Analyzing Policy Approaches to Water Scarcity in the Western United States

by

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A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Approved April 2023 by the
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ARIZONA STATE UNIVERSITY

May 2023

ABSTRACT

Water scarcity in the Western United States has been the focus of recent policy discussion. Researchers and policymakers agree that the implications of water scarcity are severe and widespread, and as such have stressed the importance of addressing water allocation in the short term and long term. However, this urgency has led to some short-term solutions, like rotational fallowing, being implemented without evaluation, or some long-term solutions, like re-structuring of rights, being suggested without precedent. This dissertation aims at reducing the gap between proposed solutions, existing data, and program evaluation by developing and analyzing two novel datasets useful for causal identification, evaluating both a long-term and short-term approach to water scarcity with these data, and finally demonstrating the ability of overlapping institutions to respond to increasing weather variability. Chapter 1 evaluates a short-term approach, rotational fallowing, and identifies the impact of this approach on water savings. Chapter 2 develops novel trade panel data and exploits the only share-based water market in the US: the Colorado-Big Thompson Project (CBT). This chapter compares trade and crop choice outside of the CBT, to those same outcomes within the CBT, and identifies the differences. Chapter 3 expands on crop choice within the CBT and identifies the extent to which overlapping institutions can mediate weather variability compared to prior appropriation.

DEDICATION

To Scott and Jann Wright, my father and mother, who taught me to love learning, to ask any question, and sacrificed countless things in order to help Ashley, Sarah, Scotty, and I succeed in life.

ACKNOWLEDGMENTS

It would be impossible for me to have produced this dissertation without the continuous support of so many people. First, I would like to thank the chair of my committee, advisor, and mentor, Dr. Bryan Leonard. Thank you for your constant support, feedback, and encouragement throughout the process. Your integrity, dedication, and relentless robustness checks have made me the researcher I am today.

To Dr. Joshua Abbott, thank you for your feedback, suggestions, challenges, and encouragement. I am so grateful that you were part of my doctorate experience. To Michelle, Grace, and Mercy, thank you for the laughter and food! It was a joy to share meals with you all; I look forward to many more.

To Dr. Abigail York, thank you for the time and energy you put in as a committee member. I am grateful to have learned from you!

To Dr. Kailin Kroetz, thank you for the countless hours of mentorship, laughter, coffee, and for signing up to run thirty-six miles with me. To Jon, the friend of the Lab, and constant supplier of Sour Scandinavian Swimmers, thank you.

To the lab, I cannot thank you all enough. You are my colleagues, friends, and workout partners. One of the best parts of ASU was learning alongside all of you. I cannot wait to see what you accomplish, and I will be cheering you all along. Special thanks to Kaitlyn Lee for taking every phone call and talking me back to reality. I could not have survived this experience without you!

To the Heather and Jeff Ventrella, you have housed me, fed me, loved me, and brought me in as one of your own! I am so grateful to have a second family in Arizona and cannot express how important you are to me.

To the Millers, thank you for the conversations, editing, and encouragement along this journey. Thank you for housing me and supporting all of my crazy adventures!

To Dr. Charles Steele, who still wrote me a recommendation to graduate school even after receiving my “academic notice” junior year. Thank you for believing that I was capable of doing this doctorate. And thank you for sharing your love of ultrarunning with me.

To Andrew Ayres, for your work on “Rotational Fallowing Falls Short of Expected Water Savings”. Thank you for your feedback and support on the data work.

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Introduction

Transitioning from common ownership of natural resources to formal property rights has improved outcomes in fisheries and forests (Arnason 2012; Leonard and Libecap 2019; Libecap 2007, 2008; Schlager and Ostrom 1999). Despite the documented improvements associated with creating formal rights, it is unclear if the specific structure of water rights are flexible enough to address variations in temperature and precipitation due to climate change (Hurlbert 2009; Omer et al. 2020; York et al. 2021). In particular, researchers cite concern over the ability of prior appropriation, the doctrine that assigns property rights to water in the Western United States, to alleviate water scarcity in the American West.

Water scarcity can be defined broadly as a mismatch between the supply of water and the demand for water (Damkjaer and Taylor 2017; Hansen 2017). When the demand for water exceeds the supply, there is scarcity. Some water scarcity can be attributed to supply limitations, where persistent increasing temperatures and decreasing rainfall limit the physical availability of water. Population growth affects demand and can exacerbate supply shortages over time; however, some water scarcity can also be attributed to allocative inefficiencies caused by prior appropriation (Burness and Quirk 1980b).

Prior appropriation allocates water based on seniority and is the primary method of water allocation in the West. Those who filed for a right first, receive their water first. In order to “perfect” a right, individuals must prove that water is being put towards beneficial use. Because prior appropriation was established during the 1800s, the doctrine prioritized agriculture, industrial, and municipal/household as qualifying uses, and discouraged speculation. Irrigation districts, conservancy districts, and conservation districts followed prior appropriation and largely evolved to address infrastructure and investment in the 19th century. Today, the problem is not one of investment, but of allocating existing supply (Hanemann 2014).

Beneficial use, seniority, and speculation affect the transferability of appropriative rights. Beneficial use restricts the types of transfers that can happen; an individual cannot transfer water allocated for agriculture to a municipal use without a "change of use" application. Non-injury restricts where the rights that can be transferred, as any transfer of water requires proof that it does not affect anyone who would have received water prior (short-distance transfers are less likely to affect other users). Speculation influenced the "use it or lose it" clause in prior appropriation. This requirement stipulates that if an individual is not continually using their water (use as in beneficial use), the water right is forfeited (abandoned). All these clauses increase the transaction costs associated with water transfers, contributing to the skepticism that prior appropriation can address current water scarcity (Schilling 2018).

Because the source of water scarcity is variable, researchers suggest a myriad of solutions to reduce this variability. The reality of water scarcity has become apparent in the West due to a "megadrought," leading to some short-term solutions, like rotational fallowing, being implemented without evaluation, or some long-term solutions, like restructuring of rights, being suggested without precedent.

Changing institutions is costly and slow, requiring short-term solutions in order to address the current reductions proposed by Congress. Short-term solutions work within prior appropriation and aim at transferring water from agriculture to higher valued uses in urban environments. In the long-run, legal changes need to be made to prior appropriation in order to eliminate allocative inefficiencies through trade. However, long run solutions will encounter obstacles within the political economy, as many of these solutions would require altering the definition of property rights.

The immediate need to address water shortages, combined with the existing legal limitations of prior appropriation, have exacerbated the lack of water data and empirical work necessary to support many of the solutions proposed by researchers and policymakers. This dissertation aims at reducing the gap between proposed solutions, existing data, and program evaluation by developing and analyzing two novel datasets to evaluate both a long-term and short-term approach to water scarcity with these data. The dissertation is as follows:

Chapter 1: This chapter addresses a current, short-term approach to mitigating water scarcity within existing institutional allocation frameworks: rotational fallowing. Rotational fallowing is when a city pays a farmer to forgo irrigation and the saved water is made available for the city to use. Cities are particularly interested in this method as it addresses their growing need for water and limited access to it. Cities are a growing demander of water, but nearly 70% of water remains in agriculture (Scientific Investigations Report 2018). Rotational fallowing is a short-term land use change, which makes it both politically and legally feasible. These attributes of rotational fallowing have made it a popular alternative to traditional long-term water trades, but despite its popularity, little research exists evaluating the ability of these programs to save water. I evaluate the longest-running rotational fallowing program in the United States by georeferencing Bureau of Reclamation reports and combining them with existing ownership and evapotranspiration data.

Chapter 2: This chapter focuses on the Colorado-Big Thompson Project (CBT), which is the largest and longest running share-based water market in the United States. Despite its long history, little research explains why the share-based system has lasted so long, and how it has affected the use of overlapping appropriative rights, including trade, crop choice, and priority. In particular, researchers have mischaracterized the institutional type of the CBT, which mirrors that of an overlapping, polycentric institution, and not solely a share-based system. I demonstrate the polycentric aspects of the CBT and compare outcomes within the CBT to outcomes outside of the CBT. I create a panel dataset from historical maps, existing water trade information, and crop data to look at two broad questions: (1) How does trade within the CBT differ from that outside of the CBT; and (2) How does crop choice differ between the boundary and within priority groups. Our findings suggest overlapping institutions dampen the impact of priority on crop-choice, alter the trade and use of appropriative rights, and could decrease farmer response to weather variability through crop choice over time.

Chapter 3: This chapter leverages the data created in Chapter 2 and incorporates PRISM climate data to study how access to shares influences agricultural sustainability and land use change in the long run. We find that individuals within the CBT have a higher likelihood of being in agriculture. We also find evidence that the CBT dampens the impact of weather variability and allows farmers to continue in agriculture.

Rotational Fallowing Falls Short of Expected Water Savings

Introduction

In July 2021, Congress declared the first shortage of the Colorado River, triggering states to implement a drought contingency plan. The plan underscores the declining river flow as well as concerns over current consumption. Over 40 million individuals will be affected by cutbacks, reductions, and future limitations stemming from the drought (Fountain 2021; US Department of the Interior and Bureau of Reclamation 2012). Short-term approaches include limits on water use for lawns and reductions in water for municipal use, while long-term reductions result in entire neighborhoods losing water and farmers losing access to water for agriculture.

About 75% of water consumption in the West comes from agriculture (Marston et al. 2020), but nearly 50% of the water purchases come from municipalities (Hanak and Stryjewski 2012; Marston et al. 2020). Marston et al. (2020) demonstrate that agricultural water use could be reduced between 6 to 23% without affecting economic production. Such reductions could benefit both municipalities, who require more water given growing populations, and farmers, but only if water trade occurs. Where such trades are permitted, municipalities are willing to pay farmers up to $17,000/af[1] for a permanent water transfer (Libecap 2011).

Economists have long advocated for water markets and water transfers because of their ability to improve allocative efficiency that reflect the scarcity of the resource

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[1] An acre-foot (af) describes how much water is required to submerge one acre in one foot of water. One acre-foot of water corresponds (roughly to) 325,000 gallons.

(Burness and Quirk 1979, 1980b, 1980a; Culp, Glennon, and Libecap 2014; Libecap 2011). In theory, water markets provide a mitigation tool for water scarcity amidst the competing demands of agricultural and municipal users. Individuals, municipalities, and irrigation districts can trade water, moving water to higher valued uses through voluntary transactions. However, the implementation of market mechanisms is much more complex than simply allowing transfers. Trades must occur within existing institutions, often meeting legal or political opposition that stymies the transfer. Most notable among opponents to water transfers, are farmers.

Farmers' concerns pertain to the permanent sale of water and are largely based on the legacy of Owens Valley. In the early 1900s, Los Angeles realized the city could not meet the growing water demand from population growth with its current water supply. The city addressed their water scarcity by buying farmland and diverting water from Owens Valley, a community of 7,000 people and located 200 miles away from Los Angeles. Less than 13 years after the initial diversion, Owens Lake lay dry, and the farming economy similarly evaporated. As a result, farmers pejoratively refer to agriculture-to-urban (ag-to-urban) transfers as "buy-and-dry" (Libecap 2005). Building on their concerns, Bourgeon, Easter, and Smith (2008) show that ag-to-urban transfers can trigger increased fallowing and lead to a per capita regional welfare decrease through labor market and income changes. These examples illustrate that caution should be used when designing market mechanisms to address water scarcity.

A possible management approach that avoids permanent transfers and addresses the above concerns is alternative transfer mechanisms (ATMs) (Dilling et al. 2019; Varzi and Grigg 2019). Alternative transfer mechanisms alleviate shortages by allowing individuals with surplus water to transfer to those who have deficit water balances on a short-term basis. Alternative transfer mechanisms avoid the legal scrutiny and transaction costs associated with traditional water transfers because they are considered a contract over changes to land use. As a result, water can be moved more quickly between individuals and institutions. One type of ATM is rotational fallowing, a process where farmers choose fields to not irrigate (fallow) on a rotational basis (e.g., yearly, seasonally, monthly). Municipalities, or other users, pay farmers and divert the temporary water saved from rotational fallowing. This process allows them to make up their water deficits based on yearly evaluation.

Rotational fallowing avoids farmers' concerns regarding permanent transfers in two ways: First, municipalities lease water from farmers, not purchase. Second, farmers rotate the fields that they select for future fallowing. Often rotational fallowing programs place caps on the total amount of land that can be fallow, which also ensures that farming activity continues season to season. Leasing ensures local farming economies continue functioning while rotational fallowing promotes long-term soil health and provides consistent water savings (Cusimano et al. 2014). When considering the agricultural margins on which farmers can save water, fallowing appears to be promising. A recent study by Plassin et al. (2021) finds that because fallowing is not widespread, fallowing remains an underused strategy to create water savings (Plassin et al. 2021).

We evaluate the longest-running rotational fallowing program, The Palo Verde Irrigation District Forbearance and Fallowing Program, that delivers water to Metropolitan Water District (see Figure 1). Metropolitan Water District (MWD) services the Los Angeles area and a total of 19 million users, making it the largest water conglomerate in the West. MWD obtains water from the Palo Verde Irrigation District (PVID) and receives 60,000 af/year through rotational fallowing. As of 2017, the program estimates 685,490 af[2] of saved water in the first ten years (U.S. Bureau of Reclamation, Palo Verde Irrigation District, and The Metropolitan Water District of Southern California 2015). Estimating the policy impact, however, depends on how accurately one can measure the water savings. Dozier et al. (2017) stress the importance of accurate spatial and temporal data in analyzing rotational fallowing policies (Dozier et al. 2017). In order to evaluate ATMs, policymakers rely on district-wide measures of land and water use to calculate water savings. In general, district-wide measures often lack the necessary precision for evaluation. Without accurate data and empirical methods that isolate policy impact, estimates of saved water contain confounding information that could inflate the total amount of water saved.

MWD measures saved water through what they call the “Annual Use Method.” The Annual Use Method calculates consumptive use as a difference between total diversions less measured and unmeasured return flows for the entire district.[3] To estimate saved water, consumptive use is divided by the total cropped acreage to estimate average water use per irrigated acre, which is then multiplied by the number of fallowed acres. This method averages over fallow and irrigated farmed fields, assuming that fallow fields will use none, or a negligible, amount of water. The method, by design, attributes any decline in water use to program enrollment. This method also fails to account for annual

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[2] 220 million gallons

[3] Total diversions are determined by BOR and measured through water meters. Total diversions represent the total amount of water a district is permitted to use. Measured and unmeasured return flows are the amount of total diversion that, after used for crop production, are returned to the stream and available for reuse.

or seasonal shocks that could affect irrigation demand district-wide, such as temperature, precipitation, crop prices, or insect infestations. By not accounting for changes to water demand over time, MWD's method may conflate exogenous changes that happen to coincide with the program with savings due to fallowing.

To accurately evaluate the extent to which ATMs generate water savings, one must be able to isolate the impact of a policy on a participating farmers' decision to irrigate. Estimating the water savings induced by program implementation requires that policy makers know how participants would have behaved without the program. Causal estimates capture the average program effect by comparing realized water use to a counterfactual scenario where the program did not take effect. By taking the difference between the counterfactual estimate and the observed estimate, we can determine to what extent ATMs increase or decrease water savings. In order to produce a causal estimate, we need to identify parcels directly affected by the program (treated) and compare them to a group that never participated (control) in the program.

We contribute to the existing research regarding market-based instruments in addressing water scarcity (Ayres, Meng, and Plantinga 2021; Ayres, Edwards, and Libecap 2017; Burness and Quirk 1979, 1980b; Culp, Glennon, and Libecap 2014; Leonard, Costello, and Libecap 2019) by combining evapotranspiration data with a two-way fixed effects model to estimate water savings. We use evapotranspiration data developed by Senay et al. (2017) combined with monthly, parcel-level treatment data (created from Metropolitan Water District and Bureau of Reclamation (BOR) documents) to estimate program impact (Senay et al. 2017). Senay et al. produced data that estimates the most precise water use on parcels in PVID to date. We use their data as an input into our two-way fixed effects model that estimates the causal effect of the program on parcel irrigation. We find that the average water saved per year due to program enrollment is 53,928 af/year. Our estimate is 56% smaller than MWD's estimate of 96,494.88 af/year.

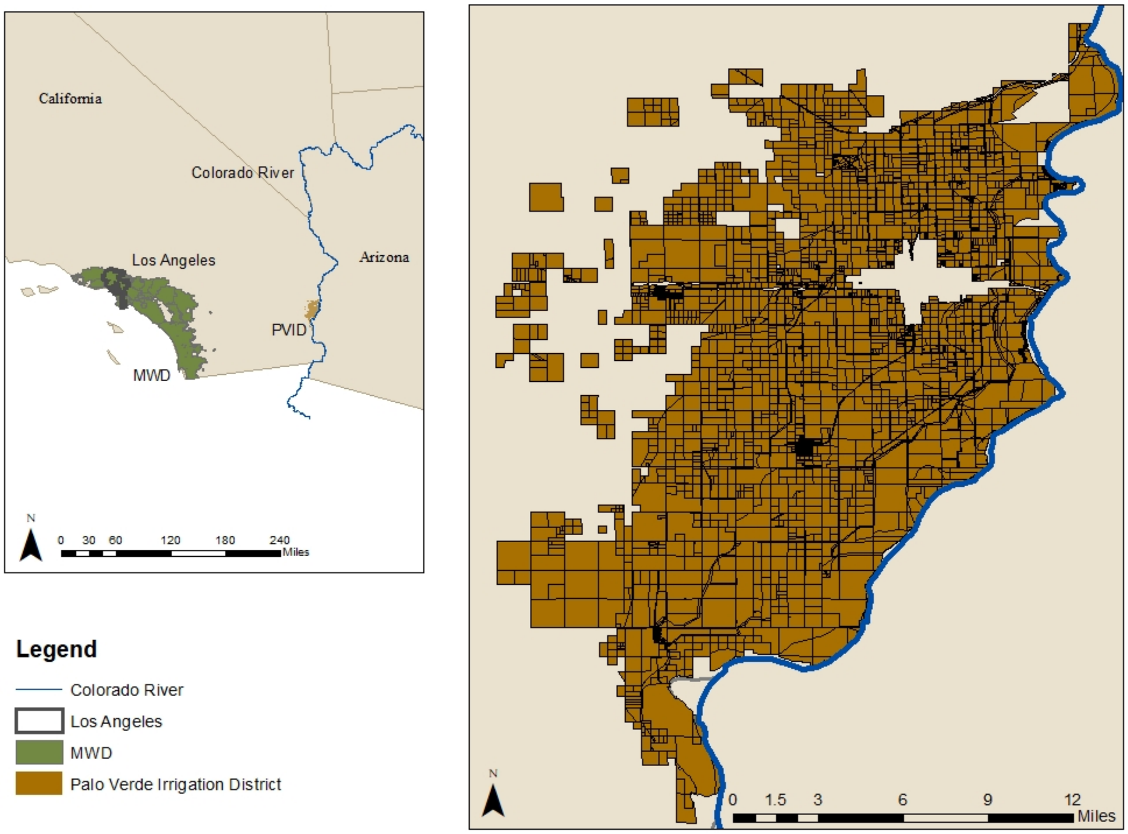
Background

Program Details

In the 1990s, MWD realized that the rate of population growth in their service territory, combined with the current water supply, would lead to inevitable shortages. Palo Verde Irrigation District (PVID), who manages water for Blythe, provided a solution: if farmers fallowed their land, MWD could use the saved water without injuring junior users. Given the infamy of Owens Valley, MWD developed the "Forbearance and Fallowing Program" with PVID to avoid concerns surrounding buy-and-dry.

