The Capitalization of Incomplete Property Rights to the Groundwater Commons

Eric C. Edwards
North Carolina State University

Nathan P. Hendricks and Gabriel S. Sampson
Kansas State University

June 2023

Abstract

Incomplete property rights are common across a range of natural resources such as fisheries and groundwater. The High Plains Aquifer region of Kansas provides one example of a complex but incomplete system of property rights. Rights to groundwater in Kansas are incomplete due to the physical characteristics of the resource, limited transferability between irrigators, and regulatory uncertainty. This paper takes a hedonic approach to understanding how three core features of prior appropriation water rights in Kansas—access, allocation, and seniority—confer value to irrigated farmland. All three water right features are priced into land values. Groundwater access rights confer an average land value premium of 71%, or $1,443/acre. Water rights having larger allocations and more seniority are more highly valued in the land market. The effect of seniority is consistent with more junior rights facing greater regulatory risk of curtailments. Our results indicate incomplete resource rights still confer value. Additionally, we use our empirical estimates to quantify the distributional costs of adopting modified groundwater governance regimes that ignore heterogeneity in allocation or seniority.

1. Introduction

The overexploitation of open access groundwater resources can impose high costs due to saltwater intrusion, land subsidence, dry wells, and reduced surface water availability. One policy solution—among others such as rationing (Ryan and Sudarshan 2022) and Pigouvian taxes (Smith et al. 2017)—is the allocation by the state of formal rights to extract groundwater. Where stringent, tradeable property rights to groundwater have been implemented, users see secure access, reductions in externalities, and increases in land values (Ayres et al. 2021). Defining groundwater property rights, however, is complex and costly, and as a result property rights are typically incomplete (Edwards and Guilfoos 2021).

Complete property rights convey exclusivity, transferability, and constitutional guarantees of ownership (Pejovich 1997). Property rights are incomplete when one or more of these characteristics is absent or not fully defined. The presence of transaction costs and bounded rationality limit the completeness of all property rights to some extent (Allen 1991). Differing transaction costs, legal definitions, and resource characteristics create variation in property right completeness. In addition to groundwater, incomplete property rights are common globally across a range of natural resources such as forests, fisheries, and grazing lands. Property rights to surface water ownership via the prior appropriation doctrine in the western US provide an example of fairly complete rights in terms of exclusivity and constitutional guarantees (with some key exceptions), but with limited transferability (Leonard et al. 2019).

In contrast, physical characteristics of groundwater, being underground, are difficult to observe and heterogeneous over space, making it costly to define and enforce complete property rights. Moreover, the transaction costs of basin-wide action to redefine existing property rights to more completely control extraction are large (Ayres et al. 2018). Thus, while there are benefits of addressing overextraction, the costs of a corrective policy, e.g. complete property rights, could exceed these benefits (Brill and Burness 1994). Although examples of complete groundwater right regimes are limited, incomplete property rights abound. The value of these incomplete property right systems can be observed in land value transactions of associated agricultural parcels. These values and the role they play in the distribution of benefits under groundwater management policy, however, are not well understood.

Kansas offers one example of a complex but incomplete system of groundwater rights which includes three core features. First, the state can close basins to new groundwater appropriations, creating a right to pump that is not automatically granted with land title (i.e., limited entry). Second, the right provides appropriators with a well-defined allocation limit on the amount of water they can pump and the acres they can irrigate. Third, groundwater property rights are assigned based on seniority, with older rights holding a priority claim.

The seniority system is a hallmark of western US property rights to surface water. This system of “first-in-time, first-in-right” has several beneficial economic properties including allowing for changes in allocations during shortfalls, providing information on scarcity, and encouraging investment (Burness and Quirk 1979; Leonard and Libecap 2019). However, allocations based on seniority are generally economically inefficient in the absence of a market for annual allocations (Burness and Quirk 1979; Earnhart and Hendricks 2022; Browne and Ji 2023). Appropriative water rights were issued for all groundwater users in Kansas beginning in 1945 but remain incomplete across all three characteristics. Exclusivity is limited by the logistical complexities and costs in enforcing rights to a common pool resource. Transferability of groundwater rights in Kansas is extremely limited, even when compared to appropriative surface rights. Finally, regulatory insecurity limits guarantees of ownership because pumping limits and seniority may be ignored under future allocation mechanisms, or may never be enforced (Grainger and Costello 2014 provide an example from fisheries management).

This paper takes a hedonic approach to understanding how the three core features of prior appropriation water rights—access, allocation, and seniority—confer value to irrigated farmland. In Kansas, water rights are generally not severed from the land and are therefore included in the price of land transactions. We combine data on every agricultural land transaction in western Kansas between 1990 and 2019 with information on irrigation water rights. Valuing water right characteristics has been a challenge because transaction data do not list water rights. We use newly available geospatial data on parcel boundaries to match water right data with each transaction.

We find all three characteristics of water rights are priced into land values. The right to pump under prior appropriation confers an average land value premium of 71%, or $1,443/acre, when evaluated at 2019 market conditions. In total, agricultural land values were $3.5 billion larger in 2019 because of access to irrigation from the aquifer. Additionally, we find that water rights having larger allocations and more seniority are more highly valued in the land market: the average marginal value of one additional acre-inch in allocation ranges from $9 to $19. The average marginal value of an additional year of seniority ranges from $5 to $8. The distribution of the effect of seniority is not necessarily linear, with more junior rights facing a larger land value discount, consistent with more junior rights facing greater regulatory risk.

A common challenge of groundwater management organizations, even after a basin is closed to new entrants, is the need to further limit extractions by allocating cutbacks (for instance because pumping exceeds a desired sustainable level of aggregate extraction). Our approach provides insight into the incidence of implemented and hypothetical cutback allocations across right seniority (Drysdale and Hendricks 2018). We also provide a hypothetical exercise that suggests eliminating the seniority system across Kansas would transfer around 2.6% of total aquifer value from senior to junior appropriators.

This paper contributes to the literature by empirically estimating how incomplete property rights are capitalized into resource values. Several previous studies estimate the value of the use of a groundwater resource (Torell et al. 1990; Buck et al. 2014; Hornbeck and Keskin 2014; Kovacs and Rider 2023) or estimate the value of the stock of the resource (Fenichel et al. 2016; Sampson et al. 2019; Perez-Quesada et al. Forthcoming). Other studies estimate the value of defining property rights, such as in the case of water right adjudication (Debaere and Li 2020; Browne and Ji 2023) or barbed wire fence to protect land (Hornbeck 2010). But there are limited studies that value the characteristics of property rights when those rights are incomplete, as is typically the case in groundwater. One notable exception is from fisheries, where Grainger and Costello (2014) estimate the market capitalization of different aspects of property right insecurity.[1] The fact that we find significant capitalization of incomplete property rights is noteworthy because it indicates that the High Plains Aquifer (HPA) is not purely open access in Kansas, otherwise these property rights would have no value above the capital cost of establishing irrigation.[2] More broadly, our results indicate that incomplete property rights can still confer value.

We also contribute to the literature on the path dependency of institutions to allocate resources (Libecap 2011). Although incomplete property rights partially enclose the commons, they can also create a challenge to the adoption of more efficient resource allocations. Transaction costs associated with reallocating benefits and costs under modified groundwater pumping regimes are a barrier to effective management (Libecap 1993; Ayres et al. 2018; Edwards and Guilfoos 2021). To get a sense of these transaction costs in our setting, we use market valuation of water right allocations to quantify the distributional costs of adopting a modified groundwater pumping regime that ignores seniority.

