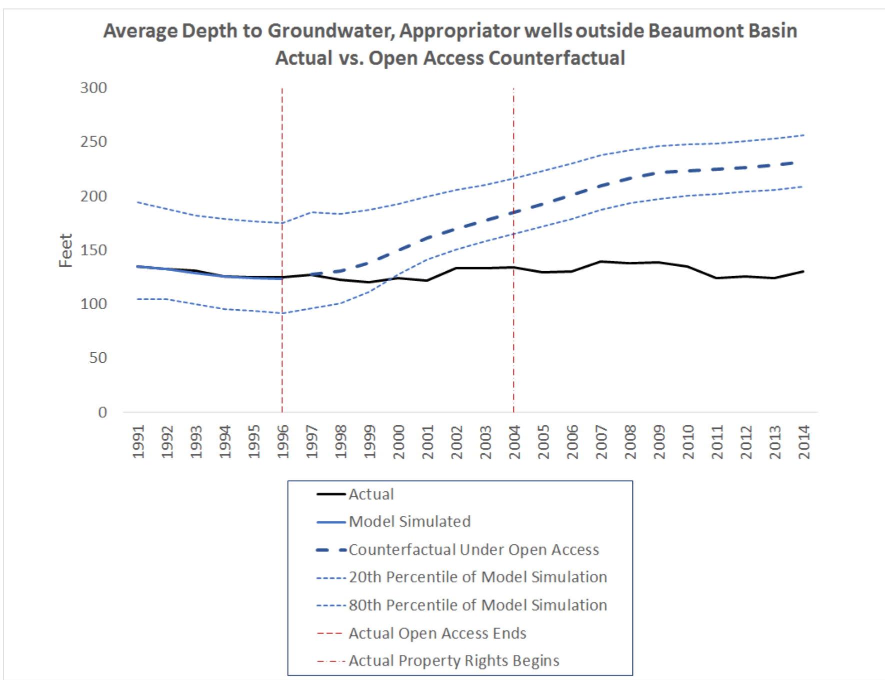


(b) Appropriator Depth to Groundwater in Beaumont Basin

Figure 8: Open Access Counterfactual vs. Actual Data
Before and After Institution of Property Rights:
Appropriators in Beaumont Basin, 1991-2014
Source: Sears et al. (2023d)



(a) Appropriator Extraction outside Beaumont Basin



(b) Appropriator Depth to Groundwater outside Beaumont Basin

Figure 9: Open Access Counterfactual vs. Actual Data Before and After Institution of Property Rights: Appropriators outside Beaumont Basin, 1991-2014
Source: Sears et al. (2023d)

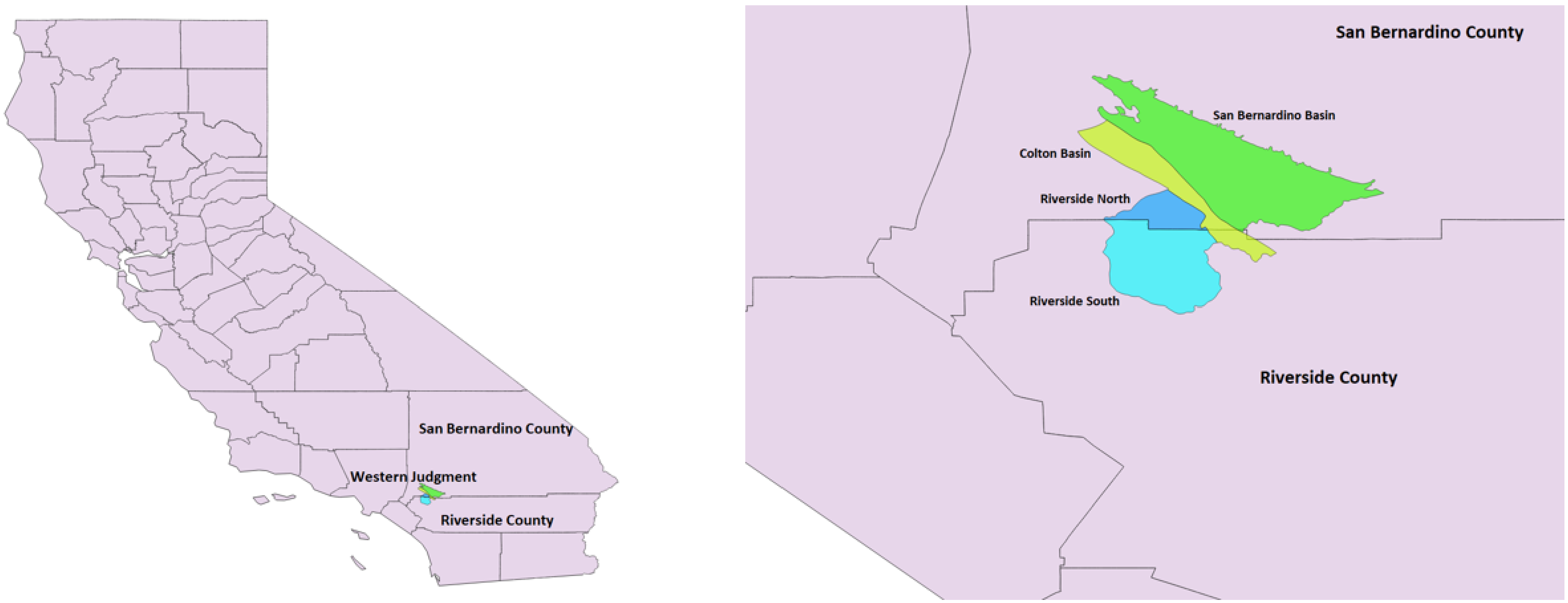


Figure 10: Western Judgment Regulatory Boundaries
Data Source: Western Municipal Water District.