Figure 1

Study Area



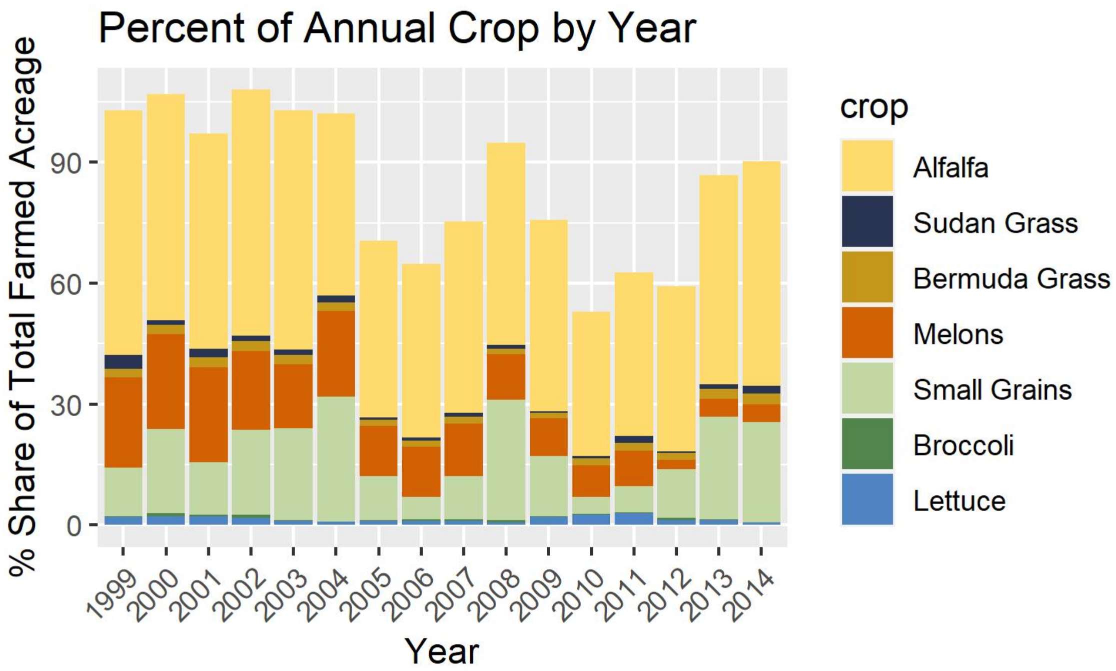
Note. MWD is the green area on the coast of California. Los Angeles is outlined in black, in the top center of MWD. About 200 miles southeast, Palo Verde Irrigation District farming acres are shown in brown. The inset map is of Palo Verde Irrigation District. Water obtained from rotational fallowing is sourced from the Colorado River, pictured to the right of PVID.

The city of Blythe—the population center of PVID—spans 26.8 square miles and sits alongside the Colorado River and the California-Arizona border (City of Blythe n.d.). About 200 miles away sits Los Angeles, a city nearly 20 times larger and 200 times more populous. Despite its small size, PVID residents hold rights to the Colorado River that are senior to more than 40 million users across the West, including those in Los Angeles

(Wilson 2021).[4] Their seniority allows agricultural production, specifically alfalfa, to be the main economic driver. Figure 2 shows the share of annual cropped acreage for the top seven most water intensive crops (by percent) grown in PVID (Palo Verde Irrigation District 2015b, 2015a, 2016, 2018a, 2018b).

Figure 2

Percent Share of Annual Cropped Acreage



Note. This figure shows the percent of total share cropped acreage that the top seven crops in PVID grow. Alfalfa, melons, and small grains make up the largest share of total cropped acreage.

In 2004, PVID and MWD signed a 35-year fallowing agreement. The agreement sought to increase water delivery to MWD through water savings obtained from fallowing in

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[4] In the west, water is allocated through the doctrine of prior appropriation. The doctrine states individuals receive water rights based on use and timing. Individuals with "senior" rights are those who have earlier dated rights. For more information regarding prior appropriation see Leonard and Libecap (2019).

PVID. When fallowing, farmers who are enrolled in the program are not allowed to grow shade crops; the only irrigation permitted is that which is required for dust control (Metropolitan Water District of Southern California and Palo Verde Irrigation District 2004a).

Fallowing saves water when agricultural fields that would have been cultivated are instead not irrigated. The magnitude of the water savings depends on crop choice, temperature forecasts, precipitation, and soil quality. Crops like melons or lettuce retain more water than grasses, meaning that there is a higher return flow and less consumptive use for grasses[5]. Higher temperatures combined with low precipitation would require more irrigation. Hence, annual variation in climatic conditions and observed decisions about what crops would have been grown affect the realized water savings associated with fallowing a given field each year.

Metropolitan and Palo Verde addressed "buy-and-dry" concerns with several conditions built into the fallowing agreement. The first condition stipulates that Metropolitan is not purchasing land from PVID farmers, only that Metropolitan is contracting with the farmer for the use of their water (Metropolitan Water District of Southern California and Palo Verde Irrigation District 2004b). The importance of this condition was underscored by PVID, when in 2014, PVID filed a lawsuit against MWD, accusing the MWD of closing on a $264 million agricultural land deal without environmental appraisal (Dehaven 2017). The land deal included "draconian like water restrictions" that would allow MWD to increase their water consumption (Riggs 2017).

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[5] Return flow describes water that is returned to the source through runoff after its initial use. Return flow is subtracted from total diversions and the remainder describes consumptive use--water that will be lost to crop production or another purpose.

In press releases, PVID called MWD's actions “predatory” and cited Owens Valley (Palo Verde Irrigation District Files Lawsuit Against MWD of Southern California to Expose Scheme to Take Colorado River Water and Threaten Lands Classified by the State of California as Farmlands of Statewide Importance 2017). While PVID eventually dropped the lawsuit, the district felt MWD had violated their original agreement regarding land purchases.

A second program condition states that farmers can enroll between 7% to 28% of their farm’s acreage. Farmers could enroll during a one-time enrollment window from 2004-2005. Farmers could not enroll in the program after this point. The final condition stipulates that farmers can opt out of the program at any time. If they leave, they must ensure that the conditions of their contract are not violated (Metropolitan Water District of Southern California and Palo Verde Irrigation District 2004b).

Once a farmer considered enrollment, MWD verified their enrollment eligibility. Eligible farmland includes any fields that were irrigated and farmed in 2003 (Metropolitan Water District of Southern California and Palo Verde Irrigation District 2004c). The contract includes payment information, fallowing enforcement, and conditions of termination. Individual farmers receive an initial payment of $3,170 per acre when they first enroll in the program (U.S. Bureau of Reclamation, Palo Verde Irrigation District, and The Metropolitan Water District of Southern California 2015). A farmer can rotate which of their enrolled fields they fallow each year, with program rules stipulating that a field cannot remain fallow for more than five consecutive years (Palo Verde Irrigation District 2002).

Each year MWD issues a "call" that corresponds to a percentage of enrolled land to fallow. A 25% call means that enrolled farmers fallow 25% of their enrolled land (rounded up to the nearest acre). It is important to note that not every enrolled parcel is used in every call. Enrollment indicates that a parcel is available and eligible for fallowing, but MWD's call determines whether a parcel is actually fallowed in a given season (Palo Verde Irrigation District 2002). When their parcel is used, a farmer receives yearly payments of $602/acre per year enrolled (Metropolitan Water District of Southern California and Palo Verde Irrigation District 2004a). If a farmer is enrolled for ten years, the $602/acre payment can rise by 2.5%. Over 25 years, they could see an increase to that percentage ranging from 2.5% to 5% (Metropolitan Water District of Southern California and Palo Verde Irrigation District 2004a).

Water Estimation Process

Metropolitan expects the annual delivery to be between 25,000 to 118,000 af of water. These estimates come from annual "Verification Reports" jointly produced by the Bureau of Reclamation (BOR) and MWD. Annual water savings are calculated with their "Actual Use Method", which combines estimates of total water use and annual fallowed acreage (Equation 1). Of particular interest is the way in which MWD measures total diversions and return flow.

Equation 1

$$Water\ Saved = \frac{(Total\ Diversions\ -\ Return\ Flow)\ -\ Diversions\ to\ Areas\ Outside\ of\ PVID}{(Irrigated\ Acres\ in\ PVID\ *\ Fallowed\ Acreage)}$$

Metropolitan estimates consumptive use, which is total diversions minus measured and unmeasured return flow, from two data sources: Total diversions through metered use and return flow with evapotranspiration (ET). Metered use means that diversions are measured through water meters placed at the point of diversion (US Bureau of Reclamation 2018). Evapotranspiration is a way of measuring the amount of water that evaporates off a given land parcel, depending on climatic conditions. The estimates are typically reported as ETo, and reflect the level of evaporation from a parcel. Evapotranspiration estimates depend upon a weather station and a satellite. A weather station records precipitation and temperature on the ground while a satellite captures land images. If crop types are known, an ETo estimate can be converted to an ETc estimate with a crop coefficient. A crop coefficient is a multiplier that indicates how much water is retained by a specific type of crop. Temperature, soil type, and precipitation are included in ETo calculations such that the final estimate yields a baseline measure of water use. While ETc can be used instead of metered use, the Bureau of Reclamation uses metered use for total diversions and ETc to calculate a coefficient for return flow (US Bureau of Reclamation 2018).

Error within metered use and ETc can contribute to inaccurate measurement of water savings. Metered use requires meters at every diversion point in order to capture a complete picture of total diversions; however, it is infeasible to place a meter at every point of diversion, meaning that some diverted water will not be captured. In addition, metered use is aggregated to be a district-wide measure; it is not parcel specific. Evapotranspiration, as mentioned above, can be reported as ETo or ETc. To estimate

ETc, knowledge of parcel-specific crop type is necessary. Particular knowledge of crop production on a parcel is rare. If a manager knows the crop grown on a parcel, they can use a crop coefficient to convert the ETo into a crop specific ET estimate (ETc). Because knowledge of crop types is inconsistent, parcel level irrigation estimates are often reported in ETo, if in ET at all. These estimates of ETo do not take into account that different crops retain different amounts of water. In addition, the ETo estimates are calibrated to the weather station's land type that could be located miles away from the point of interest.

While researchers have encouraged the use of ETc data, many ETc estimates are reported with a low resolution (Charles 2021; Howes and Styles 2014). Because ET uses both a satellite and a weather station, there are often large spatial resolution gaps that when combined, produce a 2km per pixel resolution (Hart et al. 2009). Metropolitan and the Bureau of Reclamation use ET measurements from California Irrigation Management and Information System (CIMIS) that are at a 2km per pixel resolution (U.S. Bureau of Reclamation, Palo Verde Irrigation District, and The Metropolitan Water District of Southern California 2015). Given the limitations of ET data, the BOR uses ETc data to estimate a return flow coefficient. The coefficient is not parcel specific, but a coefficient generated for the entire district, then multiplied with total diversions to yield an average return flow amount.

In addition to measurement error, the structure of the water saved equation includes several assumptions that may bias MWD's estimate. First, MWD assumes that enrolled parcels and non-enrolled parcels would create the same level of water savings. For this assumption to be true, enrolled parcels would need to irrigate at the same level as non-enrolled parcels prior to enrollment and after program start. Second, MWD assumes that after the start of the program, enrolled parcels do not change their irrigating patterns when they are not called. For this assumption to be true, non-called parcels should follow their irrigation pattern prior to treatment. Finally, MWD assumes that called parcels do not irrigate at all, or at the very least, a negligible amount, when fallow. For this assumption to be true, we should not observe any water use on called parcels. If any of these assumptions are violated, we would expect MWD's saved water estimate to be larger than the real observed water estimate.

To estimate how enrolled parcels would have been irrigated without the program, we would need to observe a counterfactual where enrolled parcels were not treated. This counterfactual would give us a causal estimate for how much water enrolled parcels would have used, and thus yielding the actual water saved. Although we never observe the counterfactual, we can estimate the counterfactual with two-way fixed effects and recover a causal estimate for how much water use changed on enrolled parcels due to program enrollment. We improve MWD's saved water estimate by using improved ETc data for consumptive use, and by contributing a causal estimate for water use.

Data

Evapotranspiration

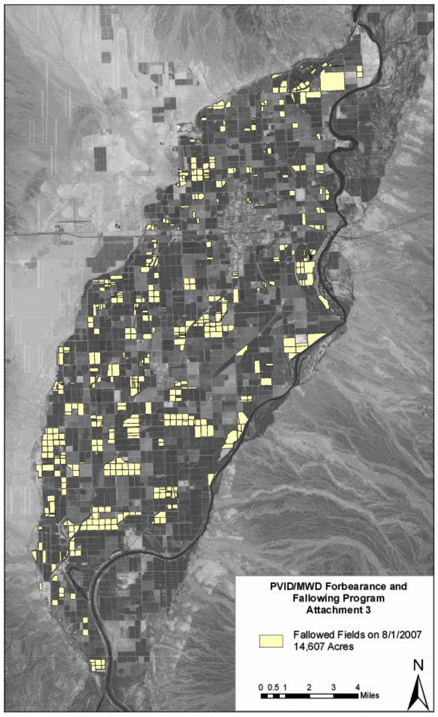
We increase the accuracy of consumptive use estimates by using parcel-level ETc estimates obtained from Senay et al. (2017). The authors use remote-sensed Landsat 8 images (15x15-meter resolution) to estimate ETc in the PVID (Senay et al. 2017). Their estimates are available at the monthly level, and we aggregate them into two irrigation seasons (7 months, 5 months). We explain the choice of irrigation seasons in the next section. We find that the average parcel size is 60 acres and the average pixel count per parcel is 186. The ETc (hereon referred to as ET) estimates provide us with parcel-level irrigation use, as opposed to the district-wide estimates used by MWD.

Enrollment

We combine the irrigation data with enrollment and call data obtained from the Verification Reports. These reports include two parcel maps for each year that identify called (fallow, yellow) parcels during the beginning and end of a seasonal call. PVID has two distinct irrigation seasons in a calendar year, and they issue a call for each irrigation season. Verification Reports submit two images, one for August and one for January (corresponding to the beginning of the two irrigation seasons), that detail which parcels were fallow in each period (Figure 3). Metropolitan issues a call each season, but farmers decide which parcels to fallow. Yellow parcels on this map are enrolled in the program and called in that irrigation season; gray parcels could be either enrolled and uncalled or non-enrolled parcels.

Figure 3

PVID Fallowing Image



Note: Verification Report Image of Fallow Land in PVID, August 2007. The map is produced bi-annually by MWD and BOR. It depicts fallow parcels as yellow and all other parcels as gray. Fallow parcels are enrolled and called to fallow by MWD, while gray parcels could be enrolled or unenrolled parcels.

We geo-reference the parcel maps in ArcGIS for all existing Verification Reports. MWD did not produce verification maps for 2005 and 2006, so we omit both years from our analysis. Resulting treatment groups vary each irrigation season consistent with the program structure. We create a time-constant enrollment variable that indicates whether a parcel was enrolled in the program; this variable is separate from the time-varying called parcel indicator. The enrollment variable indicates if a parcel was ever used during the program; the call variable indicates if a parcel was called on to fallow in a given irrigation season. We exclude irrigation season 2009 due to an Emergency Fallowing Call that enrolled an extra 13,000 parcels for that season only.

Summary

Table 1 provides the summary statistics for each outcome variable by enrollment status. Table 1 uses only pre-program years to report summary statistics for annual acre-feet, acre-feet per acre, the natural log of both, and then alternative measures for each. Our panel follows 3,606 unique parcels across 22 years for a total of 147, 845 observations. Of those 3,606 parcels, 69% are not enrolled and 31% are enrolled. Over our time period, an average of 2% of enrolled parcels are called.

Table 1

Summary Statistics by Enrollment

	Pre-Program		Post-Program		
	Enrolled	*Not Enrolled*	*Called*	*Not Called*	*Not Enrolled*
Mean AF	56.67	17.19	34.41	52.79	17.46
	(81.43)	(57.53)	(69.83)	(82.47)	(0.83)
Mean AF (Alternative)	56.64	17.23	34.39	52.75	17.49
	(81.39)	(57.53)	(69.75)	(82.42)	(58.68)
Mean AFA	1.89	1.09	1.03	1.69	0.96
	(0.92)	(0.89)	(0.90)	(0.98)	(1.00)
Mean AFA (Alternative)	1.92	1.29	1.04	1.72	1.12
	(0.98)	(1.19)	(0.91)	(1.02)	(58.68)
Mean ln(AFA)	0.49	-0.32	-0.31	0.32	-0.43
	(0.59)	(1.02)	(0.82)	(0.68)	(0.97)
Mean ln(AFA) (Alternative)	0.5	-0.21	-0.3	0.33	-0.32
	(0.61)	(1.09)	(0.83)	(0.70)	(1.02)
Mean Acres Called			31.19		
			(31.86)		

Note. This table shows summary statistics for the outcome variables used in our regressions. Standard errors are reported in parentheses below.

Empirical Strategy

Estimating Equation

Metropolitan asserts that “it is not possible to estimate the exact amount [of water saved] because the acreage and types of crops that would have been grown absent the Program are unknown. Therefore, it is necessary to develop acceptable procedures to estimate the amount of saved water to the degree of accuracy allowed by available data” (U.S. Bureau of Reclamation, Palo Verde Irrigation District, and The Metropolitan Water District of Southern California 2015). As stated, MWD identifies the two sources that could bias their estimate: inaccurate data and the absence of a counterfactual estimate of what crops would have been grown in the absence of the program. We have identified three additional assumptions that could increase MWD's bias: enrolled parcels irrigating at a different level than non-enrolled parcels prior to the program; enrolled parcels irrigating differently than their historical pattern after program enrollment; and called non-compliance from called parcels such that they emit ET readings greater than zero. All assumptions require improved data and a causal estimate for comparison.

Senay et al. (2017) provides not only a higher spatial resolution of ET, but also an ET estimate that incorporates crop choice (ETc). In this way, Senay et al. (2017) address MWD's concern regarding data accuracy; however, accurate data alone cannot contribute the causal estimate required to evaluate the water saved by the program. Without a method that controls for both time and spatial trends, accurate data will still lead to a biased water estimate. We estimate a two-way fixed effects (TWFE) model that controls for non-observable seasonal (temperature, precipitation, crop prices, insect infestations) and unit specific trends in PVID that incorporates improved data and yields a causal estimate.

Because parcels move in and out of treatment based on the call, our treated cohort varies from year to year. We use a TWFE estimator for this reason. Difference-in-differences models assume that treatment is a single event, and thus that treated units always stay treated. The TWFE method allows us to estimate the average treatment effect (ATT) by moving units in and out of treatment while controlling for unit and time unobservables. To estimate the effect of the fallowing program on water use, we estimate the following regression model:

Equation 2

$$AFA_{i,t} = \beta_1 1called_{i,t} + \tau_t + \lambda_i + \mu_{i,t}$$

We use acre-feet per acre ($AFA_{i,t}$) as our outcome variable. Our outcome variable measures water use per acre on parcel i, observed in irrigation season t. We choose to look at irrigation seasons and not monthly observations because irrigation seasons represent the timescale at which farmers are choosing crops. Farmers double crop in PVID, once beginning in August and the next beginning in January. We aggregate monthly ET observations to reflect these irrigation seasons.

The variable $called_{i,t}$ corresponds to the call issued in a specific irrigation season t. $Called_{i,t}$ is a dummy variable that equals 1 when a parcel is called during an irrigation season and 0 if it is not called. A called parcel should be fallow during an irrigation season. Our coefficient of interest is β_1, on $called_{i,t}$ and is our causal estimate. It represents the ATT, or the average change in water use on enrolled parcels, due to a program call. The units of β_1 will be in acre-feet per acre and will replace the total diversions (less measured and unmeasured return flows) in Equation 1.