Our third contribution is to the literature on seniority-based water right allocations. This is especially important because most of the water in the western United States is allocated by the prior appropriation doctrine. Brent (2017) find no significant premium for seniority among irrigation districts in Washington. Lee, Rollins, and Singletary (2020) find the more senior rights are associated with more productive land only if they have been transferred. Other studies show that seniority affects the land allocation due to uncertainty of water deliveries (Ji and Cobourn 2018; Cobourn et al. 2022). Each of these previous studies were in the context of surface water, where seniority provides a clearer property right and there is only uncertainty in the amount of water available. In contrast, regulatory uncertainty is the primary source in the groundwater context that we study.

2. Background

Groundwater supplies drinking water to approximately 50% of the world's population and accounts for 43% of total irrigation water consumption (Siebert et al. 2010; Connor 2015). While laws and groundwater governance institutions vary, it is predominantly managed as an open access resource (Edwards and Guilfoos 2021). In the United States, a common legal regime is the rule of capture, where ownership occurs once the water is pumped from underground. In a regime governed by the rule of capture, users ignore the costs their extraction imposes on neighboring parcels, leading to the tragedy of the commons, overextraction, and rent dissipation.

[1] Another related strand of literature studies how property right security affects resource depletion (Costello and Grainger 2018; Isaksen and Richter 2019).

[2] Li and Zhao (2018) also find evidence that allocations amounts are binding: water rights with 10% less allocation use 5% less water in Kansas.

Water available from an aquifer is characterized by both its stock and its flow. Each year, the flow, or recharge, replenishes the aquifer. In areas where recharge exceeds extraction and outflow, stock increases; where outflows and extraction exceed recharge, stock decreases. The optimal use of a groundwater aquifer is thus an intertemporal allocation problem, whereby high pumping reduces the stock, increasing extraction costs and decreasing water availability in future periods (Gisser and Sanchez 1980). Common pool problems occur due to subsurface aquifer connectivity. Users who extract water in excess of recharge draw down the stock under their patch of land, pulling water via gravity from adjoining patches (Brozović et al. 2010; Kaffine and Costello 2011; Sampson and Sanchirico 2019).

Property rights can partially offset externality problems created by aquifer connectivity (Edwards and Guilfoos 2021). First, certain patches can be turned off to reduce the amount of connectedness in a local area and limit aggregate extraction. We define this aspect of the property right as *access*. Second, extraction can be aligned with recharge at each patch by placing a limit on the extraction amount, or *allocation*. Third, rights can be granted so that early extractors receive legal assurance that their full right to pump will be protected in the future. *Seniority* provides right holders who begin using the resource first with security in the event the resource is overallocated, e.g., if recharge is less than originally estimated.

The prior appropriation doctrine was established in Kansas for both surface and groundwater by the 1945 Water Appropriation Act. While most other semi-arid western states in the U.S. had already adopted appropriative rights for surface water, the application of this system to groundwater was novel. Utilizing seniority to define allocations from surface water is relatively straightforward. In years with less surface water, the most senior rights receive the first allocations until the available water is exhausted. However, in shared aquifers without limits on the number of permits issued, some areas in Kansas experienced rapid depletion without a clear point at which junior pumpers should be curtailed to protect seniors (Edwards 2016). Prior appropriation therefore offers an incomplete property right, as it does not provide strict ownership over the stock of the resource (Provencher and Burt 1994) nor does it allow for the costless transfer of pumping rights from low- to high-value patches. Prior appropriation rights, however, may still create benefits at relatively low costs, potentially allowing for second-best solutions that economize on transaction costs (Edwards and Guilfoos 2021).

To obtain a permit to pump groundwater in Kansas, a user files an application with the Division of Water Resources (DWR) in the Kansas Department of Agriculture. The water right defines not only the annual quantity allocation, but also the location of the point of diversion (i.e., the well), the location where the water may be applied (i.e., place of use), the rate at which the water can be extracted, and the water right number (i.e., the seniority ranking). Individuals who used water prior to June 28, 1945 were granted vested rights that are superior in seniority to even the most senior right. However, there are few vested rights because groundwater extraction in Kansas began primarily after World War II (Table

1).[3] From 1945 to 1950, only 334 pumping permit applications were received, jumping to 5,730 applications in the 1950s and 6,433 in the 1960s (Peck 2005).

Limits on the amount of water that can be extracted can further strengthen the groundwater property right by reducing spatial externalities. The Water Appropriation Act gives the state authority to regulate and control the use of water (Peck 2015). The initial allocation of rights led to excess pumping and large externalities due to well interference and aquifer drawdown. Legislation passed in 1972 led to the formation of five Groundwater Management Districts (GMDs) between 1973 and 1976 (Edwards 2016). The new regulatory authority granted to GMDs fixed a shortcoming in the initial setup of the appropriative rights doctrine by empowering GMDs to close areas to additional development.

After 1972, allocation amounts were also determined at the GMD level. Figure 1 shows the distribution of permitted allocations and priority dates for the five districts and non-district areas. Districts 1, 3, and 4 lie in the western and most arid part of the state (Fig. 2) and have greater allocated depth per acre than the districts in more humid areas because beneficial use requirements are larger. Area closures prevented new entrants from infringing on senior pumping rights while allocations limited cross-well externalities between permitted pumpers. There is only one case in the Kansas Ogallala region where a groundwater irrigator filed an impairment complaint to reduce pumping by nearby junior rights. In 2016, the Garetson Brothers filed a case that their vested water right was impaired (*Garetson Brothers v. American Warrior, Inc.*). The court utilized the standard definition of an impairment as "to weaken, to make worse, to lessen in power, diminish, or relax or otherwise affect in an injurious manner." The Chief Engineer at DWR conducted an analysis and found that five neighboring water rights were directly interfering with the ability of the Garetson Brothers to fully satisfy their vested right due to a reduced well capacity. Given the definition of impairment, the Garetson Brothers prevailed in the case and the junior rights were curtailed. What is still unclear from the court case is whether impairment could include long term depletion of the aquifer or if impairment only includes direct (spatial dynamic) interference (Peck 2005). Nonetheless, cases of impairment filings between agricultural producers remain uncommon.

Other types of water right conflict have emerged that demonstrate the importance of seniority. In 2013, U.S. Fish and Wildlife Service (USFWS) filed an impairment complaint that junior groundwater irrigators in GMD 5 were reducing streamflow in Rattlesnake Creek due to the hydrologic connection of surface and groundwater in the region. USFWS holds a surface water right for streamflow in Rattlesnake Creek that flows into the Quivira National Wildlife Refuge. The Chief Engineer at DWR concluded that an impairment existed

[3] If the permit is approved, the user has five years to "perfect" the water right. The quantity allocated to the water right is determined by the largest beneficial use of water in any year during the perfection period, subject to certain limits. Generally, the maximum that farmers were allocated was larger in drier regions of the state and smaller in wetter regions based on differences in beneficial uses. The Water Appropriation Act states that water rights are "a real property right appurtenant to and severable from the land on or in connection with which the water is used and such water right passes as an appurtenance with a conveyance of the land" (K.S.A. 82a-701[g]).

and there were several years of negotiations to find a solution. After negotiations between irrigators and USFWS failed to reach a conclusion, DWR announced administrative allocations to resolve the impairment. DWR defined allocations as a set percentage of authorized water right quantity, where the percentage was larger for more senior water rights. Following a meeting with Senator Moran from Kansas, the USFWS committed to pursue voluntary solutions with local groundwater managers and the administrative orders were put on hold. Not satisfied with the water management plans that emerged, in 2023 the USFWS again requested to secure water in the amount of 14,632 acre-feet per year for their senior water right due to injury from more junior irrigation wells.

The seniority of water rights was also used to differentiate allocations in the Walnut Creek IGUCA (Intensive Groundwater Use Control Area) in central Kansas (Fig. A1) due to concerns about groundwater pumping reducing streamflow into the Cheyenne Bottoms wetland (Earnhart and Hendricks 2022). Under the IGUCA, vested water rights received their full authorized quantity. Senior water rights, defined as having priority dates on or before October 1, 1965, were given an allocation equal to the net irrigation requirement for corn in the respective county (12-14 inches). Junior water rights allocations were curtailed to a level equal to 44% of the amount given to senior rights (5-6 inches) so that total allocations equaled the safe yield.

Kansas enacted legislation in 2012 that allowed GMDs to design their own management plans—called Local Enhanced Management Areas (LEMAs)—that could define allocations to reduce groundwater extraction. These LEMAs include a public hearing process and must also be approved by the Chief Engineer at DWR. Several LEMAs have been implemented in the northwest and west central districts (Perez-Quesada and Hendricks 2021), with additional LEMAs under development in GMDs 1 and 5. One of these LEMAs decreased water use by roughly 26% (Drysdale and Hendricks 2018; Deines et al. 2019). While state-mandated cutbacks have followed seniority to differentially curtail allocations, none of the LEMAs have used water right seniority to define curtailments. Instead, they have either based allocations on a uniform application depth multiplied by historical acres irrigated or a percentage of historical use.

The choice of approach to cutbacks can have efficiency consequences due to limited transferability of water rights. Transfers of groundwater are complicated administratively and are not common. In 1957, the Water Appropriation Act was amended to allow the owner of a water right to apply for a change in the point of diversion, place of use, or beneficial use. Such changes are approved conditional on not impairing existing rights drawing water from the same local source of supply (K.S.A. 82a-708[b]). Kansas also allows for the transfer of water from the point(s) of diversion and place(s) of use where the water right was initially granted to a new location under the Water Transfer Act. Any transfer of a quantity greater than 2,000 acre-feet to a point more than 35 miles away requires approval of the Chief Engineer of the DWR (K.S.A. 82a-1501[a]). [4] Amongst other requirements, the transfer cannot impair existing water rights and the benefits to the state for approving the transfer must outweigh the benefits of not approving the transfer (K.S.A. 82a-1502[a]).

[4] The Water Transfer Act is thus subject to the Water Appropriation Act.

There are only a few cases where groundwater rights have been transferred from one beneficial use to another. Namely, the city of Hays purchased the R9 Ranch along with its 30 irrigation water rights in 1995. In 2016, the cities of Hays and Russell filed an application to transfer 7,625.5 acre-feet of water from the R9 Ranch to municipal use, with plans to construct pipelines to deliver the water. The Chief Engineer of the Division of Water Resources approved the transfer in 2019. Given the general inability to transfer groundwater and production functions concave in water application, reduced crop production by junior appropriators facing a large cutback will likely exceed gains to senior appropriators facing only a small cutback, relative to a uniformly applied cutback.

Our empirical strategy tests the degree to which groundwater access, allocation, and seniority are valued in the land market. By comparing dryland farms, those without pumping rights, to irrigated farms we can estimate the value of the pumping right itself, plus the investment in equipment on the land. Modern agricultural well drilling and irrigation equipment costs can exceed $1,000 per acre, so the calculation of net access right premiums per acre requires an explicit assumption about this cost. We test the extent to which higher allocation limits are valuable by estimating how variation in water allocations, measured as inches per acre, affects land sale outcomes. Finally, seniority rules apply only insofar as (i) there is an initial overallocation and (ii) junior rights are shut down or have their allocations curtailed. All else equal, where prior appropriation is binding or expected to be, more senior rights should command a premium.

3. Data

We obtain data from a variety of sources in estimating the hedonic price models. A summary of the data used in the empirical analysis is presented for irrigated and non-irrigated parcels in Table 1. We detail each data source below.

3.1. Land transactions

Data on every agricultural land transaction in Kansas of 40 acres or more are obtained from the Property Valuation Division (PVD) of the Kansas Department of Revenue for the years 1990 to 2019. In total, we obtain sales information on 158,500 parcel transactions across the state. The PVD data indicate acreage by land type and include codes for transaction type. When multiple parcels are indicated in the sale we aggregate the parcel-specific values and characteristics to the transaction-level. We restrict the analysis to arms-length transactions so that reported values are true reflections of fair market value. All values are converted to 2019 dollars using the consumer price index.

We drop observations if the PVD sales code indicates multiple parcels yet only a single parcel is observed in the transaction (4,400 transactions). We exclude from the analysis transactions that are greater than 5,000 acres (72 transactions) and those having appraised values of improvements greater than $100,000 (9,368 transactions).[5] We further

[5] The PVD data does not indicate the type of improvement. Less than 5% of the transactions having appraised value of improvements greater than $100,000 indicated any irrigated acreage.

examine the distribution of parcel values and the log of parcel values. To do this, we estimate a regression which controls for agricultural district-specific differences in the price of dryland, irrigated, and pasture and district-specific changes in prices over time. We then obtain the residuals. We define outlier transactions as those above the 75th quartile plus 3 times the interquartile range and those below the 25th quartile minus 3 times the interquartile range. In total this drops 7,982 transactions. After the initial cleaning of the PVD land sales data, we are left with approximately 76,000 observations across the entire state of Kansas.

Lastly, we restrict the analysis to only those counties overlaying the HPA (excludes 72% of remaining observations) and transactions that are indicated as being at least 50% cropland by area (as opposed to pasture). We also exclude parcels that are coded as irrigated but have no authorized irrigated acreage that can be linked to DWR (76 observations). This leaves approximately 16,000 observations. The counties in our sample and the locations of transactions are shown in Figure 2.

3.2. Parcel boundaries

The PVD sales data indicate the total acreage of each parcel in a transaction but does not include information on the parcel boundaries nor the water right numbers associated with the parcel. To ensure accurate assignment of spatially delineated water rights characteristics to land transactions, we obtain parcel boundary geodata for every county in Kansas from Regrid. The Regrid information provides geodata for each parcel within a county-specific geodatabase along with a specific identification code for each parcel. We normalize the parcel identification code in the Regrid data so that they are consistent across counties (i.e., a 21-character string). We format the parcel identification code in the PVD data likewise and then match to the Regrid data using this code. We obtain 98% match rates or greater for every county in Kansas except Greenwood, Johnson, Pottawatomie, and Sedgwick. These four counties tend to have more suburban land use and are not located over the HPA. Figure A2 provides an example of the parcel boundary data in Finney County, one of the most heavily irrigated counties in Kansas.

3.3. Water rights

As previously discussed, any individual seeking to use water for agricultural production in Kansas after 1945 must apply to the DWR for a water right. Information on authorized annual quantity of water pumped, acres authorized for irrigation, and the priority date of the water right are obtained from the Water Information and Analysis System (WIMAS) of the DWR.