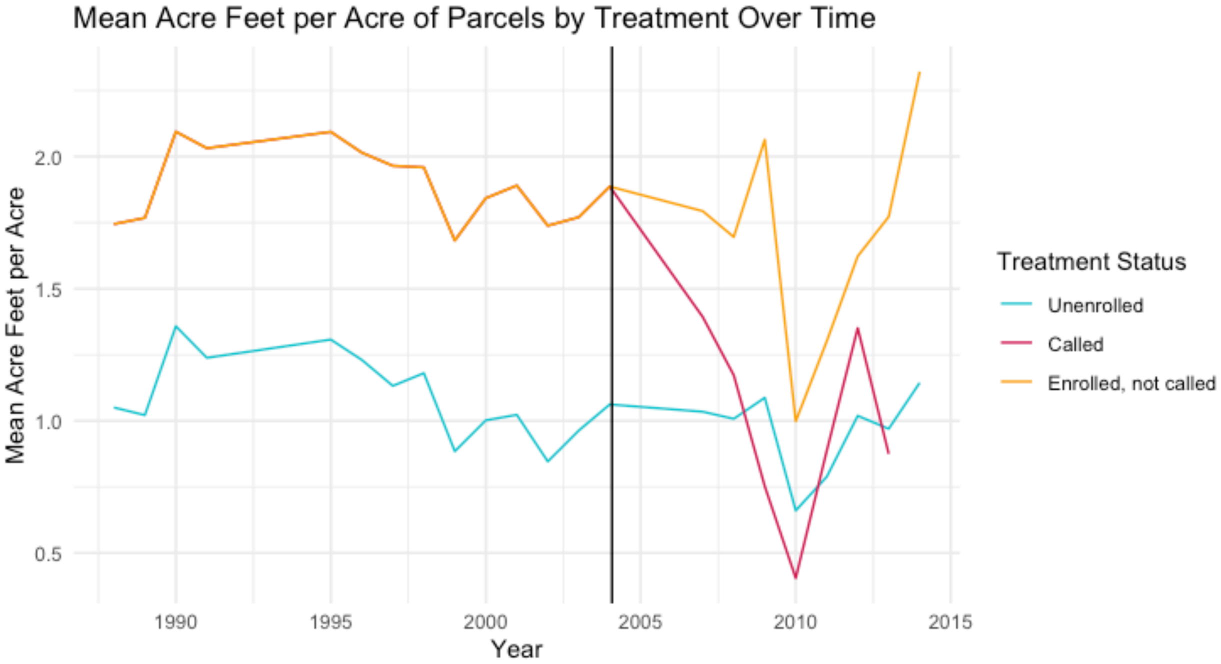
We include two sets of fixed effects in our model: season fixed effects (τ_t) and parcel fixed effects (λ_i). We use parcel fixed effects to remove any variation that is caused by soil quality or farm-specific choices. Season fixed effects control for any seasonal or temporal unobservable variation. Our season fixed effects represent a twelve-month period covering two irrigation seasons. One irrigation season begins in January and another in August. We use a unique fixed effect to represent every single year and then a dummy variable to indicate the season half. We cluster standard errors by 6x6-mile PLSS townships.

Strategic Behavior

An underlying assumption in TWFE is that treated and untreated units follow a parallel trend prior to policy implementation and that treatment is exogenous. In our case, MWD issues the call each season, representing an exogenous shock to farmers. While farmers can choose individual fields to fallow, they do not know the likelihood that their farm will be selected. Parallel trends in treated and untreated units prior to the policy start ensure that untreated units are a suitable control group. The following section discusses pre-trends and the opportunity for strategic enrollment among parcels.

Figure 4

Mean AFA over Time



Note: Pre-trend graph depicting the mean acre-feet per acre on enrolled, called parcels and our control group. Prior to 2005, the enrolled parcel group includes all parcels called in the program. After 2005, only parcels enrolled, but not called, in each irrigation season are included in enrolled (gold line). Our control line includes parcels that are never enrolled in the program and never called (blue). The maroon line represents parcels that are enrolled and called in each season (the treated parcels).

Figure 4 depicts pre-trends in average water use per acre on called versus unenrolled parcels. Prior to 2005, the enrolled group (gold) contains all enrolled parcels (parcels that were called at least once in the program). After 2005, the treatment group depicted in Figure 4 contains only parcels that were called in that irrigation season. The control group contains parcels that were never enrolled in the program. After program implementation in 2005, unenrolled parcels experienced an increase in mean AF per acre, while enrolled parcels experienced a sharp increase and then immediate decrease (-1 AF per acre) followed by a sharp increase (+2.5 AF per acre). From the graph, it is clear that the program led to some decrease of water usage, but the magnitude of savings is not obvious. Unenrolled parcels experience high variability in their irrigation, implying that district-wide consumptive use estimates may not accurately capture program savings. District-wide estimates would attribute any large changes in enrolled district-wide irrigation to water savings from the program, but the graph demonstrates that both treated and untreated parcels decreased water consumption in some years.

Comparing Figure 4 to Table 1 we can observe more trends in irrigation. Table 1 pre-program irrigation on enrolled parcels as 1.89 AFA and post-program, treated parcels as 1.03 AFA. It appears that parcels enrolled and treated in the program decrease water use by about one AFA; however, parcels that are enrolled and not treated remain at pre-program levels of irrigation, 1.69 AFA. It is important to note that enrolled parcels and unenrolled parcels differ by about one AFA, as seen in both Figure 4, which looks at mean AFA per season, and Table1, which looks at mean AFA per half season (irrigation season). And, that enrolled parcels, that are not called, increase their mean AFA over time from 1.89 AFA to 2.32 AFA.

Because MWD announced the program prior to its implementation, the lag from announcement to enrollment leaves the possibility for strategic enrollment. Strategic enrollment would occur if farmers brought marginally productive (previously fallow) land into production for the specific purpose of enrolling the land to be fallowed. The strategic choice would imply that district water savings would be less than anticipated, as long-run total water use would not change on enrolled parcels. We would observe strategic irrigation in the years preceding enrollment, during the eligibility period of 2003-2004. If parcels irrigated strategically, then we would expect to see an increase in irrigation during 2003 or 2004. Figure 4 does not indicate that enrolled parcels increased abnormally in irrigation during 2003 or 2004.

Figure 4 shows that prior to 2005, irrigation on enrolled parcels was higher than that on unenrolled parcels. Parcels appear to follow a parallel trend in irrigation prior to treatment (2005), despite the enrolled group being higher. We run an event study on the difference between the two groups and find statistically significant differences between the annual change in AFA for treated vs. untreated parcels. Results for this regression can be found in Table 5 located in the Appendix A. Table 5 includes season and township fixed effects for all parcels prior to enrollment. This significant difference could later contribute to the bias in MWD's annual estimate of water saved.

Results

Main Specification Results

Table 2 shows the results for our coefficient of interest, β_1 , on variable $called_{i,t}$. Our β_1 represents the change in AFA on called parcels due to program implementation. Each model uses a combination of season and township FE. We find a statistically significant effect of the program ($p < 0.001$) across all models. We find that in each irrigation season, parcels that are called on average save 0.8 AF of water less than those not called. We find that on average enrolled parcels save about 1.6 AF of water per acre due to enrollment.

Table 2

Main Regression Specification Results

	y = AF	y = Alt AF	y = AFA	y = Alt AFA	y = ln(AFA)	Alt y = ln(AFA)
	(1)	(2)	(3)	(4)	(5)	(6)
Acres Called	**−0.82*****	**−0.82*****				
	(0.13)	(0.13)				
Called=1			**−0.81*****	**−0.80*****	**−0.71*****	**−0.71*****
			(0.04)	(0.05)	(0.04)	(0.04)
Num. obs.	147436	147436	147436	147436	147435	147435
R^2 (full model)	0.87	0.87	0.76	0.77	0.83	0.84
R^2 (proj model)	0.03	0.03	0.04	0.03	0.04	0.04
Adj. R^2 (full model)	0.86	0.86	0.75	0.76	0.83	0.84
Adj. R^2 (proj model)	0.00	0.00	0.01	0.00	0.02	0.02
Num. groups: Parcels	3596	3596	3596	3596	3596	3596
Num. groups: Season Half	2	2	2	2	2	2
Num. groups: Year	22	22	22	22	22	22

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Note. The above table shows the main regression results for Equation 2. Columns 1 and 2 show the results when the outcome variable is in acre-feet, columns 3 and 4 when the outcome is in acre-feet per acre, and columns 5 and 6 when the outcome variable is the natural log of acre-feet per acre. “Alternative” refers to variables built with sum ET, while non-alternatives are built with mean ET. Standard errors are clustered by townships.

Robustness

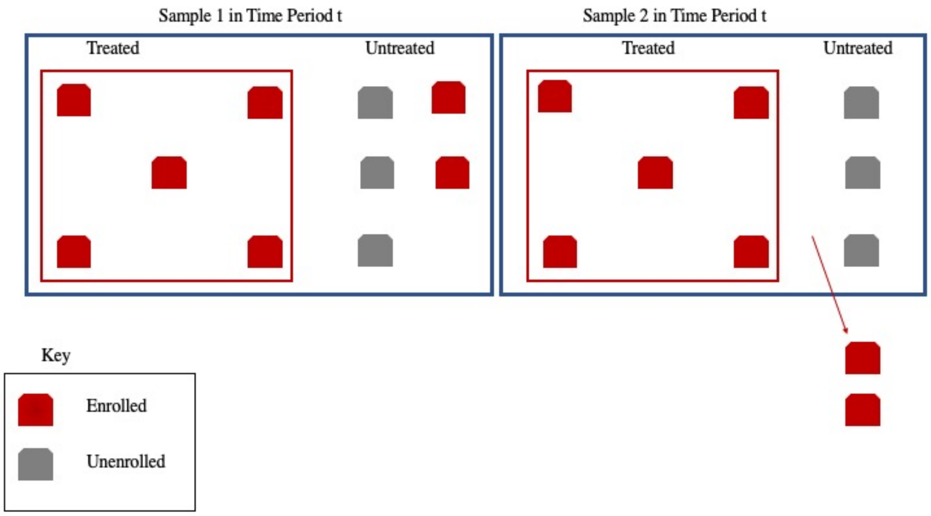
The standard way to evaluate policy as a treatment is with difference-in-difference (DD). Difference-in-difference requires that treatment be exogenous and that treated units remain treated. We deviated from DD because our treatment is not permanent. In our setting, MWD’s call “treats” parcels during an irrigation season and after the irrigation season ends, treated parcels become untreated. In this way, parcels move in and out of treatment depending on MWD’s discretion. The treatment imitates an exogenous shock more than it imitates a single, permanent event.

In panel data, many observations are followed over time. The benefit of a panel data is that they allows one to control for spatial-specific and unit-specific confounders, two way fixed effects (TWFE); however, as Imai et al. (2021) and Goodman–Bacon (2021) demonstrate, controlling for spatial and unit-specific confounders could bias the TWFE average treatment effect (Goodman-Bacon 2021; Imai and Kim 2021). Goodman–Bacon (2021) and Chaisemartin and D'Haultfœuille (2020) show that the bias stems from heterogeneous treatment or treatment that is not a single event (de Chaisemartin and D'Haultfœuille 2020; Goodman-Bacon 2021). In short, the bias comes from including treated or not-yet treated units in the control group. Because our design does not consider treatment as a single event, but instead considers treatment to be an exogenous shock, we do not believe our estimator to be biased. Nevertheless, we estimate a version of the model that omits enrolled parcels from the control group once they are not called.

Our alternative specification includes a strict control group that will not include observations that have been previously called in the control group. Figure 5 depicts the two considered scenarios: where enrolled (but not called) units are used in the control group (sample 1) and where enrolled (but not called) units are dropped from the pure control group (sample 2).

Figure 5

Example of Dropping Not-Yet-Treated



Note: This figure shows the type of observation we remove for the robustness checks. As seen on the left, enrolled parcels can end up in the untreated group. To control for this bias, untreated, but enrolled parcels are removed from the untreated group.

Table 3

Robustness Specification Results

	y = AF (1)	y = Alt AF (2)	y = AFA (3)	y = Alt AFA (4)	y = ln(AFA) (5)	Alt y = ln(AFA) (6)
Acres Called	$\mathbf{-0.82}^{***}$	$\mathbf{-0.82}^{***}$				
	(0.13)	(0.13)				
Called=1			$\mathbf{-0.81}^{***}$	$\mathbf{-0.80}^{***}$	$\mathbf{-0.71}^{***}$	$\mathbf{-0.71}^{***}$
			(0.04)	(0.05)	(0.04)	(0.04)
Num. obs.	147435	147435	147435	147435	147435	147435
Adj. R^2 (full model)	0.86	0.86	0.75	0.76	0.83	0.84
Num. groups: Parcels	3596	3596	3596	3596	3596	3596
Num. groups: Season Half	2	2	2	2	2	2
Num. groups: Year	22	22	22	22	22	22

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Note. The above table shows the robustness regression results for Equation 1, where not-called parcels are dropped. Columns 1 and 2 show the results when the outcome variable is in acre-feet, columns 3 and 4 when the outcome is in acre-feet per acre, and columns 5 and 6 when the outcome variable is the natural log of acre-feet per acre. “Alternative” refers to variables built with sum ET, while non-alternatives are built with mean ET. Standard errors are clustered by townships.

Discussion

Our results indicate that on average, parcels called in each irrigation season irrigated 81% less per acre than those not called. To compare these estimates to those produced by MWD, we convert the coefficients to acre-feet using the following equation:

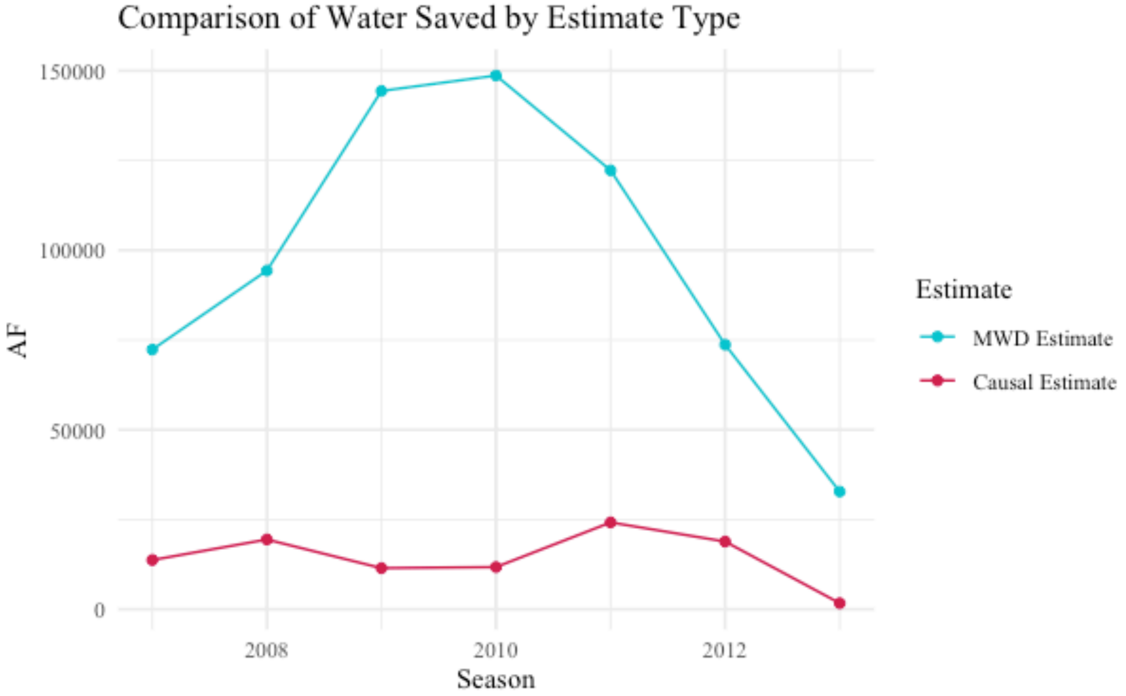
Equation 3

$$Average\ Water\ Saved\ in\ AF\ per\ year\ =\ 2\ *\beta_1\ *\ Total\ Called\ Acres$$

Using the estimates produced by Equation 3, we create Figure 6. We include an additional estimate to demonstrate the difference between using ET data and MWD estimation method to produce an annual amount of water saved (MWD Method with ET, green line). We show that the difference is our estimate is not just driven by data sources, but also by differences in MWD's assumptions about irrigation on uncalled parcels. In Figure 6, the blue line represents the amount of water that MWD estimates it saves using the Annual Use Method.

Figure 6

Policy and Causal Estimates Compared



Note: The graph depicts the average saved water estimated by MWD with Equation 3 (blue) and the average saved water estimated with Equation 2 and Table 2 (maroon).

We find that an 71% decrease in irrigation on enrolled parcels in a season corresponds to 1.6 af/acre of water saved. As an example, if parcels were growing one of the more water intensive crops, alfalfa at 3.8 af/acre, a 1.4 af/acre reduction would result in sweet corn, lettuce, or wheat (between 2.1 af/acre and 2.5 af/acre). While we do not have crop data for enrolled or unenrolled parcels, we do have district-wide crop trends. Figure 2 shows the trends in crops grown as a percent share of total farmed acreage. We select the seven most water intensive crops, which also make up most crops produced in PVID. Figure 2 does not depict a trend in sweet corn, lettuce, or wheat, but it does depict a slight increase after 2009 in small grain production, which use 1.8 af/acre, and a slight decrease in alfalfa production after 2005.

In order to estimate the average enrolled acres each irrigation season, we sum the acres called in each irrigation season as found in BOR Verification Reports. By substituting both the average AFA on an enrolled parcel and the average annual enrolled acres into Equation 3, we estimate the total saved water as 53,928 af/year. Metropolitan claims the average water saved by the program is 96,494.88 af/year; our estimate is 56% smaller than MWD.

In Water Estimation Process, we outline three sources of bias that we would expect would overestimate water savings in PVID. First, we suggest that the Annual Use Method assumes that enrolled and unenrolled parcels irrigate at the same level prior to enrollment. In both our event study, Table 4, and our pre-trend, Figure 4, we find that enrolled parcels irrigated at a higher level than unenrolled parcels, but vary significantly over time. This observation indicates that MWD's method will be biased upwards, since it assumes that enrolled and unenrolled parcels are comparable. In this way, the first assumption of MWD is not met: enrolled parcels do not irrigate at the same level as unenrolled parcels. Our Table 4 illustrates that enrolled parcels, even though they irrigate more, do not irrigate as much as MWD had estimate. We find that, on average, enrolled parcels irrigate at about 2 AFA, while MWD assumes that enrolled parcels irrigate at about 5 AFA.

Second, MWD assumes that non-called parcels will continue to irrigate at the same pre-program water level. If enrolled, non-called parcels irrigate more in seasons when they are not called, then MWD would save less water as non-called parcels would, on average, increase their water consumption. If farmers need more water in order to bring fallow fields back into production, then water use on a previously called field will be higher. Or, if farmers compensate for a called field's lost production in the year in which it is not called, then average water use will be higher. Figure 4 removes called parcels from our treated group and graphs unenrolled against non-called parcels. We observe that enrolled, non-called parcels increase in irrigation after the start of the program. Since MWD expected enrolled parcels to irrigate similarly to the level when they enrolled, uncalled parcels irrigating differently would decrease water savings. Figure 4 illustrates that differences in post-program irrigation behavior on enrolled parcels is not a source of bias. Parcels used in the program (gold line) decrease irrigation and parcels enrolled, but not called (maroon line), increase in levels of irrigation.

Building on the earlier concern of strategic irrigation, is a concern of non-additionality. Non-additionality is the concern that farmers are being paid to fallow land that they would have fallowed less regardless. One cause of non-additionality would be strategic enrollment, which we have addressed previously. A second cause of non-additionality would be if farmers irrigated enrolled fields less, even before the start of the programs. If this is the case, then we would expect to see lower irrigation when enrolled parcels are not called. Table 1 displays the mean seasonal AFA on enrolled, not called parcels, and not enrolled parcels. Table 1 identifies that enrolled parcels do not increase irrigation prior to enrollment and maintain irrigation patterns after enrollment. We do not find evidence for strategic enrollment or non-additionality in our pre-trend analysis.

Our causal estimate reveals that program savings are much lower than MWD's estimated savings. We demonstrate where the sources of bias are likely to occur, and find that one, the assumption that enrolled and unenrolled parcels are comparable, does inflate MWD's anticipated water savings. Our causal model recovers a more reliable average change in AFA for enrolled parcels that can be attributed to program implementation.

Conclusion

The “megadrought” in the West has put pressure on policy makers to reduce water consumption immediately. Because institutional change is costly and slow, short-term solutions that work within the existing legal and political environments are necessary. Rotational fallowing is an alternative transfer method that moves water from agriculture to urban environments; however, the expediency and necessity of water reductions has led to these programs being largely under-evaluated and over-implemented. While the mechanism itself reduces water consumption and successfully transfers water, it does not do so at the magnitude believed. More importantly, if these mechanisms are not evaluated with more precise, spatial data, then it can lead to an over diversion of water, exacerbating existing shortages. In the case of PVID, the lack of ET data combined with a counterfactual parcel-level estimate revealed that the program could be diverting 311,00 af over the actual, saved amount during our period of analysis.