Locations where water rights holders can exercise their water right are delineated by a "place of use", which is most often defined at the PLSS quarter-quarter section (i.e., 40 acres). We obtain place of use shapefiles from DWR, which we use to link characteristics of the water right to the parcel boundary geodata. Figure A2 provides an example of place-of-use delineations overlayed with parcel boundaries in Finney County. Spatial overlaps between parcel boundaries and place of use cluster around 0 and 40 acres, as expected (Figure A3). We choose a minimum overlap area of 50% (e.g., 20 acres) when associating

WIMAS water rights characteristics to the parcel. Volume allocations and priority dates of the water right are matched to the parcel using a unique water right identification tied to the place of use.

One challenge to using the WIMAS data is that two or more water rights can overlap in the point of diversion or in the place of use. In other words, two or more water rights may share a common point of diversion or place of use. Because of this overlap, we aggregate authorized acres and water quantities up to a “water right group” level. We define the water right group as the smallest legal combination of place of use and point of diversion such that no other places of use nor points of diversion of other water right groups overlap.

Where a water right group contains multiple water rights and therefore multiple priority dates, we compute the average priority date weighted by the volume of water authorized by the water right. Thus, the priority date attached to the largest water right volume is the most heavily weighted in the average. We also investigate alternative measures of priority date definitions in the regressions below.

For the proceeding empirical analysis, we compute a summary measure of the physical amount of irrigation authorized by DWR as the “allocated depth” (i.e., inches/acre). The depth variable is computed using the total volume of pumping authorized across all water rights in the water right group, dividing by the total acreage authorized for irrigation in the water right group. We exclude from analysis authorized depths that are unusually small or large: more than 36 inches or less than 6 inches (66 observations).

3.4. Climate

Weather data are obtained at the grid cell level from PRISM. We construct four long run climate variables from the PRISM data: average growing season precipitation, average growing season reference evapotranspiration, the average number of degree days between 10°C and 34°C during the growing season, and the average number of degree days greater than 34°C during the growing season. We also construct a water deficit variable defined as the difference between reference evapotranspiration and precipitation. Regions having a larger water deficit are expected to have greater demand for irrigation and thus place more value on irrigation. The PRISM grid cells are merged to sections of the PLSS. The centroid of the nearest PLSS section that intersects a PRISM grid cell is matched to the parcel boundary. Long run values for these climate variables are constructed as 10-year rolling averages up to the year of the land transaction. For example, the average growing season weather over 1985-1994 is used for a parcel that sold in 1995.

3.5. Hydrology

We develop saturated thickness data from a set of 1,002 monitoring wells over the HPA as described in Sampson et al. (2019). For each monitoring well, we compute a 3-year average spread over 5-year intervals, starting in 1990 and ending in 2020. Thus, each 5-year interval is the center of a 3-year average. Saturated thickness is then spatially interpolated from the monitoring well data using inverse distance weighting for each of the 5-year intervals. The resulting raster is clipped to PLSS sections which are then merged to the parcel boundary data. Years between the 5-year intervals are filled using linear interpolation.

3.6. City population

Census shapefile data are obtained from the 1990, 2000, and 2010 census. This data includes the geolocation of cities of various sizes. We compute straight-line distances from the centroid of each PLSS section to cities having populations of at least 100, 1,000, and 10,000. These distances are then merged to the nearest parcel boundary. Rural regions of Kansas typically have road networks at the intersection of each PLSS-section, so a straight-line distance provides a close approximation of travel time.

3.7. Soils

Soil characteristics which are likely to affect agricultural productivity are obtained from the SSURGO soil survey. The PVD land transaction data provide information on the acres represented by each SSURGO soil type. Soil types are linked to SSURGO data and the characteristics are aggregated up to the parcel. Included in our regressions are saturated hydraulic conductivity of the soil (i.e., ease of water movement), soil organic carbon, slope, and proportion of the parcel with soil pH greater than 8.0 (basic soils). We do not have any soils with pH less than 5.5, so we do not include a control for acidic soils.

4. Methods

We model land prices in a hedonic price framework (Rosen 1974; Palmquist 1989), where the value of farmland is determined by the bundle of agricultural (e.g., irrigation availability) and non-agricultural (e.g., proximity to towns) observable attributes. Farmland possessing desirable attributes will be bid up by consumers in a competitive market. The degree to which a parcel possessing a particular attribute fetches a premium over similar parcels not possessing that attribute provides evidence for how that attribute is valued in the market. Of particular emphasis in this paper is to quantify the capitalized premium (if any) of the three components of the property right for groundwater: right to access, amount of allocation, and seniority.

Our regressions are specified using the common semi-log functional form for two reasons. First, the coefficient estimates can be intuitively interpreted as proportional changes. Second, farmland values take on only positive values and can differ widely in relative terms. We first pool irrigated and non-irrigated transactions to estimate the real price per acres for parcel i in year t as:

$$\ln \frac{Price}{Acre}_{it} = \beta_1 IRR_{it} + IRR_{it}(\Omega' W_{it} + \beta_2 ST_{it} + \beta_{22} ST_{it}^2 + \Gamma' \mathcal{C}_{it} + \beta_3 HC_i) + \cdots$$
$$\beta_4 ST_{it} + \beta_{44} ST_{it}^2 + \psi' \mathcal{C}_{it} + \beta_5 HC_{it} + \zeta' SOIL_i + \phi' \mathcal{Z}_{it} + \eta_\ell + \tau_{G,t} + \epsilon_{it}. \quad (1)$$

In equation (1) IRR_{it} is a variable which measures the proportion of parcel i that is irrigated at the time of sale in year t, W_{it} is a vector of characteristics defining the water right (e.g., priority date, depth), ST_{it} is the saturated thickness of the aquifer, $\mathcal{C}_{it}$ is a vector of climate characteristics, and HC_i is the hydraulic conductivity of saturated soil. Thus, characteristics of the aquifer (ST_{it}), soil-water properties (HC_i), and climate ($\mathcal{C}_{it}$) can differentially affect the price of parcel i if it is irrigated. Included in W_{it} is a count of the number of distinct water rights transferred in the land transaction and a dummy for whether one or more of the water rights is a vested right. The coefficient β_1 provides the land market premium for a fully irrigated parcel relative to a dryland parcel, or the value of right to access to groundwater. The coefficients in the vector Ω provide the capitalized value of the allocation and seniority.

We specify a quadratic function of saturated thickness to account for diminishing marginal values of water stored in the aquifer. Additionally, $SOIL_i$ is a vector of all other soil characteristics (e.g., soil pH) and $\mathcal{Z}_{it}$ is a vector of all other time-varying characteristics of the land transaction (e.g., proximity to towns). Spatial dummies at the scale of PLSS townships (6 miles X 6 miles), η_ℓ, are used to control for unobserved heterogeneity in farmland values that are temporally stable. Lastly, temporal dummies ranging from year level to GMD-year level, $\tau_{G,t}$, are included to account for unobserved factors such as interest rates that change over time. With township and GMD-year controls included, the identifying variation in water rights definitions derives from cross-sectional and time series variation in water rights within a township that is not common across townships within a GMD.

We include only irrigated farmland transactions in the second estimating equation due to the possibility that all hedonic covariates confer differential implicit valuations across irrigated and non-irrigated transactions (Schlenker et al. 2005). Additionally, the spatial dummies in equation (1) average across irrigated and non-irrigated transactions. For this analysis, we define an irrigated parcel as being at least 50% irrigated land by total parcel area. The regression that we estimate for irrigated transactions is:

$$\ln \frac{Price}{Acre}_{it} = \Omega' W_{it} + \beta_2 ST_{it} + \beta_{22} ST_{it}^2 + \Gamma' \mathcal{C}_{it} + \beta_3 HC_i + \zeta' SOIL_i + \phi' \mathcal{Z}_{it} + \eta_\ell + \tau_t + \epsilon_{it}. \quad (2)$$

In equation (2), we include spatial dummies at the township-level and temporal dummies at the year-level and all covariates are as previously described. We do not include spatial-temporal dummies at the GMD-year level as in equation (1) due to concerns that such controls would eliminate too much identifying variation with a smaller number of observations.

A concern with using such a rich set of controls is leaving too little residual variation in authorized depth and seniority. To explore this possibility in the context of equation (2), we report estimates using county-level dummies in Table A4 of the supplementary appendix. The estimates are robust to either specification.

To avoid bias in OLS estimates of binary variables in the log-linear model and to avoid problems of back-transforming the dependent variable to obtain levels predictions, we estimate equations (1) and (2) using a generalized linear model (GLM) with a log link function and Poisson family. We complete the models in (1) and (2) by clustering standard errors at the township to account for heteroskedasticity and spatial correlation of the errors within townships.

We conduct several simulations of our models with the entire population of water right groups located over the Kansas portion of the HPA. Water right groups constitute non-overlapping groups of water rights as discussed in the data section. We merge the same independent variables used in the regression analyses to the population of water right groups. As with the regression data, we omit water right groups having allocated depth less than 6 inches or greater than 36 inches (190 observations). In total, we obtain information on 9,342 unique water right groups. The water right group data also contain information on the address of the water use correspondent. We define a unique irrigator by a unique address for the water use correspondent. This allows us to also aggregate results by irrigator.

5. Results

Regression coefficients and marginal effects in level terms of the key variables of interest are shown in Tables 2 and 3. Table 2 shows results from estimating equation (1) with all cropland transactions, irrigated and non-irrigated. Table 3 shows results from estimating equation (2) with only irrigated transactions. We organize our discussion of the results in terms of each characteristic of the property right: proportion of the parcel with irrigation access rights (right to access), authorized depth (allocation limits), and priority date (seniority). The full set of regression coefficients, including the controls, are provided in Tables A1 and A2 in the supplementary appendix.

5.1. Access Rights

We begin by discussing the capitalization of the property right to access groundwater shown in Table 2. The first column of Table 2 includes township and year fixed effects while the second column includes township and GMD-year fixed effects. The dependent variable is the log of the real price of farmland. We find that the availability of irrigation confers a large premium to farmland values.[6] When evaluated at average irrigation characteristics, the prediction of the proportional premium for a fully irrigated parcel compared to a dryland parcel is 71%. In levels terms, the average premium for a fully irrigated parcel over a dryland parcel is $1,002/acre. However, that premium is averaged across the entire sample period and land values have increased significantly in real terms over the period. Evaluated at 2019 land market conditions, the premium is $1,443/acre.

Direct interpretation of the coefficient on irrigation access rights as a valuation of the right to access groundwater, however, is complicated by the fact that the cost of irrigation capital (e.g., well development and irrigation infrastructure like a center pivot) is also captured by this coefficient. Land sale and WIMAS data lack sufficient detail for the separate identification of the contribution of irrigation capital investment and legal groundwater

[6] Our estimate of the land market premium of irrigated land is similar to Sampson et al. (2019). However, Sampson et al. (2019) do not compare this value to irrigation capital costs and they do not estimate valuation of the allocation or seniority of the water right due to data limitations.

access. Survey information from 2017 indicates the cost to develop a 200ft well with pump and gearhead were approximately $64,000 in Kansas.[7] Additionally, the cost of a center pivot system capable of irrigating 130 acres was approximately $69,000 (Tsoodle 2019). Thus, to irrigate a typical 130 acres, the total installation cost of a well with pump and center pivot structure would be approximately $1,023 per irrigated acre.[8] The irrigation premium of $1,443/acre estimated above is larger than the cost to install a new irrigation system. And because the useful life of a well and center pivot combination is approximately 25-30 years, depreciation of the system at the time of sale would be factored into bids made by prospective buyers, marking $1,023/acre as an upper bound for the value of irrigation capital. Therefore, a lower-bound estimate of the value of right to access groundwater is $420/acre.

To illustrate that the magnitude of our results is reasonable, we compare our estimates to Conservation Reserve Enhancement Program (CREP) payments for users to voluntarily retire water rights in parts of GMD 3 and GMD 5 (Manning et al. 2020; Rosenberg 2020). Using the average signing bonus and the range of the lowest and highest rental rates for pivot irrigated fields advertised in the 2016 program brochure over a 14-year contract at a 6% discount rate, farmers can expect a present value of enrollment of $1,500-$1,900/acre.[9] By comparison, we estimate an average land market premium that a fully irrigated parcel confers over a non-irrigated parcel of approximately $1,174/acre in GMD 3 and $2,447/acre in GMD 5, when evaluated at 2019 market conditions and average characteristics.

To calculate the total capitalized value of irrigation access rights, we predict the irrigated land value premium for the population of 9,342 water right groups over the Kansas portion of the HPA using the specification in column 1 of Table 2. We compute the total value of the Kansas HPA as measured by the cumulative irrigation premia summed over all water right groups. This is done by multiplying the predicted per-acre irrigation premium for each of the 9,342 water right groups by the number of acres authorized for irrigation, and then taking the sum across water right groups. Using 2019 market conditions, the total capitalized value of rights to irrigation access is $3.5 billion. As mentioned before, this value includes irrigation capital. Assuming an upper bound of $1,023/acre for irrigation capital, a lower bound estimate for the net capitalized value of rights to irrigation access is $761 million.

5.2. Allocation Limits

We estimate the value of the allocation limit (i.e., the authorized depth) using equation (1) that combines irrigated and non-irrigated parcels (Table 2) and equation (2) that restricts the analysis to only irrigated parcels (Table 3). Table 2 indicates that a 1-inch increase in the authorized irrigation depth increases irrigated farmland values by approximately 0.6%. In level terms, a 1-inch increase in authorized depth increases irrigated land values by

[7] Average depth to water across the aquifer in 2019 was approximately 130 feet.
[8] A center pivot circle irrigates most, but not all, of a standard 160 acre square parcel.
[9] Using the range of program incentives in 2022, the present value of enrollment estimates range from $1,450-$2,050/acre.

approximately $9-10/acre. When we restrict the sample to irrigated parcels, we also estimate that a 1-inch increase in authorized depth increases the value of the right by 0.6% ($10/acre).

Our estimate of the value of authorized depth is robust to alternative specifications. Column 2 in Table 3 restricts the sample to transactions involving only a single water right with the cleanest match of a water right to a transaction. We include only county fixed effects in column 2, because we lose 80% of the observations when restricting to transactions of a single water right. The marginal effect of an additional inch of authorized depth increases to approximately $19/acre, but the standard error is more than twice as large. In column 3, we define the authorized depth as the difference between the authorized depth of the water right group and the local water deficit. The result in column 3 indicates that an additional inch of authorized depth compared to local historic water deficit increases the value of land by approximately $12/acre.