We demonstrate the importance of employing ET in estimating water savings by using ET as a direct input into our causal model. As critical as accurate data are, they cannot estimate a counterfactual world without empirical assistance. We contribute a causal estimate of water savings that employs the best available water use data and current econometric approaches. We find that, on average, the program caused called parcels to save 1.6 af/acre per year. While the rotational fallowing program did create water savings, we find that our estimated water savings are 56% of MWD’s estimate. Our findings demonstrate the importance of using causal inference to evaluate alternative transfer mechanisms. As more policy makers and researchers advocate for market-based approaches, it is imperative that we evaluate these approaches with methods that incorporate current data and empirical methods. Our findings do not invalidate ATMs as an approach to managing water scarcity, but rather underscore the importance of using current data, methods, and counterfactual estimates in policy evaluation. Without proper evaluation techniques and access to data, policy makers and farming communities cannot measure the unfolding impacts of market-based approaches.

The Colorado Big Thompson Project: Impact of Share-Based Water Allocation on the Use of Prior Appropriation Water Rights

Introduction

Western cities have increased their demand for water and lack the supply of water to meet this demand, having rights to only 20% of the water supply. Economists have estimated that cities are willing to pay up to $16,000 per additional acre-foot[6] of water. Farmers, on the other hand, hold the remaining 80% of the water and value their water at about $1,000 per acre-foot (Libecap 2011). As drought is expected to persist, the supply of water will decrease, causing cities and industries to reevaluate their water needs (Bond et al. 2019; Engelbert and Scheuring 2022).

One method of addressing this water scarcity is through trade. Trade enables water to move from lowered valued uses to higher value uses through the coordination of the price system. Under a well-functioning market, one would expect farmers to sell their water to cities to meet this new municipal demand (Libecap 2011). Given the magnitude of these gains, it appears that trade would help alleviate future water scarcity; however, water transfers in the American West are costly and these costs–political, economic, and legal–have historically hindered past water trade (Getches-Wilkinson Ctr. for Natural Res., Energy, and the Env't 2013). Prior appropriation, the doctrine that allocates water in the American West, is one example of a legal institution that increases the costs associated with trade.

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[6] An acre-foot describes the amount of water required to cover one acre with one foot of water, or 326,000 gallons of water.

Economists have demonstrated that prior appropriation is inefficient at addressing current water allocation because it creates high trading costs (Burness and Quirk, 1980a). To decrease these transaction costs, researchers suggest moving towards share-based allocation (Carey and Sunding 2001; Culp, Glennon, and Libecap 2014; Leonard, Costello, and Libecap 2019). Some of these same researchers use theoretical models that identify gains from transitioning away from prior appropriation to a share system but have not demonstrated these gains empirically. Where empirical work on prior appropriation exists, it focuses on either prior appropriation or shares, not both (Cobourn et al. 2022; Xu, Lowe, and Zhang 2014; Ji and Cobourn 2018; Howe and Goemans 2002; Womble and Hanemann 2020).

Researchers have treated share-based and appropriative rights as if they exist in isolation as mutually exclusive systems. On the contrary, where share-based markets exist, they are often overlapping with existing appropriative claims. This treatment of shares and appropriative rights as mutually exclusive overlooks two critical issues: (1) any future implementation of shares would likely overlap with existing appropriative rights and (2) attributing successful outcomes to shares when shares often coexist with appropriative rights may ignore the contribution of polycentric institutions (Anderies and Janssen 2013; Lofthouse and Herzberg 2023).

The Colorado-Big Thompson Project (CBT) is the best example of a large-scale share-based market, and is often treated as if it were only a share-based system (e.g. Carey and Sunding 2001; Howe and Goemans 2002). The CBT allocates supplemental water as shares, but overlaps with existing appropriative rights. This interaction means that individuals within the CBT have access to both supplemental, share-based water and appropriative rights. The past research on the CBT has looked at aggregate trade data that describes broad patterns in water use (Howe and Goemans 2003; Womble and Hanemann 2020). By looking at aggregate share data, research may be misleading in its conclusions, as it does not consider the overlapping nature of the two institutions in place and the changes in appropriative claims over time.

We develop a novel, spatial panel that captures changes in crop choice and trade in the CBT and compare these observations to a panel of appropriative rights outside of the CBT. By focusing on appropriative rights, we can better compare the outcomes of overlapping institutions to the outcomes of non-overlapping institutions. Specifically, we are interested in how overlapping institutions create differences in the use of existing appropriative rights. We characterize transfers, priority, and crop choice associated with appropriative rights and compare those outcomes of rights under overlapping institutions the rights under non-overlapping institutions. We follow the example of prior literature and separate priority into three tertiles of low, medium, and high priority water rights, based on the location of that water right and the year (Ji and Cobourn 2018).

We find that there is a significant difference in the number of trades, the amount of water transferred from ag-to-urban, crop choice, and priority within crop choice when comparing appropriative rights within to outside the CBT. In particular, we find that appropriative rights holders transfer less water from ag-to-urban than those outside the CBT, and that individuals within the CBT are less diverse in their crop choice between priority tertiles.

We begin by providing context on the two current approaches to allocating water, prior appropriation and shares. We demonstrate how both approaches are used within the

CBT and classify it as an example of polycentricity. Finally, we discuss how overlapping institutions might impact key decisions over the use of appropriative rights, such as trade, priority, and crop choice.

Background

Prior Appropriation

Prior appropriation defines water rights through seniority. Senior, or the oldest, claims receive their water first, with more junior claims receiving water after the senior user's right has been fully delivered. The doctrine requires that a water right prove two qualities: consistent use and beneficial use. All water rights must have a specified quantity of water that is being put towards "beneficial use," which most states identify as for industry, agriculture, or a municipality. They must consistently use this amount of water, for the specified beneficial use, else it is reallocated to another user who requires water. This doctrine, initially designed to combat speculation in water, sharply weakens incentives to conserve among current rights (Libecap 2011).

Because water is allocated through priority, there are high costs associated with trading (Banks and Nichols 2015; Libecap 2008). Under prior appropriation, users who want to trade water or change its use, must prove the trade does not alter the ability of other users to receive water. If a senior user wants to change the use of their right or the location of their diversion, they must also prove that it does not impact return flow. Return flow is the water that seeps back into the waterways after being applied to irrigated land. Since the return flow on some crops can be up to 50%, junior users rely on this process for the majority of their water allocation. This condition is called "proof of non-injury" and is very costly and litigious to prove (Womble and Hanemann 2020). In fact, legal scholars, theorists, and case studies on prior appropriation cite this requirement as preventing most water trades (Burness and Quirk 1980; Libecap 2008; Smith 1989; Thompson 1993). Trade is particularly important as it would alleviate some water scarcity by allowing individuals to put water to its highest valued use (Culp, Glennon, and Libecap 2014).

If trade is costly, research has shown that farmers use crop choice and crop composition as a response to water scarcity. Cobourn et al. (2022) and Xu, Lowe, and Zhang (2014) find that low priority farmers in the Snake River Basin grow drought resistant crops and less water intensive crops (including fallowed land), which could make them less susceptible to climate variability. This change also decreases the income in a growing season as these crops have lower profit margins than more water intensive crops, like alfalfa or corn. Because prior appropriation is ubiquitous across the West, there are few empirical studies that compare crop choice under various allocation systems for water.

Comparing Prior Appropriation to Shares

Because of these restrictions on trade and use, researchers argue that trading appropriative rights will not result in a sufficient response to growing scarcity; but rather, appropriative rights could be replaced by shares to yield higher gains from trade (Burness and Quirk 1979, 1980a, 1980b). Share-based allocation entails a total consumption amount that corresponds to a sustainable rate of resource withdrawal. This total allowable withdrawal is then divided into shares that individuals have a right to use, sell, or in some cases, rollover to the next season. Because shares are not allocated through priority, they do not have the same limitations on trade or use. Farmers, cities, environmentalists, or interested parties can purchase the shares. These shares can be sold, leased, or banked depending on the preferences of the owner. If an owner has excess shares of water, they can sell them on the current market, or bank them in a reservoir to sell or use during a dry season, as other users do not rely on this return flow for their allocation, unlike in prior appropriation. In this way, shares provide a method of smoothing water supply, but do not provide the same level of certainty as prior appropriation for senior users.

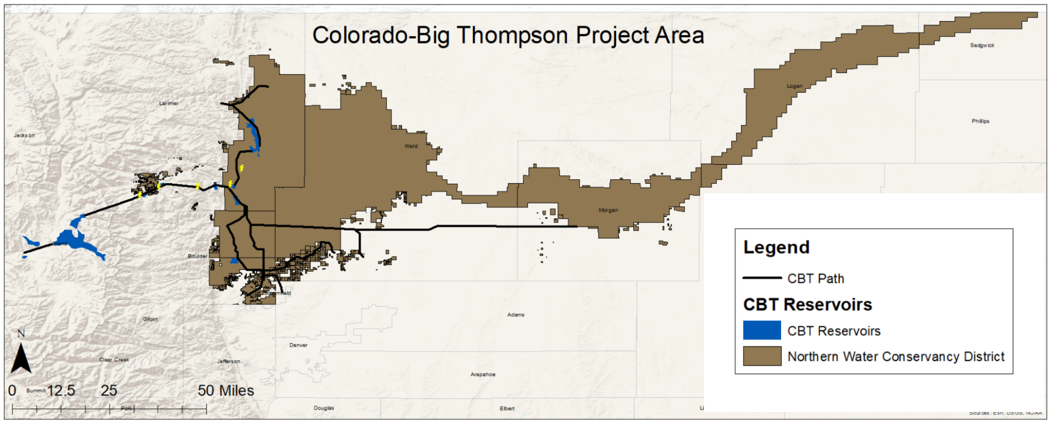
Underlying both allocation structures is variability due to precipitation, temperature, and snowpack. This variability changes the amount and timing of water flow (Gordon et al. 2022; Kiewiet et al. 2022). One approach to mitigating flow variability is trade (Culp, Glennon, and Libecap 2014). Under prior appropriation, users would have to prove non-injury for every proposed water transfer. This transfer process would be costly and slow, possibly limiting the ability of appropriative rights to alleviate water scarcity in a way that allocates water to its highest valued use. Shares would not carry this costly process, as water is divided proportionally amongst users and not allocated according to priority. Users who want to trade their water do not have to prove that others' priority would be affected by this trade, and are not required to use their water for a particular purpose. In addition, users can bank water during wet seasons, smoothing the supply of water during a drought.

The Colorado-Big Thompson Project

One of the longest and largest examples of share-based allocation is the CBT. In the 1900s, eastern Colorado, where the CBT is located, required a higher supply of water than was consistently available. This shortage was due to an increasing population that outpaced the current supply of water. Politicians and local businessmen developed “The Colorado-Big Thompson Project” that secured up to 310,000 acre-feet (af) to be delivered annually. Figure 7 illustrates the CBT project area, boundary (which is also the Northern Water Conservancy District boundary), and infrastructure used.

Figure 7

CBT Area and Infrastructure



Note: Figure 7 is a map of the Colorado-Big Thompson Project area in Northern Water Conservancy District (brown). The project is a system of tunnels (black) and reservoirs (blue). Tunnels take water from Horsetooth Reservoir and transfer it nearly 2,600 ft lower and 250 miles away to the Greeley/Denver area.

The project was largely possible because of the surplus water available on the Western slope, which was due to little development and population on the western side of the state. Water used for this project was not allocated under prior appropriation, meaning the water used was not allocated through priority, and thus was not subject to the same rules and did not have residual claimants. Individuals within Northern Water Conservancy District (Northern Water) have access to CBT “project water,” and retain their existing appropriative rights.

Project water is allocated as shares, or units, that can be bought, leased, or stored annually. One unit represents one acre-foot of water, if the quota is equal to 100%. The quota represents the percentage of each CBT unit that is available for use and is based on the total available CBT water in a given year. For example, a 100% quota implies that 100% of one unit of CBT water is available. If the quota is 90%, then 90% of one unit of CBT water is available. Each Spring, board members hear reports on water availability before announcing the quota. The quota is countercyclical, meaning a higher quota implies a dry year (and thus more of a need for supplemental water).

The only current restriction on CBT water is that it cannot be moved outside the boundary of Northern Water. Earlier iterations of program rules required that CBT water could not be used to increase the total number of irrigated acreage in the district and that it could only be used to top off existing prior appropriation claims (Tyler 1992). Over time, CBT water was not restricted to topping off appropriative claims, but instead included opportunities for non-appropriative rights’ holders to purchase units. Individuals, municipalities, and businesses can submit an application to Northern Water to receive CBT water in any given year. As a result, individuals inside of the CBT can hold appropriative rights, shares, or both at any given time.

The CBT as an Overlapping Institutional Example

Literature that focuses on the CBT largely treats it as an idealized share-based system, despite individuals within it still holding prior appropriative rights (e.g. Howe and Goemans 2002; Womble and Hanemann 2020). This oversight could create problems. Policymakers advocate for share-based systems to address water variability, and use the CBT as that justification; however, using the CBT as an example of share-based allocation is not accurate. The CBT is an example of two property rights systems that overlap, and thus outcomes cannot be attributed to solely share-based allocation.

This overlap creates questions regarding how share-based rights interact and change appropriative rights and vice versa, especially over time. Overlapping institutions, both in scale and in scope, can decrease the robustness of a system's response to change (Jagers et al. 2020; Morrison 2017). In other cases, they might create confusion about which set of rules will be enforced, thus weakening the ability of both institutions to allocate resources (Firmin-Sellers 1995). Competing interests, heterogeneity, multiple sources of information, or lack of clear enforcement of rules can weaken the effectiveness of institutions to respond and adapt to participants' choices (Firmin-Sellers 1995; Ostrom 1990; Varughese and Ostrom 2001).

In contrast, some literature would suggest that overlapping institutions increase the resilience of a system. The overlapping informational links of a system can create redundancies that protect an institution, if one link is severed (Marshall 2009; Ostrom 2009), and create a policy environment that promotes learning and adaptation (Anderies and Janssen 2013; Lubell and Robbins 2022). In addition, overlapping, polycentric systems may increase the ability of that system to solve issues related to climate change

(Lofthouse and Herzberg 2023). Thus, where we see overlapping institutions, it is important to understand how these institutions interact with each other and to compare the resulting outcomes.

We look at outcomes examined by both the share and appropriative literature: trade, priority, and crop choice. These outcomes are often used because they can reflect the transaction costs (e.g. Culp, Glennon, and Libecap 2014; Womble and Hanemann 2020) and the ability of farmers to response to weather variability over time (e.g. Cobourn et al. 2022; Xu, Lowe, and Zhang 2014). For example, a farm within the CBT has access to share-based water, which carries lower transaction costs, but also retains prior appropriative rights, then that farm has more than one option for responding to weather variability. A low-priority farm in the CBT may choose to permanently transfer or abandon appropriative rights and rely solely on share-based water for their crops. Or, that same farm may choose to change their crop production and retain the same combination of appropriative and share-based rights. Or, even still, that farm may choose to not use share-based water and obtain more senior rights to maintain crop production. It is not clear that crop choice or trade are mutually exclusive responses to weather variability.

Over time, as individuals in the CBT respond to weather variability, they might transfer appropriative rights away, creating different trade patterns, priority, and crop choices across the boundary. In the second case, individuals within the CBT might be indistinguishable from those outside the CBT, as multiple sets of rules create confusion and lead to low adoption of the new institution. In either case, it is of primary importance to determine whether access to a share-based market changes the behavior of appropriative rights holders because new implementation of shares would often overlap with existing appropriative rights. Thus, understanding how mechanisms like priority, trade, or crop choice change over time as a result of this overlap could provide the necessary information to policymakers and managers to help ease this transition.

Data and Methods

We create novel panel data to track appropriative water rights from 1936-2023 (87 years) to provide an assessment of the long run performance of appropriative rights under overlapping institutions. Previous work has focused on shorter periods such as 15 years (Cobourn et al. 2022), 14 years (Li, Xu, and Zhu 2019), 7 years (Ji and Cobourn 2018), or 29 years (Xu, Lowe, and Zhang 2014). By expanding the timeframe as well as using a larger sample of water rights in northern Colorado, we can better understand the effect of temporal trends in temperature and precipitation, as well as capture long-term impacts of access to share-based water.

Appropriation Claims and Trade

The Colorado Decision Support System (CDSS) keeps a database of every appropriative claim in the state–its location, its use, the associated ditch structure, and any changes made to this water right over time. We use all of the rights associated with Division 1, which includes the CBT and surrounding area. Each water right has a unique structure identifier (WDID) and appropriation date. For each unique water right, we identify if the right is an original or traded right. If the right is traded, we use an algorithm that matches the transfer, extracts the location of the transfer, and assigns a trade year to the transfer.[7] We observe 77,013 changes that occur over 1859 to present. Of those 77,013 changes, 6,044 are abandoned rights, and 13,571 are transfers, and 57, 398 original rights. We track 58,928 unique water rights over time; a unique water right represents a creation of a new appropriation point, or in some cases, an alternative point of diversion.[8] Our water rights begin in 1859 and our transfers end in 2063.[9] We allow our sample to include all original claims, but restrict transfers and abandoned rights to after 1936 and before 2020.[10]

Crop Choice

CDSS also produces a shapefile that contains polygons of irrigated acreage in each water division. Each polygon contains crop choice and land use data, as well as a unique identifier (WDID) that indicates the water right(s) associated with that polygon. The polygon itself represents a field in Division 1. We used these data and matched them to a shapefile of the CBT (Division 1 - South Platte Irrigated Lands (1956-2020) 2022). We are able to identify which irrigated polygons fall inside of the CBT, which diversion points irrigate a specific polygon, and what was being grown. These data allow us to observe crop choice in the following years: 1956, 1976, 1987, 1997, 2001, 2005, 2010, and 2020.

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[7] For a detailed explanation of how the ID and matching occurs, see Appendix B.

[8] Some transfers have new identifications, but are not logged with an original entry. This process leads to the total unique water rights exceeding the original water rights.

[9] Water transfers after 2023 are typically part of an augmentation plan or reservoir storage, or a location transfer of an abandoned right to a reservoir. These future transfers make up 28 observations.

[10] We look only at transfers that occurred during the CBT, but want to include water rights that were established prior, since they are still in use.

Colorado-Big Thompson Project

We obtained a shapefile of the CBT project area, which is also the district boundary of Northern Water, from Colorado Decision Support Systems (CDSS). The shapefile indicates when individuals, institutions, and counties joined Northern Water. We use this area to determine if irrigated land falls within or outside of the Northern Water, and thus if the water from a particular water right is used within the CBT. In the case that a water right did not match irrigated land, we coded based on location of the right. If an appropriation point fell inside of the CBT, it was included in the district. Because land is added to the district up until 2013, we use the intervals of our crop data to identify the boundary in that time.

We outline the hypotheses we test in each section and then use a combination of t-tests, ANOVA, Tukey HSD, and Kruskal-Wallis to determine if the means between samples are significant. We interpret these results with existing work on appropriative and share-based rights.

Hypotheses, Results, and Discussion

Trade

We first examine how overlapping institutions differ from non-overlapping institutions in terms of trade. Trading rights under prior appropriation is often costly and uncertain, as an individual must prove through water court non-injury and beneficial use. Thus, appropriative transfers usually follow economies of scale, where larger amounts are transferred in a single trade. The likelihood that a water transfer occurs is related to the size, use, location, priority, and whether or not the transfer crosses water division boundaries (Bovee 2020; Hagerty 2022; Howe and Goemans 2002; Value of Water – Selling Colorado Water 2022; Womble and Hanemann 2020). In the case of the CBT, individuals within the boundary have access to supplemental water in addition to their appropriative rights (PA rights), while individuals outside of the CBT only have access to appropriative rights.

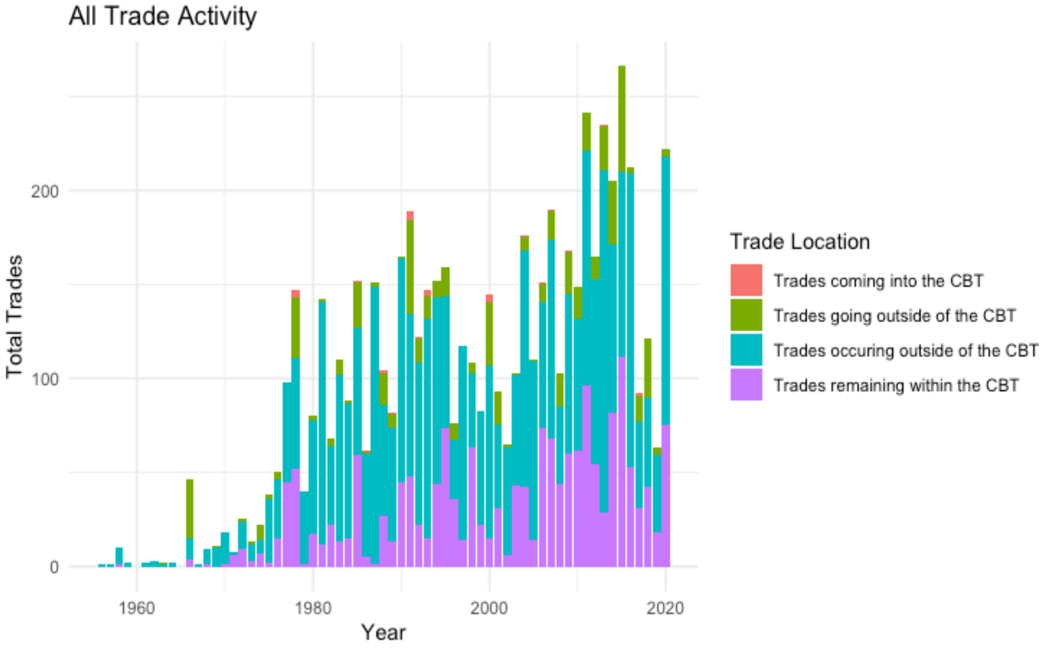
The overlap of institutions within the CBT could alter the behaviors of individuals within it, as the relative cost of trading or using water changes. For example, we expect that under low transaction costs, there would not be a difference in the number of appropriative rights traded; however, if high transaction costs are present, we would expect higher valued appropriative rights to be traded. We would also expect that lower transaction cost trades (trade of shares) would occur prior to higher transaction cost trades (appropriative trades). Thus, we would expect fewer appropriative rights to be traded within the CBT when compared to outside of the CBT.

We look at trade patterns within and outside of the CBT of PA rights. We analyze the total amount of water traded (location change), total number of use changes, composition of use changes, and characteristics of trades. Because trading appropriative rights is costly, the number of transfers, as well as the quantity of water traded within a boundary, could indicate the relative costs within that location for trade. Trades can take two forms: they can either be within the boundary, that is between individuals within the CBT or between individuals outside of the CBT, or they can be over the boundary. In this case, a trade could be from the CBT to outside of the CBT, or from outside of the CBT to the inside of the CBT.

Figure 8 shows the overall number of trades occurring in Division 1. We observe few trades coming into the CBT, but many trades flowing from the CBT to outside of the CBT each year. Both groups are actively trading rights within their boundaries, with the CBT trading more rights within the boundary.

Figure 8

All Trade Activity



Note. The above figure shows the number of trades, including both location and use changes, that occur from 1956 to present. Purple represents trades that occur within the CBT, blue represents trades that occur outside the CBT, and peach and green represent trades occurring between, with the color reflecting the place of origin.

We use an ANOVA test to test for difference in means in both types of trades. [11] We find that individuals within the CBT tend to transfer fewer rights in a year on average compared to individuals outside of the CBT ($p < 0.001$). When looking at transfers that occur from the outside of the CBT to inside of the CBT and transfers that occur from

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[11] ANOVA tests are used to compare means of more than one group. In this case, I test the means of trades belonging to a boundary group across all years, thus having more than two means.

within the CBT to outside of the CBT, we do not find any significant difference in the number of transfers that occur each year. This conclusion holds when we test the amount of water traded between the boundary; we find that there is no difference in the amount of water traded from outside of the CBT to inside of the CBT, or vice versa ($p = 0.3$).

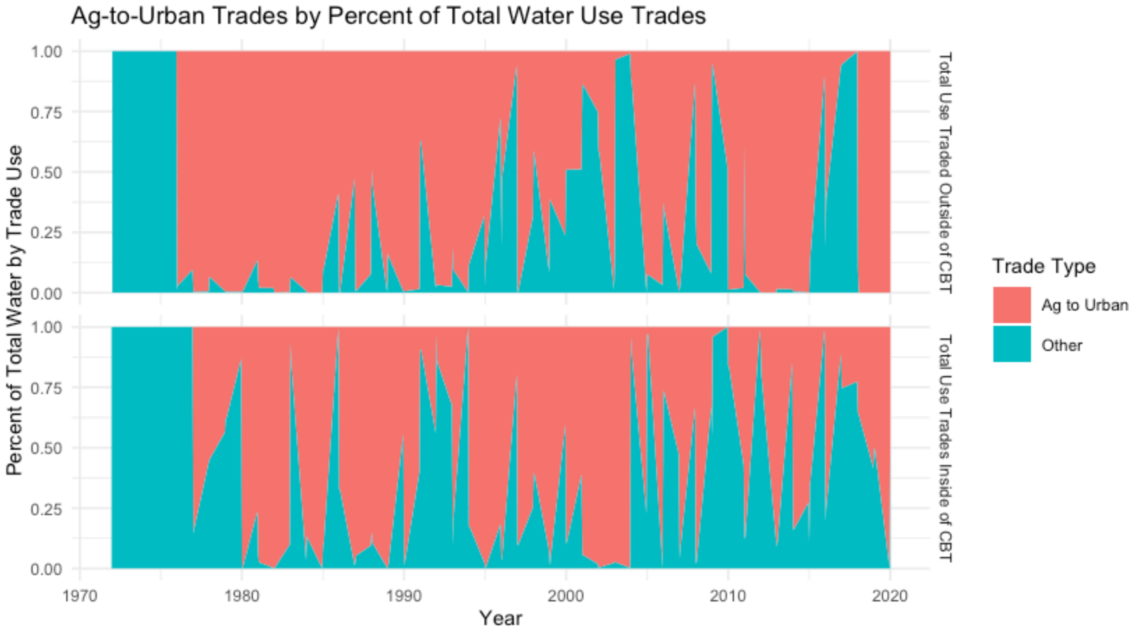
Trade can also change the spatial composition of priority over time. If an individual transfers a more senior right, the seller's location loses a senior right while the location receiving the right increases in priority. Higher priority transfers tend to entail lower costs, so if transaction costs are high, we would expect transfers to have high priority. On the other hand, if transaction costs are low, then we would expect to see no difference in the priority transfers.

We sort traded rights into three tertiles: low priority, medium priority, and higher priority based on the appropriation years of all trades in that year. We find that transfers outside of the CBT are, on average, four years senior to those rights being traded within the CBT ($p <0.001$), and transfers outside of the CBT are, on average, of slightly higher priority tertile ($p < 0.001$). This is in contrast to the baseline differences in priority: rights within the CBT have a mean appropriation year of 1894, while rights outside of the CBT have a mean appropriation year of 1892. When we look only at transfers that occur across the boundary, we find that rights coming from outside into the CBT are of a higher tertile ($p<0.05$) than rights moving from inside out of the CBT.

Another contributor to the value of a trade is the difference in use. Appropriative rights specify a quantity, priority, and use. Recently, demand for water has increased due to growing populations. Many cities require more water than they have had access to in the past and this need has led to "ag to urban" transfers, where water is transferred from agricultural use to municipal use. Historically, these transfers have been politically contentious, but highly valued (Libecap 2011). We pay particular attention to this type of trade within our data. Figure 9 shows the percent of total amount of water that went from agriculture to urban areas outside of the CBT. The bottom panel shows the percent of total water transfers that occurred inside of the CBT. The color represents the change associated with the trade: peach represents an agriculture to urban transfer and blue represents "other". The category "other" represents any trade that did not occur from ag-to-urban, such as ag-to-ag, urban-to-urban, reservoir to ditch, etc.

Figure 9

Ag-to-Urban Transfers



Note. The above figure shows the percent of total water transferred from agriculture to urban over time and by location. Other refers to any transfer that occurs outside of ag-to-urban (urban-to-urban, ag-to-ag, etc).

We test the null hypothesis that the amount of water associated with ag-to-urban transfers within the CBT is not different from those same transfers outside of the CBT over time. We use a Tukey-HSD test to determine if the mean amount transferred is statistically significant based on location and use ($p < 0.05$).[12] We find that the amount of water transferred from ag-to-urban outside of the CBT is greater than inside the CBT, averaged over all years ($p < 0.001$).

In the CBT, municipalities have grown to own nearly 60% of the CBT units, which helps contextualize our finding that less appropriative water within the CBT is traded to urban use. Instead, shares would meet urban demand, leaving farmers to use appropriative rights or the remaining shares. Although municipalities own most of the shares, they lease much of this water to farmers when it is not needed (Northern Colorado Water Conservancy District 2023). Because cities outside of the CBT do not have access to shares, they would likely obtain urban water from agriculture, as agriculture holds most of the appropriative water rights (Libecap 2011).

As mentioned, trade can influence the priority within a location, which research has shown can alter water use. Priority has been shown to influence crop choice, as more junior users will have a higher level of uncertainty in water allocation and will adjust by growing more drought resilient crops. Next, we shift our focus from trade to crop choice to better understand how changing priority interacts with crop choice.

Crop Choice

Existing research finds that individuals who only have access to prior appropriative water will adjust their crop choice based on their relative priority status

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[12] While ANOVA tests can determine whether there is a significant difference between groups, it cannot identify which groups are different from each other. A Tukey-HSD performs comparison of means on all possible combinations of groups to indicate which group combinations have means that are significantly different from each other.

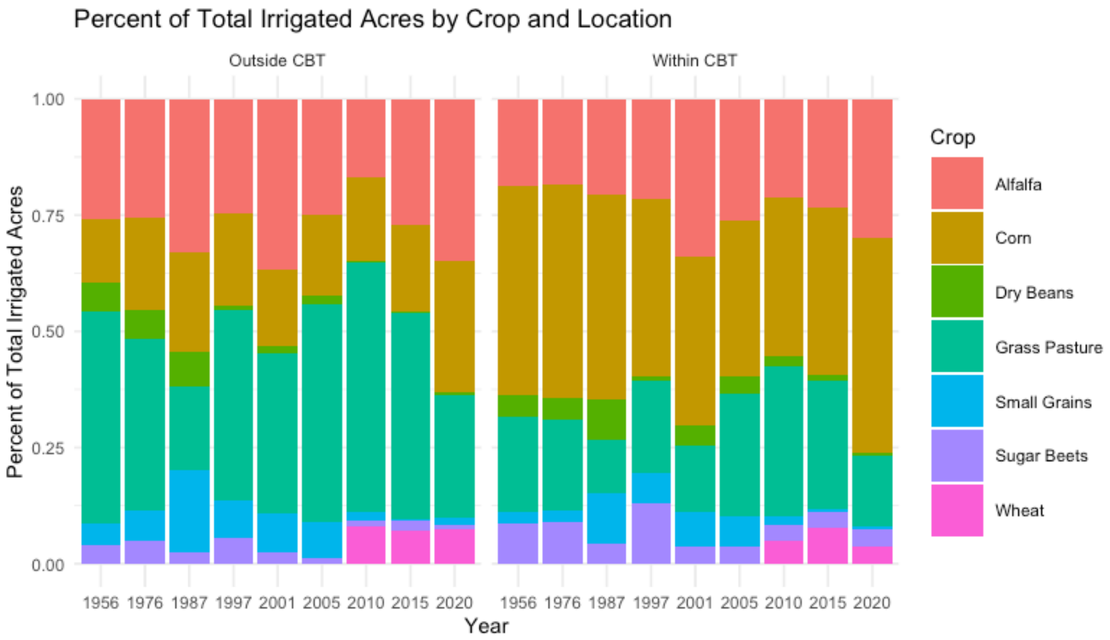
(Cobourn et al. 2022; Hagerty 2022; Ji and Cobourn 2018; Xu, Lowe, and Zhang 2014). Cobourn et al. (2022) find that lower priority individuals adapt to water uncertainty by growing less water-intensive crops and fallowing land. Hagerty (2022) finds that communities respond to long-term water scarcity by growing more grassland and changing crop production to manage losses, but does not find that farmers switch from high intensive to low intensive water crops.

If access to shares smooths weather variability, we may see less differentiation between the share of crops grown within priority groups when compared to areas that do not have access to shares. For example, low priority individuals without access to shares may grow more grassland, while low priority individuals in areas with access to shares may grow the same share of crops as medium priority individuals.

Figure 10 demonstrates the trends in crop choice on irrigated land within versus outside the CBT. Overall, land that was within the CBT grew a higher proportion of corn compared to land outside of the CBT. Land outside of the CBT grew a higher proportion of grass pasture, which is typically associated with ranching. After 2005, farms inside and outside of the CBT began growing wheat, with those outside of the CBT growing a higher proportion.

Figure 10

Percent of Total Irrigated Acres



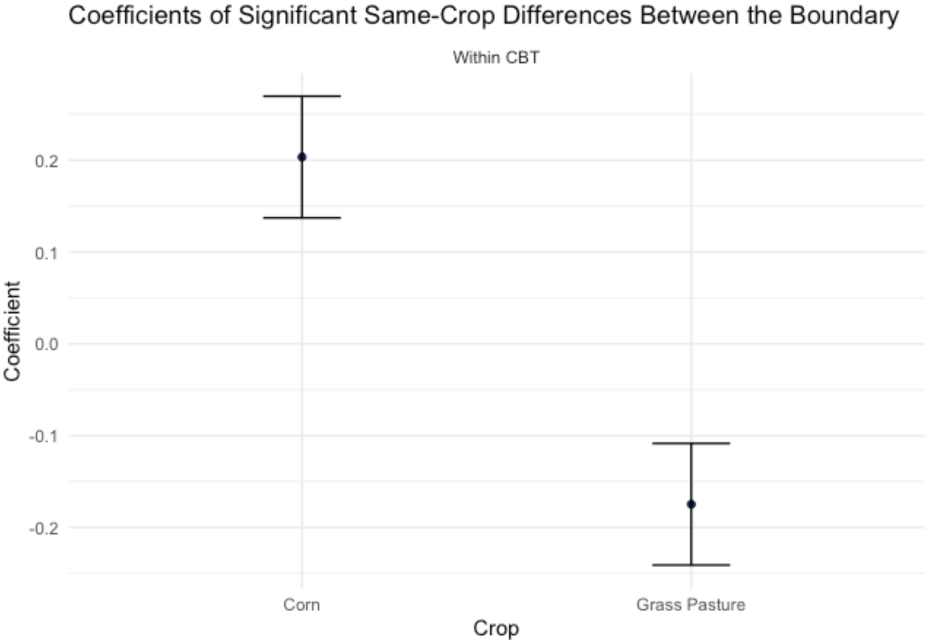
Note. The above figure depicts the percent of total irrigated acres by year, crop, and location. We have selected the top seven most frequent crops to display by color.

Individuals varied in the proportion of crops they chose to plant each season, but consistently planted more corn, alfalfa, and grass. Over time, individuals decided to grow more corn and alfalfa, but decreased the proportion of grass that was grown. We see the opposite trend in dry beans, sugar beets, and small grains, where farms devoted less acreage over time to the crop. Total irrigated acreage has declined from about 700,000 irrigated acres to about 490,000 irrigated acres.

Next, we test if the acreage devoted to crops within the boundary is different from the acreage devoted to crops outside of the boundary in each year. Given the crop trends in Figure 10, we would expect to see a difference in the level of corn and grass pasture being grown inside or outside of the CBT. Figure 11 shows that the differences in Figure 10 are associated with the CBT boundary; for example, individuals outside of the CBT grown a significantly greater amount of grass than individuals inside of the CBT boundary. We find that those inside of the CBT grow more alfalfa and corn, compared to the those outside of the CBT. Individuals outside of the CBT grow more grass pasture than those inside of the CBT.

Figure 11

Coefficients of Significant Crop Differences



Note: This figure shows the significant same-crop differences with the CBT as reference. The graph can be interpreted similarly to this example: within the CBT, the coefficient on corn is positive. This implies that individuals within the CBT grow more corn relative to individuals outside of the CBT ($p < 0.01$).

To better understand the relationship between crop choice and priority, we look at the water rights associated with a particular field. We take the mean appropriation year of all of the rights and assign it to the field.[13] After identifying the priority of each field, we classify them into three priority tertiles (Low=3, Medium=2, and High=1) based on the year. Each field also grows a number of crops, which are now associated with a

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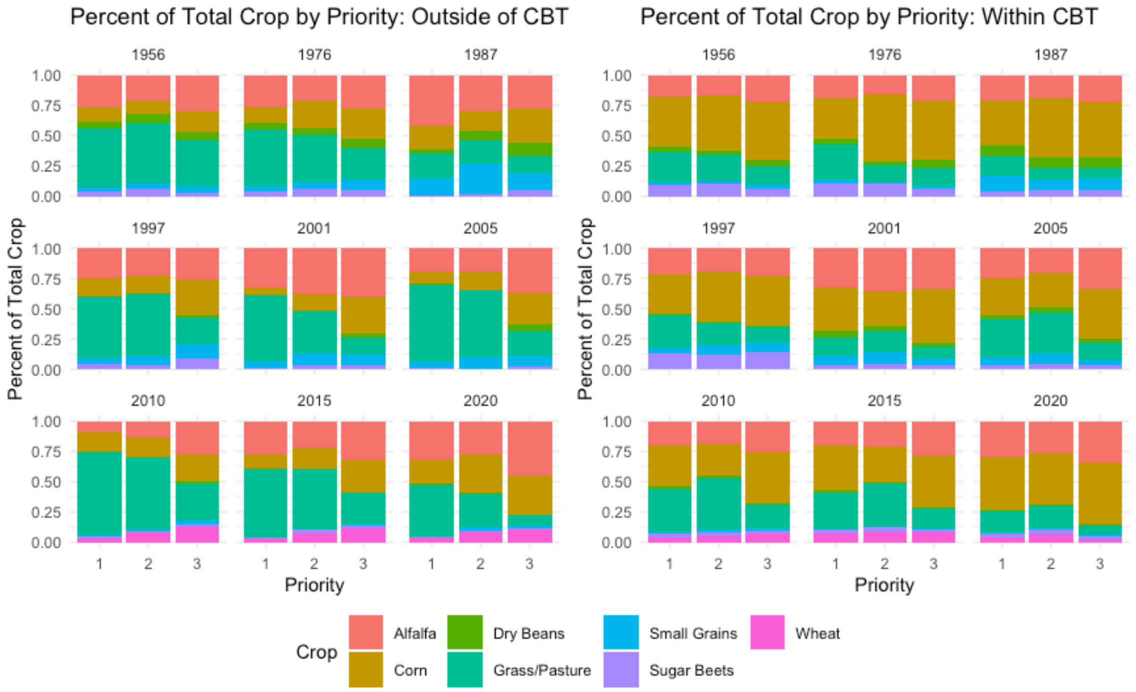
[13] We repeat this exercise for the minimum appropriation year. Figures, results, and further discussion are included in the appendix.

priority group. Figure 10 helps visualize broad differences over time and show the spread of crops within year and location. The differences found in Figure 11 are reflected in Figure 12, below. Individuals inside the CBT grow a larger proportion of corn compared to individuals outside of the CBT. Individuals outside of the CBT grow a larger proportion of grass compared to those inside of the CBT.