Climate and aquifer characteristics vary across the five GMDs in Kansas. Additionally, governance and groundwater management plans differ across the GMDs (e.g., presence of LEMAs), which could manifest in different implicit valuations of water right characteristics. Table A3 reports GMD-specific estimates from equation (2) that restricts the sample to irrigated parcels. We only include county fixed effects due to smaller sample sizes. We find that the marginal implicit valuation of authorized depth ranges from about $23/acre in GMD 4 to about $14/acre in GMD 1, with the estimates statistically significant at the 0.05 level or better. Marginal valuations for GMDs 2, 3, and 5 suffer from a lack of precision. Average annual precipitation in the western portions of GMDs 1, 3, and 4 are the lowest in the state. Consistent with this, our regressions indicate large and statistically significant marginal valuations of allocated depth in GMDs 1 and 4.

To illustrate the economic implication of authorized depth, we next estimate the total redistribution in value across irrigators due to variation in allocation limits. To calculate the total redistribution, we use the population of water right groups to simulate the value with a uniform authorized depth within each GMD using our regression result in column 1 of Table 3. We calculate a GMD-specific authorized quantity because typical authorized quantity varies across GMDs according to precipitation (Fig. 1). Then we perform a search function within each GMD to find the uniform authorized depth that gives the same total value for the GMD as predicted with the actual authorized depth. The difference between the predicted value with actual authorized depth and the simulated value with a uniform authorized depth represents the value to that water right group of its authorized depth.

The total redistribution in value due to allocation limits is $78 million, or 2.2% of the total gross value of the aquifer. However, some irrigators operate multiple water rights with various allocation limits. The water right data contains information on the address of the person who files the water use report (i.e., the water use correspondent). After accounting for irrigators with multiple water rights, we find that the redistribution across irrigators is $65 million.

5.3. Seniority

Water right seniority is also capitalized into land value. A 1-year increase in the seniority of the volume-weighted priority date increases irrigated farmland values by 0.5%, or approximately $8/acre (Table 2). Restricting the analysis to irrigated transactions gives similar results with a 0.4% ($6/acre) increase in land values (Table 3).[10] Variability in seniority has a larger effect on land values since a one standard deviation increase in priority year increases land values by $58/acre and a one standard deviation increase in authorized depth increases land values by $48/acre when using estimates from column 1 of Table 3.

We also explore the effect of seniority in alternative specifications. An additional year of seniority is estimated to increase land values by about $5/acre when we restrict the analysis to transactions involving a single water right (column 2, Table 3). While column 2 allows a more precise matching of seniority with a transaction, it is a much smaller sample. Column 4 measures seniority as the priority date of the most senior water right in a transaction instead of a volume-weighted average measure over all water rights in the transaction. Column 5 measures seniority as the priority date of the most junior water right in the transaction. In these cases, we find no significant impact of seniority on farmland values. The majority of irrigated land transactions in Kansas involve multiple water rights, so focusing on the priority date of the most junior or senior water right omits key water right information available to buyers.

To explore potentially nonlinear impacts of seniority on land values we fit a restricted cubic spline with 3 knots placed at the 10th (1956), 50th (1974), and 90th (1997) percentiles of the priority data distribution for the full population of water rights in Kansas. Figure 3 traces out the predicted value of the estimated nonlinear relationship over a range of priority dates along with a histogram of priority dates. Priority dates up until about 1975 have little differential effect on farmland value, after which junior rights begin to impose a notable penalty to irrigated farmland values. However, there are relatively few water rights developed after 1980 as illustrated with the histogram because many basins in western Kansas were closed to additional irrigation development around this time (Sampson and Perry 2019).

Seniority may also be capitalized into land values differentially across GMDs. Table A3 reports GMD-specific regression estimates. An additional year of seniority is valued the highest in GMD 5 at $9/acre and is significant at the .05 level. Landowners are expected to value seniority in GMD 5, which contains a portion of the Walnut Creek IGUCA and the Rattlesnake Creek that affects streamflow to Quivira National Wildlife Refuge. Seniority factored into the allocations of the Walnut Creek IGUCA and has been discussed in resolving the Quivira dispute. Seniority is similarly valued in GMD 2 that is to the east of

[10] One additional aspect of seniority that merits discussion is vested status, granted to groundwater rights established prior to the 1945 Water Appropriation Act. Vested rights hold stronger priority claims than even the most senior appropriative water right and are often excluded from local conservation orders such as LEMAs. The vested status covariate in Tables A1 and A2 is equal to one if at least one of the water rights in the transaction is recognized as vested and zero otherwise, but there are few transactions involving vested rights and we are unable to detect a land market premium with precision.

GMD 5 and where surface water interactions similar to those in GMD 5 are a larger concern. In GMD 3 where a groundwater irrigator filed an impairment complaint against neighbors, an additional year of seniority is valued at about $6/acre and is significant at the 0.10 level. Estimates for seniority in GMDs 1 and 4 are not statistically different from zero.

We also estimate the total redistribution in value due to differences in seniority. The method is similar as described above for estimating the value of authorized depth. We perform a search function within each GMD to find the uniform priority date that gives the same total value for the GMD as predicted with the actual priority date using the population of water right groups. Then we calculate the difference between the value with the actual priority date and the simulated uniform priority date.

If each water right group were owned by a separate entity, we predict that the magnitude of the redistribution from junior to senior water right groups would amount to $103 million. This reflects 3% of the total gross value of the aquifer. Figures A4-A9 illustrate the transfer within each GMD. However, as previously discussed, it is common for irrigators to operate multiple water rights, with there being potentially large spans between the most senior and most junior priority dates. Thus, an accurate accounting of the welfare redistribution due to variation in seniority should account for transfers that occur within irrigators. We aggregate the gains and losses for each irrigator and plot the distribution in Figure 4, where the x-axis indexes the most senior priority date held by the irrigator. There are a mix of winners and losers even for those irrigators having their most senior priority dates prior to 1970. Accounting for multiple water rights for irrigators, we calculate the total redistribution of value due to seniority of $92 million.

We also explore if seniority is related to productivity of the land. For example, it could be the case that the land that was most profitable to irrigate was developed with irrigation wells, and thus has more senior groundwater pumping rights, while the less profitable land was set aside for later irrigation development. While we reduce concerns about this biasing our regression results by including township fixed effects and a rich set of soil and climatic controls, we can also check the correlation between productivity and seniority using two simulations. First, we use the specification in column 1 of Table 2 to predict the value of irrigation right access (i.e., the difference in value with 100% irrigated versus 0% irrigated) holding the authorized depth and priority date equal to the population mean. Second, we use the specification in column 1 of Table 3 to predict the per-acre irrigated value holding the authorized depth and priority date equal to the population mean. We then assess whether these measures of irrigated land value are related to seniority.

Figure A10 shows the predicted value of irrigation right access plotted against the priority date. Figure A11 plots the total predicted land value against priority date. In both figures, there is no evidence that senior rights are held on more productive irrigated land, as measured by the land value. In fact, we find that the opposite is true. More senior rights tend to be located on less productive land.

6. Discussion and Conclusion

Like other basins across the US and throughout the world, a key policy challenge of groundwater resource management occurs when a basin has excess extraction requiring pumping curtailments. Pumping cutbacks reassign rights to the resource, and in the bargaining over the distribution of cutbacks, users better off under the status quo will oppose, even if aggregate welfare increases (Libecap 1993). Under appropriative rights, the legal method of cutbacks is to reduce the most junior irrigators' diversions. Our results show that ignoring seniority when defining allocations would result in a total loss to senior appropriators of $92 million after accounting for irrigators owning multiple water rights. Ignoring authorized quantities would result in a total loss of $65 million to those with larger allocations. While the capitalization of these water right characteristics is statistically significant, they are not economically large. The redistribution by seniority only represents 2.6% of the total gross value of irrigation rights and redistribution by authorized quantities only represents 1.9% of the total gross value.