Figure 12

Comparing Priority and Crops Over Time



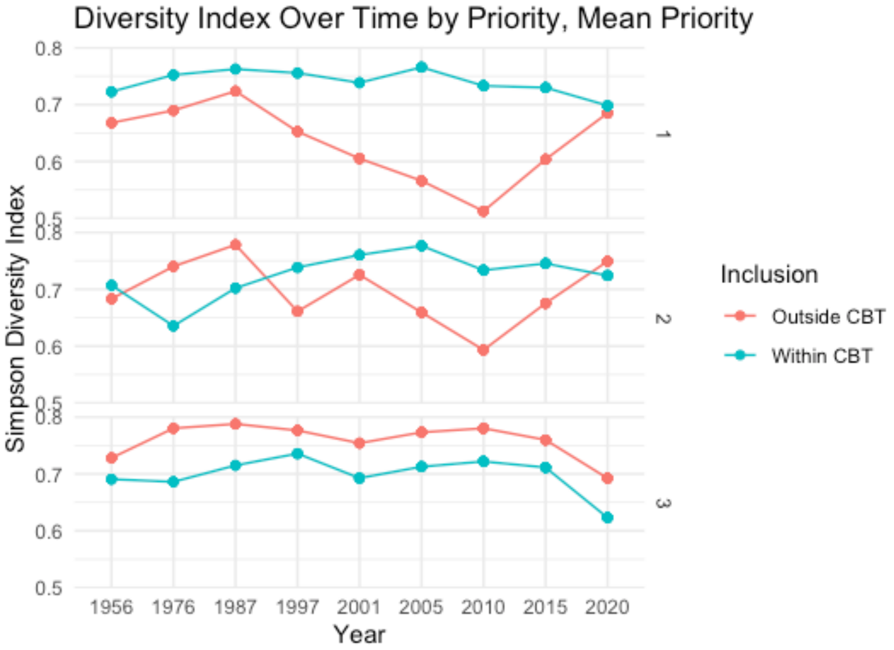
Note. The above figure shows the percent of total crop grown by year and location, inside (right) or outside (left) of the CBT. We select the seven crops that are grown consistently over our time period.

Figure 12 shows that over time, individuals in the CBT converge to a similar composition of crops, while individuals outside of the CBT increase in diversification over time. We use a Simpson Index of Diversity (SI) to measure the evenness in crop acreage for each priority index and CBT inclusion to better observe how priority tertiles diversify their crop mix. Because diversification is considered a response to expected water delivery, it could indicate the relative variability of water delivery within an area. The index ranges between 0 and 1 with an index of 1 indicating that crop acreage across that priority index is highly diverse.

Figure 13 shows the SI for each priority tertile inside and outside of the CBT. Note that over time, both groups approach the same level of diversification (SI= 0.70); however, those inside the CBT hover around this level consistently, while individuals outside the CBT oscillate, depending on tertile. It appears that tertile 2 outside the CBT is more diverse than tertile 1, but less diverse than tertile 3. In other words, diversity increases as priority tertile decreases outside of the CBT. This trend follows prior literature that identifies crop diversification as a response mechanism for lower priority individuals. We test to see if there are significant differences in tertiles within the CBT across all years, and find that the only significant within-CBT difference is between tertile 1 and tertile 3 ($p < 0.001$). On the other hand, outside of the CBT, each tertile is significantly different from each other ($p < 0.001$).

Figure 13

Diversity Index Over Time



Note. The above figure plots our Simpson Index of Diversity (SI) over time by location. A SI of 0 implies no diversity in crop selection, while a SI of 1 implied a high diversity in crop selection. Mean priority refers to the selection criteria applied if a farm owned multiple rights. Because farms often own multiple rights, priority could be measured as the mean of all of those rights, or the most senior water right. We opt to use the mean Priority 1 is high priority and priority 3 is low priority.

Conclusion

Overall, these findings suggest that overlapping institutions do yield different outcomes when compared to non-overlapping institutions. In particular, we find evidence that individuals within the CBT transfer a lower amount of appropriative water rights from agricultural to urban uses than those outside of the CBT. These differences could suggest that access to supplemental water creates more flexibility in transfers, in appropriation and use.

We also find evidence that access to supplemental water creates differences in crop choice and diversification. Our results aggregate over time, and it is likely that crop diversification occurs in response to a number of factors like temperature, precipitation, expected water delivery, and crop prices. Further research should investigate how overlapping institutions affect crop choices, given our evidence that a difference exists.

Our results suggest that access to supplemental water shares is associated with markedly different behavior around the use and transfer of appropriative rights. We find there are fewer appropriative rights traded inside the CBT, fewer ag-to-urban trades (of appropriative rights) inside the CBT, and less differentiation between priority groups within the CBT. All of these results indicate that the use of appropriative rights are different inside of the CBT. Our results, however, do not empirically test the extent to which participation in the CBT, access to supplemental shares, or relative priority have a causal effect on these choices. Further research should examine the relationship between these choices and crop choice, and incorporate climate variability. In particular, research should examine the choice between corn and grassland, as they create two different vulnerabilities to climate change (Engelbert and Scheuring 2022; Hagerty 2022).

It is clear that overlapping institutions are associated with differences in the decisions taken by the holders of appropriative water rights. As water scarcity and climate variability will persist, it is important to understand if overlapping institutions can absorb or dampen those shocks (Kiewiet et al. 2022; Williams, Cook, and Smerdon 2022). Past literature uses crop choice or trade as an indicator for community responses to climate change (Cobourn et al. 2022; Ji and Cobourn 2018; Li, Xu, and Zhu 2019; Xu, Lowe, and Zhang 2014). Further research should incorporate climate variation and examine the its impact on the crop choice of individuals who have access to supplemental water and individuals who do not. In addition, further research should also treat irrigation districts as overlapping institutions, and compare their performance to share-based systems.

The contentious history of interstate water transfers, lack of supplemental water, and increasing uncertainty caused by climate change, imply that approaches to water scarcity must be compatible with existing institutions if they are to be politically feasible, but also that existing institutions may interact in unexpected ways with new institutions. The CBT is an example of a hybrid system where individuals can hold prior appropriative rights, but also have access to supplemental shares. As share-based allocation grows in popularity, further research must examine the relationship between overlapping institutions and climate variability.

The Long Term Impact of Shares on Land Use Change

Introduction

Changes in precipitation affect the water available for agriculture. Farmers can mitigate these changes by adjusting the types and amount of crops they choose to grow. Due to constraints in water law, farmers are required to use their full entitlement of water each year and are limited in the amount of water they can trade and in the use of that water. These restrictions are outlined by prior appropriation, the doctrine that allocates water in the American West. This doctrine dictates the order that water is delivered (priority) and the amount that farmers receive. The combination of these mechanisms can lead weather variability to be borne disproportionately by farmers.

Past literature examines the relationship between crop choice and water variability, demonstrating that farmers who are exposed to higher levels of uncertainty in water allocation will compensate by fallowing land or switching to less-water intensive, lower value crops under prior appropriation (Cobourn et al. 2022; Hagerty 2022; Ji and Cobourn 2018). Over time, though, these farmers may sell their water rights to cities and leave agriculture permanently. This process, where cities purchase water from farmers, is pejoratively called “buy-and-dry” because it can leave agricultural economies at risk of collapse or consolidation over time (Devine 2015; Udall and Peterson 2017; Varzi and Grigg 2019).

One approach to managing water scarcity is trade (Carey and Sunding 2001; Easter, Rosegrant, and Dinar 1999; Griffin and Hsu 1993; Libecap 2008). Within prior appropriation, individuals must prove that a transfer does not negatively impact any other water user before the transfer can occur, to maintain the order in which the doctrine specifies delivery (Bretsen and Hill 2009). This process can increase the costs associated with transferring water, thus limiting the size and number of transfers that occur (Ayres, Edwards, and Libecap 2017; Womble and Hanemann 2020).

One proposed alternative to avoid the high costs of trade under prior appropriation is share-based allocation. Under share-based allocation, water is distributed as a percent of the total available amount. In this way, a reduction in the total available water supply is distributed evenly across all users. Unlike prior appropriation, water is not allocated by priority and does not require a consistent amount to be used to maintain the right (Anderson and Libecap 2014; Libecap 2008; Seidl, Wheeler, and Zuo 2020). In theory, allowing prior appropriative rights to be traded, or converting appropriative rights to shares and trading those, would alleviate some shortages caused by allocative inefficiency (Burness and Quirk 1979, 1980a).

Two issues emerge when introducing shares as an alternative allocation scheme: first, water has already been allocated through prior appropriation, thus shares would likely overlap with existing appropriative rights; and second, little to no research has examined how the overlapping nature of these two institutions would impact land use over time. As policymakers increasingly contemplate share-base allocation (Young 2015), it is imperative to understand how overlapping shares and appropriative rights might impact the decision to bring land in and out of production, thus affecting the long-term viability of agricultural economies. Cities are increasing in their demand for water, 70% of which is in agriculture (Scientific Investigations Report 2018). This pressure to move water from agriculture to urban areas can leave agricultural communities, who face persistent water shortages, vulnerable to permanent transfers of their water to cities.

The long-term impact of water allocation schemes has direct policy relevance as historically, alternative water allocation options (including rotational fallowing, shares, or alternative transfer mechanisms) that negatively impact agricultural communities stymie these program implementations by generating political and legal backlash. Farmers point to examples like Owens Valley, where Los Angeles purchased water from ranchers with the intent of fallowing that land, as an example of these mechanisms changing local economies (Libecap 2005, 2009). While weather variability may already introduce higher risk into farmers' decisions, it is not clear how that risk shifts in practice when shares and appropriative rights overlap.

The Colorado-Big Thompson Project (CBT) provides a unique opportunity to examine how overlapping water allocation mechanisms impact the decision to bring land in and out of agricultural use. Individuals within the CBT have access to both share-based and appropriative rights, while individuals outside the CBT have access only to appropriative rights. We build a dataset that spans 1974-2012 and tracks land use and weather variability. These data allow us to understand first how overlapping institutions affect crop choice, and second, how overlapping institutions may mediate weather variability. In light of the historical concerns of farmers, it is imperative to understand whether overlapping institutions increase the resilience of agricultural communities or contribute to their vulnerability. This question is particularly important as these communities become more exposed to weather variability due to climate change.

We examine the decision to bring land in and out of agricultural production and find that individuals within the CBT are more likely to use land for agricultural production. Using spatial regression discontinuity design, we compare land use change on nearby parcels and find that parcels within the CBT are 3% more likely to remain in agriculture over 1974 to 2012 than those outside. A substitute for agricultural land use is often development, which is permanent. We find that parcels within the CBT are 7% less likely to develop over 1974 to 2012 than those outside. During a drought, we also find that the negative impact of a drought on agriculture inside the CBT is roughly 50% of that outside the CBT. Our results suggest that overlapping shares with appropriative rights can absorb the impact of weather variability, such as drought, on agricultural land use, further supporting past research on the ability of overlapping institutions to manage climate change (Baldwin et al. 2018; Lofthouse and Herzberg 2023; Ostrom 2009).

Background

The doctrine of prior appropriation allocates water in the American West. This doctrine uses priority to distribute water, allowing "senior" users to receive their water in full prior to more "junior" users. For example, a senior user might have a right established in 1800, while a junior user might have a right established in 1980. In a period of water scarcity, the senior users receive their water in full before the junior user. In some cases, this shortage may result in no junior users receiving water. These rules were associated with the priorities of the early 1800s, when it was first implemented. At the time, the US government was concerned with development of the western states and economic growth. Land in the west required water for improvement, so in order to make land arable, settlers needed security in their right to water to motivate investment the infrastructure to move that water (Leonard and Libecap 2019).

Because water is allocated through priority, transfers must prove “non-injury,” that is if an individual transfers water, they must ensure that no other senior or junior users’ priority are affected. This process is both costly and lengthy. For example, appropriative water transfers in Colorado take, in some cases, five years to move a “cup’s worth of water” (Banks and Nichols 2015), with the legal process incurring up to 70% of the total transfer cost (Womble and Hanemann 2020).

Share-based allocation is applied sparingly in the American west, but is used in some Bureau of Reclamation projects and irrigation districts. Under this alternative system, the total amount of water allocated towards the project or area is divided into shares that individuals can buy, sell, lease, or store. Unlike appropriative water, all shares are decreased if there is a water shortage, not just junior users, and there is no beneficial use or non-injury requirement.

These two allocation mechanisms distribute water variability differently, which can impact a farmer’s expected water deliveries of water in any given year. If an individual holds a senior appropriative right, the probability of getting water under prior appropriation is the probability that the flow exceeds the sum of all senior users’ rights (Burness and Quirk 1979). Thus, the risk faced by a user is a combination of the rights senior to them and the available water in any given year. The more senior a user is, the higher the probability that they receive their water allocation in full, despite any weather variability.

On the other hand, a junior user is less likely to receive water the more weather variability increases. Thus, there is a difference between junior and senior users in how weather variability informs their expectation of water delivery. Under the share-based allocation, risk is distributed equally across all users. In a year where water availability is low, all shares face the same reduction in available water. While there is still uncertainty in how much water will be available from one year to the next, all users face the same probability distribution of receiving water.

Unlike appropriative rights, share-based rights do not carry the same transfer costs. Individuals can buy, sell, or store their shares to hedge against weather variability. Appropriative users, limited by non-injury and beneficial use, are not as likely to use trade to mitigate weather variability. Instead, research suggests these individuals will change crops to manage water variability. In these models, the margin of response is not additional water, but crop choice, including the option to fallow land. This structure reflects the decision facing most appropriative water users: if they do not have access to additional water, then changing their crops is the next best margin for mitigating water scarcity. Some literature has shown that individuals within irrigation districts are able to dampen the effects of weather variability through alternative water allocation (Ji and Cobourn 2018).

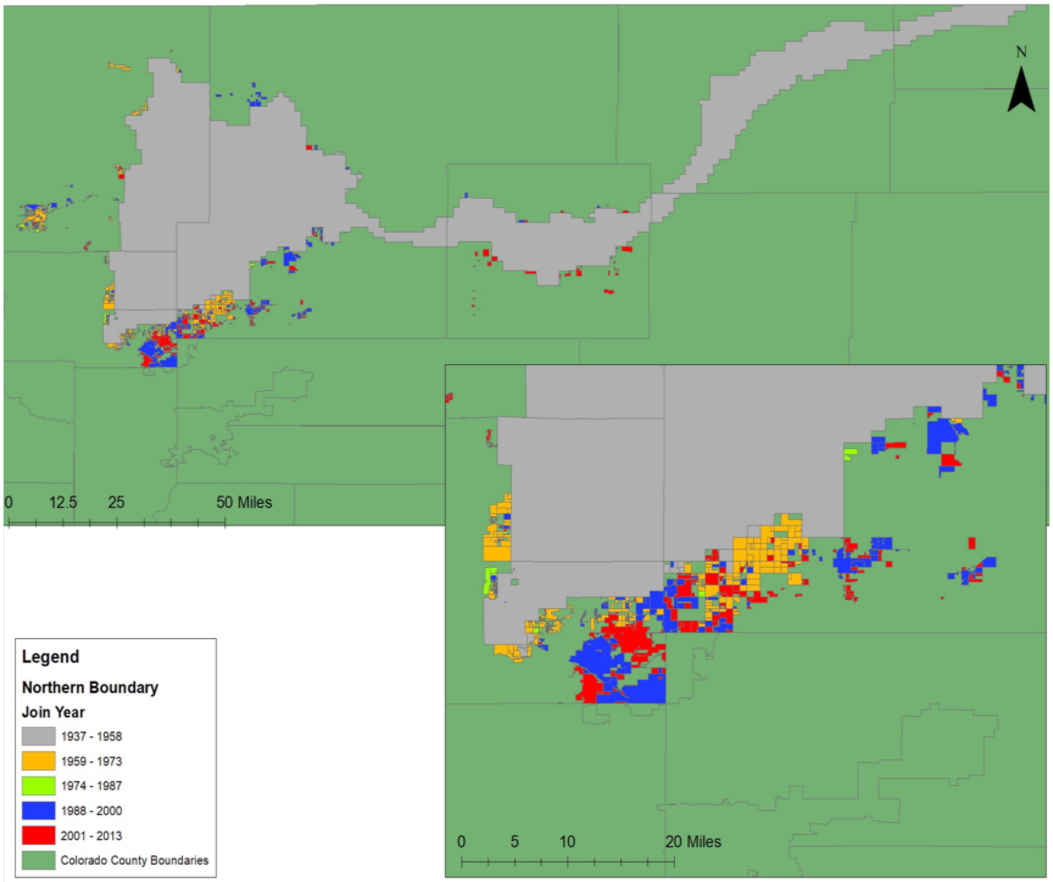
To understand how share-based water allocation affects individuals' ability to respond to weather, we build a novel dataset that spans nearly a century (1920-2012) in Colorado's Division 1. Our data allows us to examine the relationship between prior appropriation and access to supplemental water, and how land use varies when individuals have access to both. By comparing individuals who hold prior appropriative rights to individuals who hold both supplemental and prior appropriative rights, we can capture the impact of this access on land use. In addition, we can capture the period prior to supplemental water (1930), so we are able to understand which changes are due to supplemental water, and which changes are characteristics of the sample area.

The Colorado-Big Thompson Project

The Colorado-Big Thompson Project (CBT) is perhaps the most well-known example of share-based allocation. The project allocates up to 310,000 acre-feet (af) of supplemental water that is made available to individuals through contracts. Users can own, lease, or share the contracted water, with each contract representing different restrictions associated with the supplemental water. The project boundary is the same as Northern Water Conservancy District's boundary (Northern) and serves only individuals within that boundary. Individuals can join the district over time, thereby acquiring access to the supplemental water, but shares cannot be transferred outside the boundary. Figure 14 shows the original territory (in gray) and the subsequent parcels that joined the district over time.

Figure 14

CBT Area Map



Note. The above figure shows the area of the CBT. The area in grey represents the original boundary, created in 1956 and also the boundary of Northern Water Conservancy District. The colored parcels are parcels that joined after the 1956 original boundary was created.

Each contract identifies a number of CBT shares that an individual can use. A share represents a number of units, where one unit of CBT contract water changes based on the total available water supply. For example, if the CBT has access to maximum supplemental water, 310,000 af, then one CBT unit is equal to one af. If the maximum is not available, then a quota is announced. This quota represents the percent of the 310,000 af that is available, and the corresponding percent of one unit that is also available. For example, if there is a 70% quota, then 217,000 af are available, and 7/10th of one CBT unit (7/10th of one af) are available. An individual can buy, lease, or store their contract water.

The project began in the 1930s and was marketed as a solution to the Great Depression in eastern Colorado. Proponents of the project argued that current water supplies could not meet the population's growing demand, and as such additional water was required. After securing excess water from western Colorado, the Bureau of Reclamation funded a series of infrastructure projects that would carry the water over 200 miles and down 2000 feet. Northern Water's board would contract the water out for about $1.50/af. The board prioritized contracts that went to junior users who were not receiving their full water claim.

Senior members of Northern were concerned with this supplemental water and argued against its introduction. These senior farmers worried that the additional water would increase irrigated land, leading to lower crop prices. This issue was compounded by the fact that these farmers would not qualify for contracts but would be required to pay for the infrastructure. The district reached a consensus by capping the total irrigated land during the early years of the project. The first water deliveries started in 1956 and continue today.

While the CBT has been treated as share-based allocation, individuals within the district often hold appropriative rights and have access to supplemental water. This overlap creates two methods by which a user can obtain water, which alters the margin of response to climate change. Past research has shown that users with less certainty in their water allocation (junior users) grow less water intensive crops. However, an understudied aspect in current literature is the extent to which overlapping institutions mitigate the impact of water scarcity, and thus, affect the land use decisions of individuals. Theoretical literature argues that overlapping institutions can decrease the responses, such as land use choices, of communities to climate change (Jagers et al. 2020; Morrison 2017) or increase it (Lofthouse and Herzberg 2023; Marshall 2009). We use the outcome of land use as a measure for the extent to which overlapping institutions impact climate-induced responses.

Data

PLSS Grid

Our basic unit of analysis is the Public Land Survey Section (PLSS) quarter section (QS) that represents 160 acres (Figure 15). We use quarter sections as our unit of analysis because they remain stable throughout our time period of 1920-2020 and because most homesteads and many land sales correspond to QS. We identify the number of water rights, the land use, transfers, and climatic conditions associated with each QS over time. We remove QS that are not labeled in the PLSS system and aggregate polygons up to the QS level when applicable.

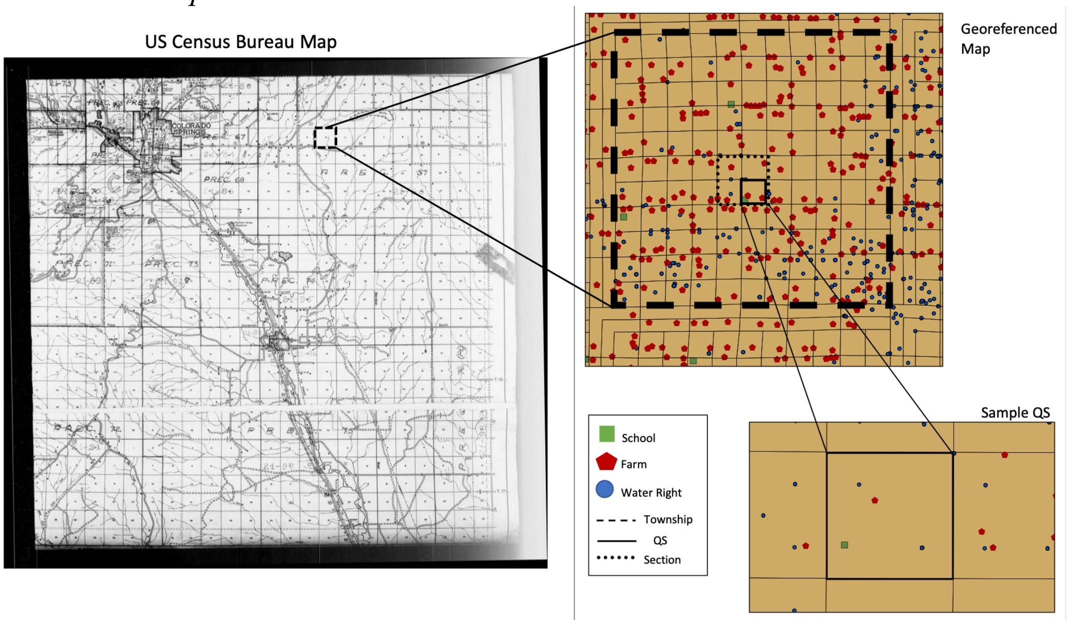
Land Use

Our crop data is built from the National Wall to Wall Land Use Trends (NWALT) data produced by USGS (Falcone 2015). The data uses satellite imagery at 60m x 60m resolution to extrapolate current and historical land uses. While the data identifies over twenty uses, we look at development, crops, and pasture. NWALT includes the years

1974, 1982, 1992, 2002, and 2012. We classify a QS being in agriculture if the QS has crops or pasture, as defined by the NWALT index.

Figure 15

PLSS Grid Sample



Note: This figure shows a sample of available data. On the left is an image of a US Census Bureau map. The PLSS grid can be seen in it. On the right is the spatial data resulting once the left image has been fully georeferenced.

Institutions

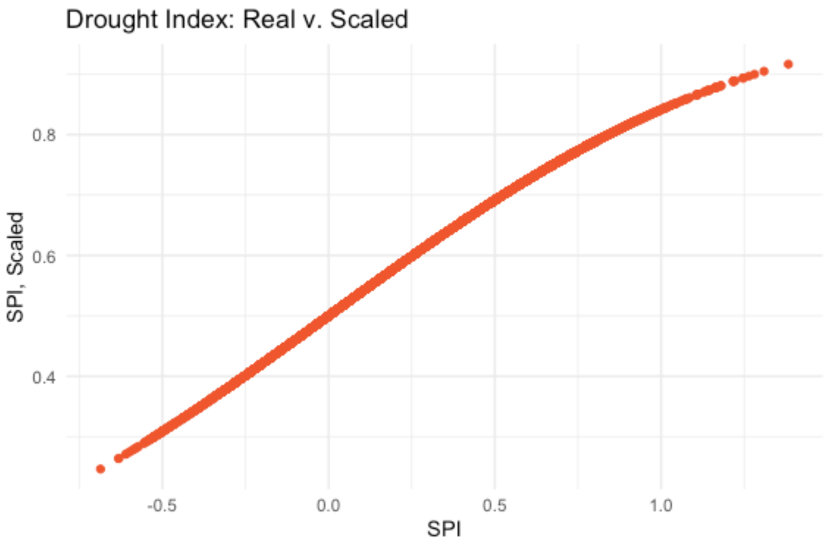
Our boundary for the CBT comes from Northern Water. Northern Water provides shapefiles that include information about the district boundary and how it has changed over time. The district allows parcels to join the CBT over time, so we have information about the original boundary and each additional change to it over our time period.

Climate

We use mean temperature and precipitation data at the 800m x 800m resolution estimated and aggregated by PRISM (PRISM Climate Group 2014). We use monthly estimates and use zonal statistics to build local estimates in ArcGIS for our research area. We use a drought index to indicate the level of drought a QS experiences in a time period. We use a Standardized Precipitation Index (SPI) that is re-scaled to be between 0 and 1, as a measure of drought. The SPI uses the average annual level of rainfall over the past decade minus the average annual level of rainfall over the past 30 years and divides this difference by the standard deviation of the past 30 years. We rescale this index such that 0 represents the highest level of precipitation in our time period and 1 represents severest drought in our time period. Figure 16 shows the SPI versus our scaled SPI, which lies between 0 and 1. We repeat this process for a temperature index, where 0 represents the lowest temperature variation for all seasons and 1 represents the most extreme temperature for a growing season. We consider a growing season in Colorado to be April through October.

Figure 16

SPI Original and Scaled



Note. The above figure shows the scaled SPI compared to the original SPI. We scale negative values (extremely high values of rainfall) to 0, such that the average amount of rainfall for a time period would be an SPI of 0.5.

Method and Model

We are interested in the ability of overlapping institutions to mitigate the impact of weather variability on land use change; however, there are several confounding factors that might obscure this relationship. First, individuals who joined the CBT might have higher quality land, consistently higher priority of water, better land quality, or other similar parcel specific qualities. To control for this, we use quarter section (QS) fixed effects that absorb all time-constant differences between parcels and prevent our model from attributing causality due to these characteristics. Second, some parcels might have differential land use trends that further obscure the true treatment effect inside the CBT. Coupled with this concern is that parcels within the CBT have access to both shares and appropriative water, meaning that individuals within the district have access to more water overall. To isolate the effect of overlapping institutions on land use, and not the effect of access to more water on land use, we use a spatial regression discontinuity design (RD) that allows us to compare suitable parcels across the border.

We use a dynamic regression discontinuity that interacts a spatial regression discontinuity set-up with time-series variation in outcomes of interest. The RD exploits a spatial boundary, or cutoff, and running variable (distance to the boundary) to identify the average treatment effect across individuals within the border. We exploit the discontinuity at the boundary of the CBT to address the concern about surplus water. At the boundary, individuals within the CBT have access to supplemental and appropriative water, but in practice, so do individuals across the border. Individuals at the border share the same infrastructure, allowing the transfer of appropriative rights. Because individuals in the CBT can sell prior appropriative water to individuals not in the CBT, and replace that water with share-based water, the boundary creates a sharp discontinuity where the difference represents the institutional framework. In other words, lands just outside of the CBT can indirectly benefit from the availability of supplemental water, but can only do so through the transfer of appropriative rights across the boundary. Hence, the boundary captures differences in the cost of transferring water rights via alternative institutions. We exploit this discontinuity at the boundary to estimate the effect of being inside the CBT on land-use. Equation 4 represents this method more formally.

Equation 4

$$Pr(y_{i,t} = \{0,1\}) = \beta_0 + \beta_1 * dist_i + \beta_2 * drought_{i,t} + \sum_{t=1974}^{2012} \beta_t * time_t * cbt_i + \beta_4 * temp_{i,t} + \alpha_t + \gamma_i + \mu_{i,t}$$

The variable $y_{i,t} = 1$ if quarter section i chooses agriculture (or, development) in time period t. We include a drought index such that β_2 represents the average effect of drought on our outcome variable. Our coefficient of interest is β_t which represents the difference in the discontinuity around the border of the CBT in year *t* relative to the base year of 1974. In other words, this coefficient represents the average treatment effect of being inside the CBT on probability of a QS being in agriculture during a given year. We control for several other factors in our model with fixed effects. We use time, α_t , and quarter section, γ_i, fixed effects and cluster standard errors by township.

We further explore the relationship between the CBT and weather variability in Equation 5. Equation 5 interacts our drought index with our CBT dummy to estimate the differential effect of drought on agricultural land use inside of the CBT. In this equation, θ_2 is our coefficient of interest, estimating the effect of drought on land use on a QS inside the CBT compared to a QS outside of the CBT.

Equation 5

$$Pr(y_{i,t} = \{0,1\}) = \theta_0 + \theta_1 * dist_i + \theta_2 * drought_{i,t} * cbt_i + \theta_3 * drought_{i,t} + \alpha_t + \gamma_i + \mu_{i,t}$$

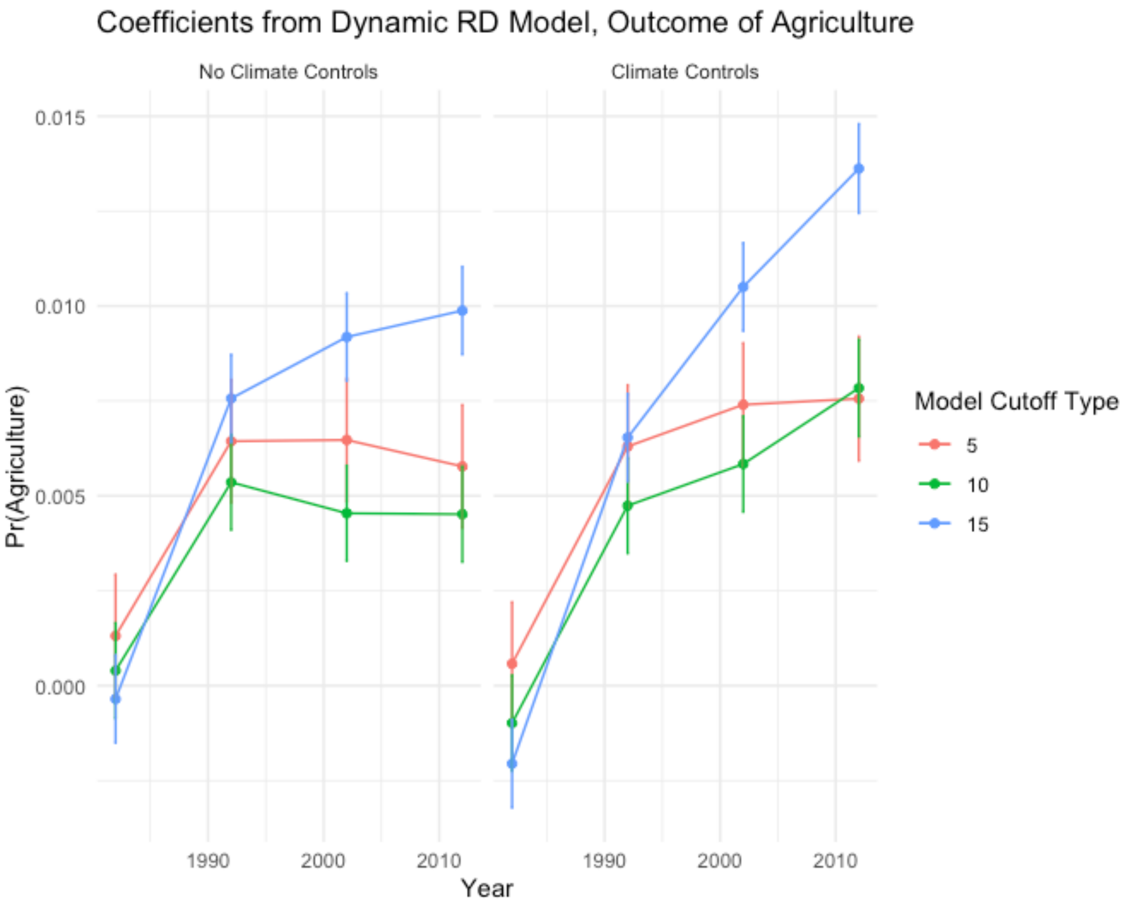
We restrict our sample in two important ways: by join year and by distance. Our regressions include individuals who were part of the original 1956 boundary, to avoid the endogeneity created by parcels joining over time. Second, we restrict the estimating sample to parcels within of five, ten, or fifteen miles from the border. We demonstrate that our results are robust to each cutoff distance in Appendix C Tables 8-11.

Results

We present the results of estimating Equation 4 for two cases: the first, where we do not control for weather variability (Figure 17, left panel; Table 8 in Appendix C) and the second, when we do control for weather variability (Figure 17, right panel; Table 9 in Appendix C). The right figure indicates that the impact of the CBT on the probability that a QS is in agriculture, grows over time. We find that at the 10 mile cutoff in 2012, our coefficient of interest is 0.0078. This coefficient indicates there is a 0.78 percentage point increase in the likelihood that a QS is in agriculture in 2012. To contextualize this result, the probability that a QS is used for agriculture outside of the CBT is 0.26. This indicates that QS in the CBT are about 3% more likely to be in agriculture relative to the baseline.

Figure 17

Coefficients from Spatial RD Model, Outcome of Agriculture

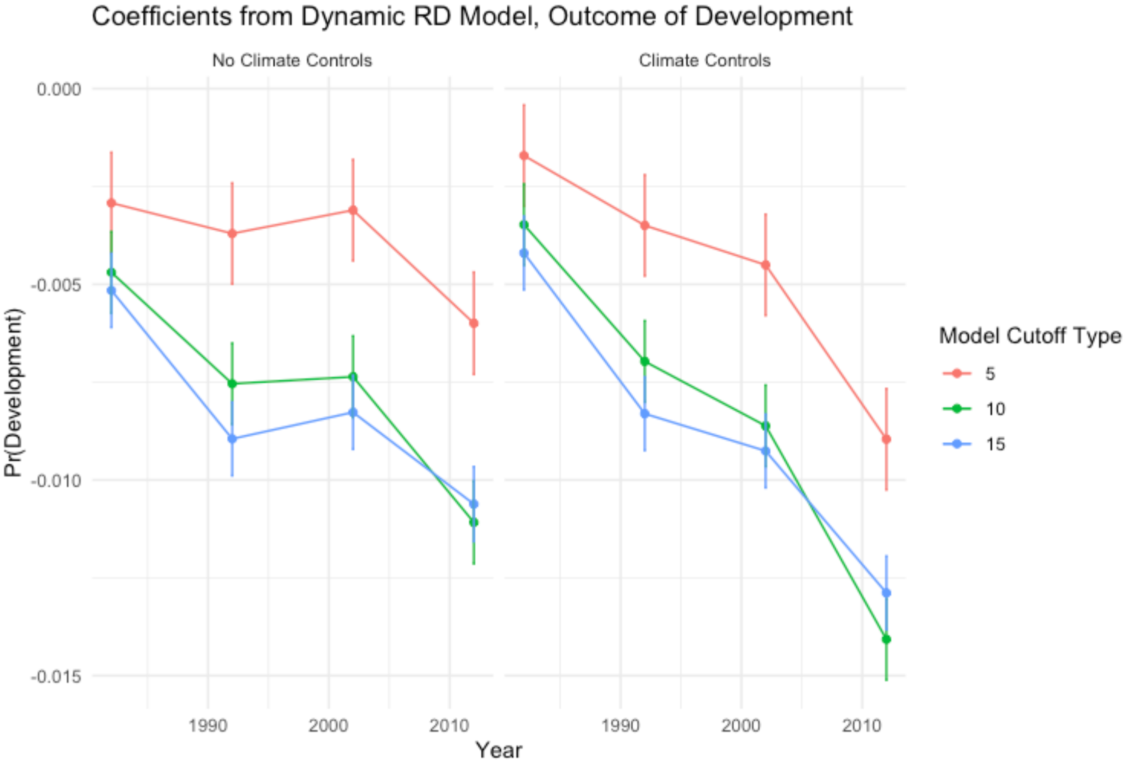


Note. The above figure shows the coefficients produced by equation 4, where the outcome is agriculture. The left graph shows the interaction coefficients, β_t for 1982, 1992, 2002, and 2012, without controls for weather variability. The graph on the rights depicts the same coefficients, with controls for weather variability. Each line color represents the cutoff distance for included observations.

A question that accompanies these results is the relationship between agriculture and development. Whereas a lack of agriculture on a parcel in a given year may reflect temporary fallowing, the decision to develop land implies that a parcel cannot be used for future agriculture. To explore this more permanent form of land use change, we replace our outcome variable in Equation 4 with development to understand the relationship between development and the CBT. We present these results in Figure 18, regression results can be found in the Appendix C, Table 10 and Table 11. Figure 18 shows the results for Equation 4 with the outcome of development.

Figure 18

Coefficients from Spatial RD Model, Outcome of Development



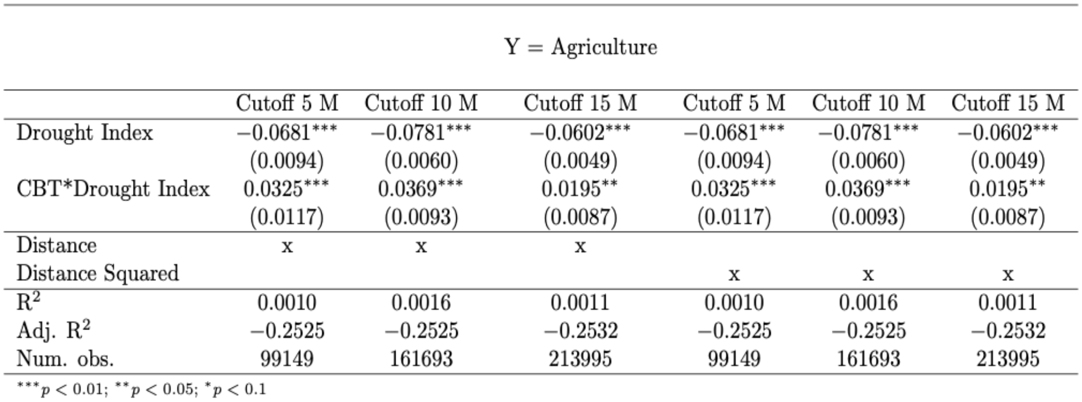
Note. The above figure shows the coefficients produced by equation 4, where the outcome is development. The left graph shows the interaction coefficients, β_t for 1982, 1992, 2002, and 2012, without controls for weather variability. The graph on the rights depicts the same coefficients, with controls for weather variability. Each line color represents the cutoff distance for included observations.

We find there to be a strong, negative relationship between QS in the CBT and development over time. A QS in the CBT has a coefficient of -0.0141, meaning that a QS inside the CBT is 1.4 percentage points less likely to develop. After controlling for weather variability, we find that the effect decreases to 1.1 percentage points less. This shifts the likelihood that a QS inside the CBT develops from 9% to 7% less likely to develop, as the probability that a QS outside the CBT is developed is 0.15. Over time, there is a significant, negative relationship between development and being inside of the CBT, compared to 1974 development. This result runs contrary to the hypothesis that transition to share-based management, or introduction of shares, would result in consolidation of water to municipalities, and thus, retirement of agricultural land.

However, these results do not isolate the extent to which lands within the CBT are able to adapt to weather shocks over time, or if adaptation affects the likelihood of QS within the CBT being in agriculture during a drought. Both margins indicate how the CBT affects the long run sustainability of agriculture under increased weather variability. To estimate this relationship, we use Equation 4 and show the results in Table 4.

Table 4

Regression Results for Equation 5



Y = Agriculture

	Cutoff 5 M	Cutoff 10 M	Cutoff 15 M	Cutoff 5 M	Cutoff 10 M	Cutoff 15 M
Drought Index	-0.0681^{***}	-0.0781^{***}	-0.0602^{***}	-0.0681^{***}	-0.0781^{***}	-0.0602^{***}
	(0.0094)	(0.0060)	(0.0049)	(0.0094)	(0.0060)	(0.0049)
CBT*Drought Index	0.0325^{***}	0.0369^{***}	0.0195^{**}	0.0325^{***}	0.0369^{***}	0.0195^{**}
	(0.0117)	(0.0093)	(0.0087)	(0.0117)	(0.0093)	(0.0087)
Distance	x	x	x			
Distance Squared				x	x	x
R^2	0.0010	0.0016	0.0011	0.0010	0.0016	0.0011
Adj. R^2	-0.2525	-0.2525	-0.2532	-0.2525	-0.2525	-0.2532
Num. obs.	99149	161693	213995	99149	161693	213995

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Note. The above table shows the regression results for equation 5. Results are shown for distance and distance squared, as well as three different cutoffs. Standard errors are clustered by township.

We find that there is a strong, negative relationship between severe drought and the decision to bring a QS into agricultural production. The coefficient on our Drought

Index is negative and significant, meaning that as drought intensifies, a QS is less likely to be in agriculture. This relationship follows prior literature that finds that farmers decrease crop production, or do not have access to water to grow crops, when there is drought (Cobourn et al. 2022; Ji and Cobourn 2018; Li, Xu, and Zhu 2019; Libecap 2005; Xu, Lowe, and Zhang 2014).