Ignoring seniority in defining new allocations does not necessarily demonstrate that senior irrigators would oppose an alternative allocation mechanism. Given the difficulties of trading groundwater rights, this approach allocates water without consideration for its marginal product. If the alternative allocation mechanism is more efficient (e.g., marginal curtailments), then an irrigator with multiple water rights of varying seniority may prefer the alternative allocation over a seniority-based allocation. Indeed, our results indicate that there would be significant economic inefficiencies because senior rights are not associated with more productive land. Allocating cutbacks uniformly across users, rather than by priority, may also satisfy a general desire for proportional changes to the property right system across users (Ostrom 2000).

In fact, recent experience in Kansas highlights that irrigators choose to ignore seniority when they participate in defining a new allocation mechanism. For example, the Sheridan LEMA and Walnut Creek IGUCA in Kansas. The LEMA was implemented using uniform allocations while the IGUCA defined allocations by priority date, with water rights junior to October 1, 1965 bearing the greatest burden in meeting the conservation target. The process of defining these two allocations was starkly different. The LEMA was initiated by local irrigators to preserve the life of the aquifer and included a series of 13 stakeholder meetings before it was approved through a public hearing process. The IGUCA was initiated by the Chief Engineer for the state to increase streamflow to a wetland.

To obtain a first order understanding of how the LEMA and IGUCA might differentially affect senior and junior water rights, we examine the distribution of water rights seniority dates within irrigators for both areas. Figure 5 shows the difference between the most senior water right held (green line) and the most junior water right held (orange line) for each irrigator. The x-axis in Figure 5 indexes the number of unique irrigators in the LEMA and IGUCA, starting from the most senior water right within each respective policy area. Where the orange line and green line overlap, the irrigator possesses a single water right. Figure 5 highlights the fact that there are few senior irrigators that do not also have junior water rights. This may explain why the LEMA process that started with stakeholders ignored seniority while the IGUCA process that started with the state defaulted to the legally defined seniority structure.

Complete property rights allow price alone to direct resource allocation to the highest value uses (Barzel 1997, p.114). By this logic, all environmental and natural resource problems arise from incompletely defined and enforced property rights (Libecap 2009; Allen 2015). In most natural resource settings property rights are incomplete, creating an open empirical question about their ability to address overextraction problems. In this paper, we show that appropriative rights to groundwater, even when incomplete, are capitalized into agricultural land prices. We estimate a lower bound estimate of the value of the right to access irrigation water in western Kansas at $761 million after accounting for the cost of irrigation capital. The property right has value because prior appropriation in Kansas created limited entry to irrigated production, with few water rights issued after the 1980’s (Sampson and Perry 2019). This finding is in notable contrast to other farmland hedonic studies in states not having restricted access to groundwater (Kovacs and Rider 2023). This indicates that the right to access is binding in Kansas and the aquifer is not purely open access; property rights are incomplete but not absent.

Tables

Table 1 – Summary statistics.

		> 50% irrigated			Non-irrigated		
Variable	Units	Obs.	Mean	Std. D	Obs.	Mean	Std. D
Land value	$/acre	2,626	1,589.09	928.41	13,077	1,029.50	692.24
Authorized depth	inches/acre	2,626	18.17	4.64	13,077		
Volume-weighted priority year	Years relative to 2019	2,626	-45.62	9.94	13,077		
Water right county	Number	2,626	4.13	3.46	13,077		
Vested status	0,1	2,626	0.05	0.21	13,077		
Surface water source	0,1	2,626	0.01	0.06	13,077		
Aquifer saturated thickness	100 ft	2,626	1.44	1.08	13,077	0.60	0.82
Degree days 10C - 34C	10 degrees * days	2,626	221.90	16.29	13,077	219.03	17.61
Degree days > 34C	10 degrees * days	2,626	1.74	0.49	13,077	1.71	0.49
Water deficit	inches	2,626	25.18	4.42	13,077	23.40	4.81
Soil hydraulic conductivity	micrometers/second	2,626	25.41	37.23	13,077	13.76	22.90
Soil organic carbon 150cm	kg/m^2	2,626	8.38	3.49	13,077	9.38	2.98
Basic soils	0,1	2,626	0.23	0.42	13,077	0.30	0.46
Slope	%	2,626	2.14	2.41	13,077	2.71	2.56
Number of parcels in transaction	Number	2,626	1.71	1.37	13,077	1.50	1.18
Distance to town of 100	10 km	2,626	1.17	0.59	13,077	1.21	0.68
Distance to town of 1,000	10 km	2,626	1.71	0.87	13,077	1.89	0.98
Distance to town of 10,000	10 km	2,626	6.70	4.87	13,077	7.59	5.32

Table 2 – Regression results for irrigated and non-irrigated transactions.

	(1)	(2)
Proportion with irrigation access rights	1.024***	1.092***
	(0.371)	(0.386)
Access right x Authorized depth (inches)	0.006**	0.005*
	(0.003)	(0.003)
Access right x Priority date (years)	-0.005***	-0.005***
	(0.001)	(0.001)
Marginal Effects:		
Irrigation average effect	1002.15***	1019.41***
Authorized depth average marginal effect (at 100% access rights)	10.30**	9.28*
	(4.66)	(4.77)
Priority date average marginal effect (at 100% access rights)	-8.10***	-8.27***
	(2.06)	(2.07)
Spatial Controls	Township (919)	Township (919)
Temporal Controls	Year	GMD-Year
Observations	15,703	15,703

Standard errors clustered at townships in parenthesis

Marginal effects are computed at average characteristics for irrigated transactions

*** p<0.01, ** p<0.05, * p<0.10

Table 3 – Regression results for irrigated transactions.

	(1)	(2)	(3)	(4)	(5)
Authorized depth (inches)	0.006***	0.011**	0.007***	0.007***	0.007***
	(0.002)	(0.005)	(0.002)	(0.002)	(0.002)
Priority date (years)	-0.004***	-0.003*	-0.004***	0.001	-0.002
	(0.001)	(0.002)	(0.001)	(0.001)	(0.001)
Marginal Effects:					
Authorized depth average marginal effect	10.34***	18.57**	11.83***	10.95***	10.47***
	(3.75)	(8.52)	(3.79)	(3.76)	(3.75)
Priority date average marginal effect	-6.01***	-4.90*	-6.25***	0.02	-2.65
	(2.27)	(3.00)	(2.34)	(1.68)	(1.63)
Spatial Controls	Township (525)	County (36)	Township (525)	Township (525)	Township (525)
Temporal Controls	Year	Year	Year	Year	Year
Observations	2,626	520	2,626	2,626	2,626

Standard errors clustered at township (columns 1, 3-5) and county (column 2) in parenthesis
Marginal effects are computed at average characteristics for irrigated transactions
*** $p<0.01$, ** $p<0.05$, * $p<0.10$