We find a robust positive coefficient on the interaction of the drought index and the CBT dummy variable. As drought intensifies, individuals are still less likely to bring a QS into agricultural production, but QS that are in the CBT are less affected by the drought relative to the baseline. Our model predicts that as drought severity increases, a QS within the CBT experiences a 3.3 percentage point decrease in its likelihood to be in agriculture; however, a QS outside of the CBT during a drought is 7.8 percentage points less likely to be in agriculture. The probability that a QS is in agriculture during 2012 is 0.26, implying that the effect of a drought on QS inside the CBT in agriculture is roughly half. A QS outside of the CBT during a drought is 30% less likely to be in agriculture, while a QS inside the CBT is only 13% less likely to be in agriculture compared to the baseline. This relationship suggests that overlapping institutions absorb some of the impact that droughts cause in agriculture.

Because individuals inside the CBT have access to shares and appropriative rights, individuals are less vulnerable to weather variability. If a farmer is junior, under prior appropriation they would have a singular choice margin to manage water variability in the short run: more or less agriculture. Within the CBT, a junior farmer would have the option of acquiring additional water by purchasing CBT shares, instead of a more uncertain, appropriative claim. Moreover, if a junior farmer was forward thinking, they might store water in the year prior, allowing them more flexibility in a drought.

Conclusion

As policymakers continue to discuss solutions to water scarcity, shares are increasingly being proposed (Culp, Glennon, and Libecap 2014; Seidl, Wheeler, and Zuo 2020; Young 2015). Policymakers cannot escape the historical context associated with some of these policy recommendations. Farmers express concern over past negotiations and policy solutions that have left their communities vulnerable to economic and environmental shocks. Share-based allocation is no exception to this scrutiny, particularly because its introduction would overlap with existing appropriative rights.

Our results suggest that this historic scrutiny of overlapping institutions and share-based allocation may be based in just that, the past. We find that since the implementation of the CBT, QS are more likely to be brought into agriculture, and the overlapping institutional nature of the CBT dampens the shocks of drought. These results imply that solutions to water scarcity do not require the complete transition of historic rights to a new system, but rather that there are benefits to allowing both systems to coexist. Moreover, the historic concern that share-based allocation would result in the consolidation of rights to municipalities, thus leaving the agricultural sector vulnerable, is not supported. Instead, we find that QS within the CBT are less likely to develop, and the agricultural sector is more resilient to weather shocks.

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APPENDIX A

CHAPTER 1

Table 5

Pre Trend

	Y = AF
Enrolled*Y1989	0.90
	(0.89)
Enrolled*Y1990	**4.51*****
	(1.41)
Enrolled*Y1991	**5.20*****
	(1.44)
Enrolled*Y1995	**6.30*****
	(1.48)
Enrolled*Y1996	**5.13*****
	(1.29)
Enrolled*Y1997	**6.10*****
	(1.35)
Enrolled*Y1998	**4.84*****
	(1.33)
Enrolled*Y1999	0.48
	(1.15)
Num. obs.	64727
Adj. R^2 (full model)	0.87
Num. groups: Parcels	3596
Num. groups: Year	2

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Note. The above table depicts the pre-trend results. We include parcel and year fixed effects and cluster are standard errors by townships.

APPENDIX B

CHAPTER 2

Identifying Water Transfers

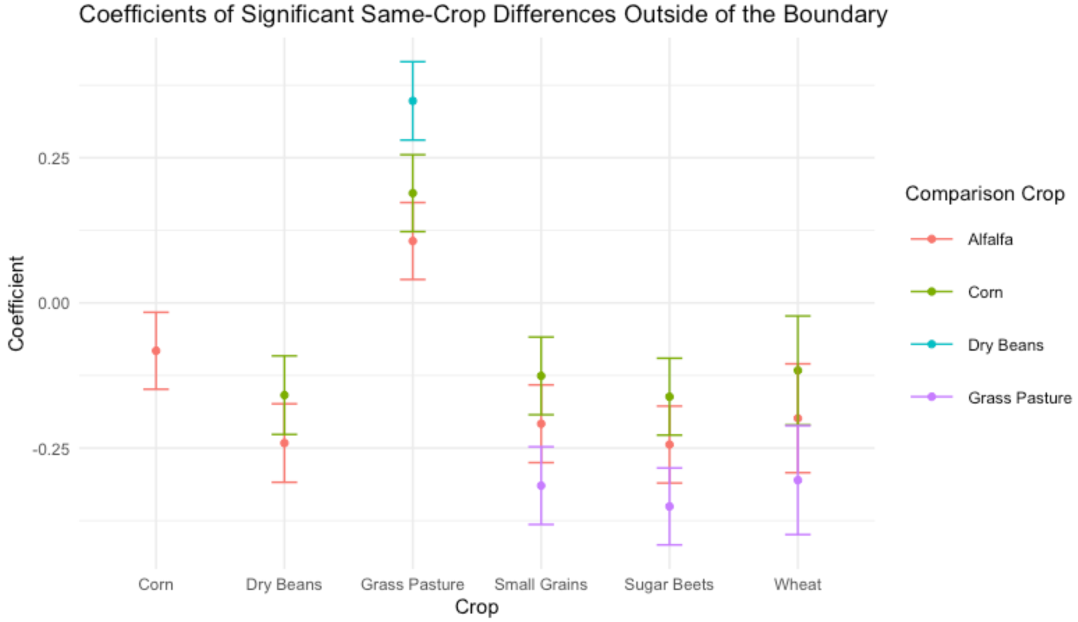
CDSS records the location of the initial appropriation claim, but does not record the location of a claim over all time. If water is diverted at point A and later transferred to point B, CDSS records only point A and that the water was transferred to another WDID. As a result, one cannot observe easily where the water associated with an original diversion point is over time. We use the information recorded by CDSS to build a panel that addresses this location issue. The trade year associated with each water right was listed in one of two locations. Primarily, observations contained a trade year in the comments that explained the purpose of the transfer, the timing, and additional details relevant for the trade. We scraped the comments to remove only dates and then formatted these dates in the same manner. We randomly checked to ensure that the scraped date was referring to the trade date, and not to another date included. In the second case, the comments contained no date and so the case number date was used as a substitute. Often the trade date was identical to the case number date, but in some cases, it differed by a year. We use first the trade date scraped from the comments and then second, when the trade date was missing, the court date associated with the case number.

A single water right might be matched to more than one parcel, so when identifying transfers, we look at the unique identifier for each right, not the total farms or plots a right is associated with. This process means that while one right might be transferred, multiple parcels could be affected.

Tukey HSD Results

Figure 19

Coefficients of Significant Same-Crop Differences



Note. The above figure compares the Tukey HSD results for significant crop differences outside the CBT. It can be interpreted similarly to the following example. If one wants to know the difference outside of the CBT between crop selection, they first select a crop on the x axis. For example, if we select corn on the x axis, we see one significant crop comparison choice, alfalfa. The coefficient on our crop, corn, is negative, meaning that individuals outside of the CBT select less corn to grow compared to alfalfa. This process can be repeated for all crops.

APPENDIX C

CHAPTER 3

Table and Summary Statistics

Table 6

Summary Statistics for 1(Agriculture)

		Outside CBT			Inside CBT		
		n	*Mean*	*Standard Deviation*	*n*	*Mean*	*Standard Deviation*
5 Mile Cutoff	1974	16677	0.2625	0.4400	15354	0.2638	0.4407
	1982	16677	0.2611	0.4392	15354	0.2627	0.4401
	1992	16677	0.2635	0.4405	15354	0.2701	0.4440
	2002	16677	0.2691	0.4435	15354	0.2749	0.4465
	2012	16677	0.2711	0.4445	15354	0.2769	0.4475
10 Mile Cutoff	1974	6251	0.2544	0.4355	13420	0.2596	0.4384
	1982	6251	0.2526	0.4345	13420	0.2592	0.4382
	1992	6251	0.2550	0.4359	13420	0.2667	0.4422
	2002	6251	0.2600	0.4386	13420	0.2717	0.4448
	2012	6251	0.2625	0.4400	13420	0.2735	0.4458
15 Mile Cutoff	1974	26126	0.2324	0.4224	16261	0.2672	0.4425
	1982	26126	0.2315	0.4218	16261	0.2660	0.4419
	1992	26126	0.2310	0.4215	16261	0.2734	0.4457
	2002	26126	0.2339	0.4233	16261	0.2778	0.4479
	2012	26126	0.2350	0.4240	16261	0.2797	0.4489

Note. The above table shows summary statistics for the outcome variable of agriculture, according to cutoff and year.

Table 7

Summary Statistics for 1(Development)

		Outside CBT			Inside CBT		
		n	*Mean*	*Standard Deviation*	*n*	*Mean*	*Standard Deviation*
5 Mile Cutoff	1974	6788	0.1176	0.3221	13753	0.0835	0.2766
	1982	6788	0.1223	0.3221	13753	0.0860	0.2804
	1992	6788	0.1255	0.3313	13753	0.0874	0.2824
	2002	6788	0.1301	0.3364	13753	0.0913	0.2881
	2012	6788	0.1383	0.3453	13753	0.0953	0.2937
10 Mile Cutoff	1974	18281	0.1232	0.3287	15710	0.0866	0.2813
	1982	18281	0.1288	0.3350	15710	0.0889	0.2846
	1992	18281	0.1336	0.3403	15710	0.0901	0.2864
	2002	18281	0.1388	0.3457	15710	0.0936	0.2912
	2012	18281	0.1480	0.3551	15710	0.0973	0.2964
15 Mile Cutoff	1974	28490	0.1246	0.3303	16626	0.0896	0.2856
	1982	28490	0.1307	0.3371	16626	0.0917	0.2886
	1992	28490	0.1360	0.3428	16626	0.0929	0.2903
	2002	28490	0.1403	0.3473	16626	0.0962	0.2948
	2012	28490	0.1478	0.3549	16626	0.1001	0.3001

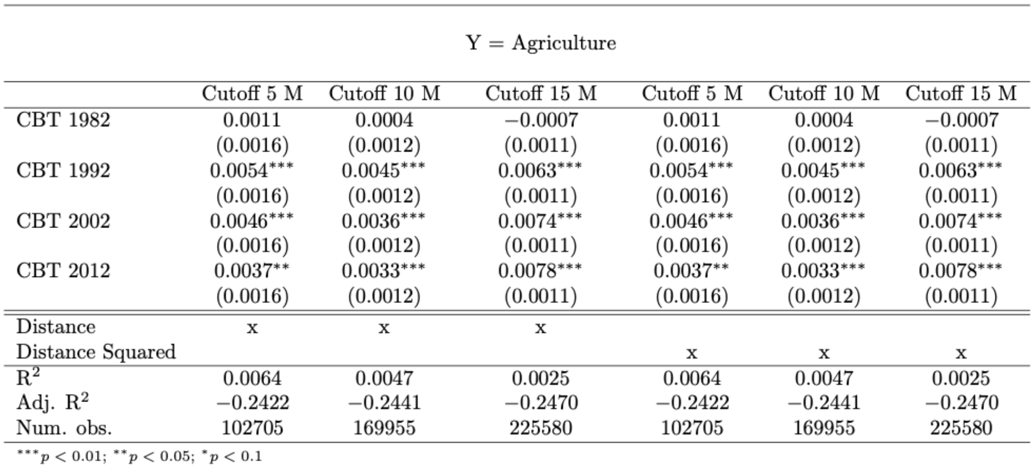
Note. The above table shows summary statistics for the outcome variable of developed, according to cutoff and year.

Note that we impose several critical conditions on our models: (1) that individuals in the CBT have joined only in 1956 and not after; (2) that the variable for agriculture be defined in each year for the QS to be included; (3) that the drought indicator and temperature index be defined in each year for a QS to be included. The number of QS in agriculture increases with each cutoff and is greater than the total number of observations since the number of observations does not change over time. The majority of parcels in the CBT are within ten miles of the boundary, as are the majority of parcels outside of the CBT.

Regression Tables

Table 8

Spatial Regression Results for Equation 4, Outcome of Agriculture



Y = Agriculture

	Cutoff 5 M	Cutoff 10 M	Cutoff 15 M	Cutoff 5 M	Cutoff 10 M	Cutoff 15 M
CBT 1982	0.0011	0.0004	−0.0007	0.0011	0.0004	−0.0007
	(0.0016)	(0.0012)	(0.0011)	(0.0016)	(0.0012)	(0.0011)
CBT 1992	0.0054***	0.0045***	0.0063***	0.0054***	0.0045***	0.0063***
	(0.0016)	(0.0012)	(0.0011)	(0.0016)	(0.0012)	(0.0011)
CBT 2002	0.0046***	0.0036***	0.0074***	0.0046***	0.0036***	0.0074***
	(0.0016)	(0.0012)	(0.0011)	(0.0016)	(0.0012)	(0.0011)
CBT 2012	0.0037**	0.0033***	0.0078***	0.0037**	0.0033***	0.0078***
	(0.0016)	(0.0012)	(0.0011)	(0.0016)	(0.0012)	(0.0011)
Distance	x	x	x			
Distance Squared				x	x	x
R^2	0.0064	0.0047	0.0025	0.0064	0.0047	0.0025
Adj. R^2	−0.2422	−0.2441	−0.2470	−0.2422	−0.2441	−0.2470
Num. obs.	102705	169955	225580	102705	169955	225580

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Note. The above table contains results for equation 4, where the outcome is agriculture, and no weather controls are included. Each column contains the results based on a different cutoff, with columns 1-3 containing a cutoff distance in miles and columns 4-6 containing a cutoff distance in miles squared. Standard errors are clustered by township.

Table 9

Spatial Regression Results for Equation 4, Outcome of Agriculture with Weather Controls

	Y = Agriculture					
	Cutoff 5 M	Cutoff 10 M	Cutoff 15 M	Cutoff 5 M	Cutoff 10 M	Cutoff 15 M
Drought Index	-0.0612^{***}	-0.0755^{***}	-0.0848^{***}	-0.0612^{***}	-0.0755^{***}	-0.0848^{***}
	(0.0087)	(0.0072)	(0.0065)	(0.0087)	(0.0072)	(0.0065)
Temperature Index	-0.0281^{***}	-0.0497^{***}	-0.0507^{***}	-0.0281^{***}	-0.0497^{***}	-0.0507^{***}
	(0.0065)	(0.0053)	(0.0047)	(0.0065)	(0.0053)	(0.0047)
CBT 1982	0.0006	-0.0010	-0.0021^{*}	0.0006	-0.0010	-0.0021^{*}
	(0.0016)	(0.0013)	(0.0012)	(0.0016)	(0.0013)	(0.0012)
CBT 1992	0.0063^{***}	0.0047^{***}	0.0065^{***}	0.0063^{***}	0.0047^{***}	0.0065^{***}
	(0.0016)	(0.0013)	(0.0012)	(0.0016)	(0.0013)	(0.0012)
CBT 2002	0.0074^{***}	0.0058^{***}	0.0105^{***}	0.0074^{***}	0.0058^{***}	0.0105^{***}
	(0.0016)	(0.0013)	(0.0012)	(0.0016)	(0.0013)	(0.0012)
CBT 2012	0.0076^{***}	0.0078^{***}	0.0136^{***}	0.0076^{***}	0.0078^{***}	0.0136^{***}
	(0.0016)	(0.0013)	(0.0012)	(0.0016)	(0.0013)	(0.0012)
R^2	0.0073	0.0063	0.0042	0.0073	0.0063	0.0042
Adj. R^2	-0.2411	-0.2422	-0.2448	-0.2411	-0.2422	-0.2448
Num. obs.	98355	160155	211935	98355	160155	211935

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Note. The above table contains results for equation 4, where the outcome is agriculture, and weather controls are included. Each column contains the results based on a different cutoff, with columns 1-3 containing a cutoff distance in miles and columns 4-6 containing a cutoff distance in miles squared. Standard errors are clustered by township.

Table 10

Spatial Regression Results for Equation 4, Outcome of Development

	Y = Development					
	Cutoff 5 M	Cutoff 10 M	Cutoff 15 M	Cutoff 5 M	Cutoff 10 M	Cutoff 15 M
CBT 1982	-0.0017	-0.0035^{***}	-0.0042^{***}	-0.0017	-0.0035^{***}	-0.0042^{***}
	(0.0013)	(0.0010)	(0.0009)	(0.0013)	(0.0010)	(0.0009)
CBT 1992	-0.0035^{***}	-0.0070^{***}	-0.0083^{***}	-0.0035^{***}	-0.0070^{***}	-0.0083^{***}
	(0.0013)	(0.0010)	(0.0009)	(0.0013)	(0.0010)	(0.0009)
CBT 2002	-0.0045^{***}	-0.0086^{***}	-0.0093^{***}	-0.0045^{***}	-0.0086^{***}	-0.0093^{***}
	(0.0013)	(0.0010)	(0.0009)	(0.0013)	(0.0010)	(0.0009)
CBT 2012	-0.0090^{***}	-0.0141^{***}	-0.0129^{***}	-0.0090^{***}	-0.0141^{***}	-0.0129^{***}
	(0.0013)	(0.0010)	(0.0009)	(0.0013)	(0.0010)	(0.0009)
Distance	x	x	x			
Distance Squared				x	x	x
R^2	0.0100	0.0128	0.0125	0.0100	0.0128	0.0125
Adj. R^2	-0.2376	-0.2341	-0.2344	-0.2376	-0.2341	-0.2344
Num. obs.	98355	160155	211935	98355	160155	211935

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Note. The above table contains results for equation 4, where the outcome is development, and no weather controls are included. Each column contains the results based on a different cutoff, with columns 1-3 containing a cutoff distance in miles and columns 4-6 containing a cutoff distance in miles squared. Standard errors are clustered by township.

Table 11

Spatial Regression Results for Equation 4, Outcome of Development with Weather Controls

	Y = Development					
	Cutoff 5 M	Cutoff 10 M	Cutoff 15 M	Cutoff 5 M	Cutoff 10 M	Cutoff 15 M
Drought Index	-0.0890^{***}	-0.0732^{***}	-0.0605^{***}	-0.0890^{***}	-0.0732^{***}	-0.0605^{***}
	(0.0069)	(0.0060)	(0.0053)	(0.0069)	(0.0060)	(0.0053)
Temperature Index	-0.0512^{***}	-0.0424^{***}	-0.0258^{***}	-0.0512^{***}	-0.0424^{***}	-0.0258^{***}
	(0.0052)	(0.0044)	(0.0038)	(0.0052)	(0.0044)	(0.0038)
CBT 1982	-0.0029^{**}	-0.0047^{***}	-0.0052^{***}	-0.0029^{**}	-0.0047^{***}	-0.0052^{***}
	(0.0013)	(0.0010)	(0.0009)	(0.0013)	(0.0010)	(0.0009)
CBT 1992	-0.0037^{***}	-0.0075^{***}	-0.0089^{***}	-0.0037^{***}	-0.0075^{***}	-0.0089^{***}
	(0.0013)	(0.0010)	(0.0009)	(0.0013)	(0.0010)	(0.0009)
CBT 2002	-0.0031^{**}	-0.0074^{***}	-0.0083^{***}	-0.0031^{**}	-0.0074^{***}	-0.0083^{***}
	(0.0013)	(0.0010)	(0.0009)	(0.0013)	(0.0010)	(0.0009)
CBT 2012	-0.0060^{***}	-0.0111^{***}	-0.0106^{***}	-0.0060^{***}	-0.0111^{***}	-0.0106^{***}
	(0.0013)	(0.0011)	(0.0010)	(0.0013)	(0.0011)	(0.0010)
Distance	x	x	x			
Distance Squared				x	x	x
R^2	0.0135	0.0148	0.0136	0.0135	0.0148	0.0136
Adj. R^2	-0.2333	-0.2315	-0.2330	-0.2333	-0.2315	-0.2330
Num. obs.	98355	160155	211935	98355	160155	211935

$^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$

Note. The above table contains results for equation 4, where the outcome is development, and weather controls are included. Each column contains the results based on a different cutoff, with columns 1-3 containing a cutoff distance in miles and columns 4-6 containing a cutoff distance in miles squared. Standard errors are clustered by township.