Figures

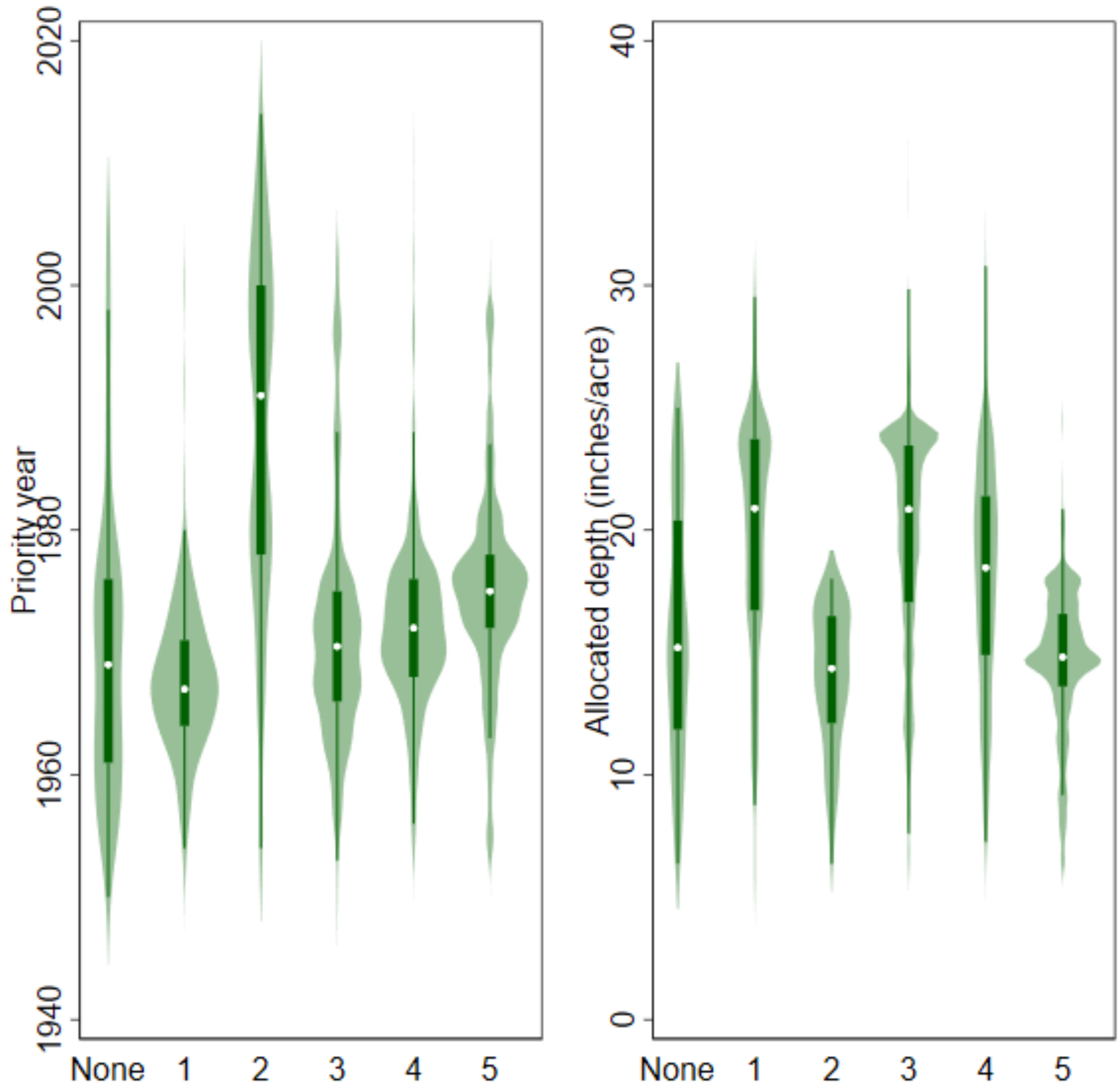

Figure 1 – Distribution of priority year (left panel) allocated depth (right panel) by GMD.

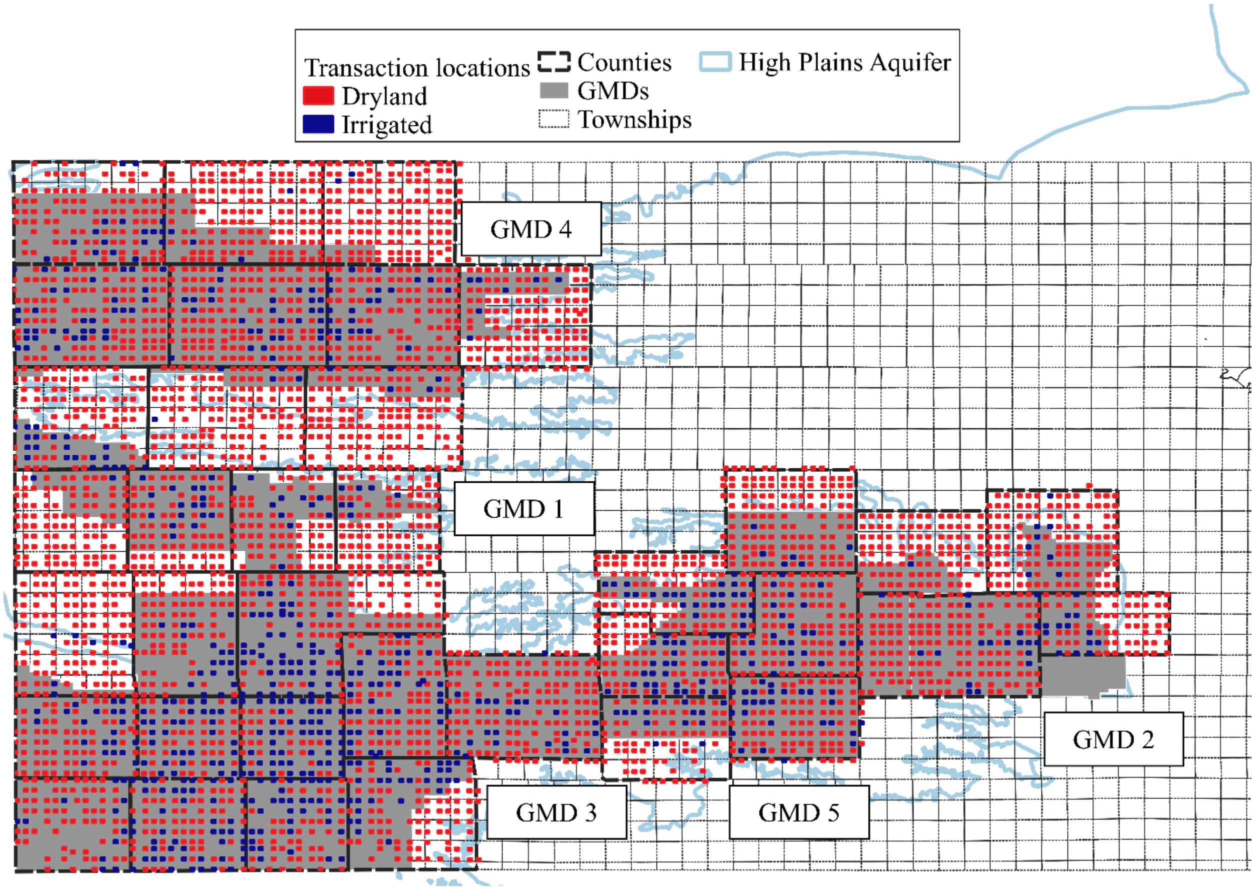

Figure 2 – Location of irrigated and dryland transactions.

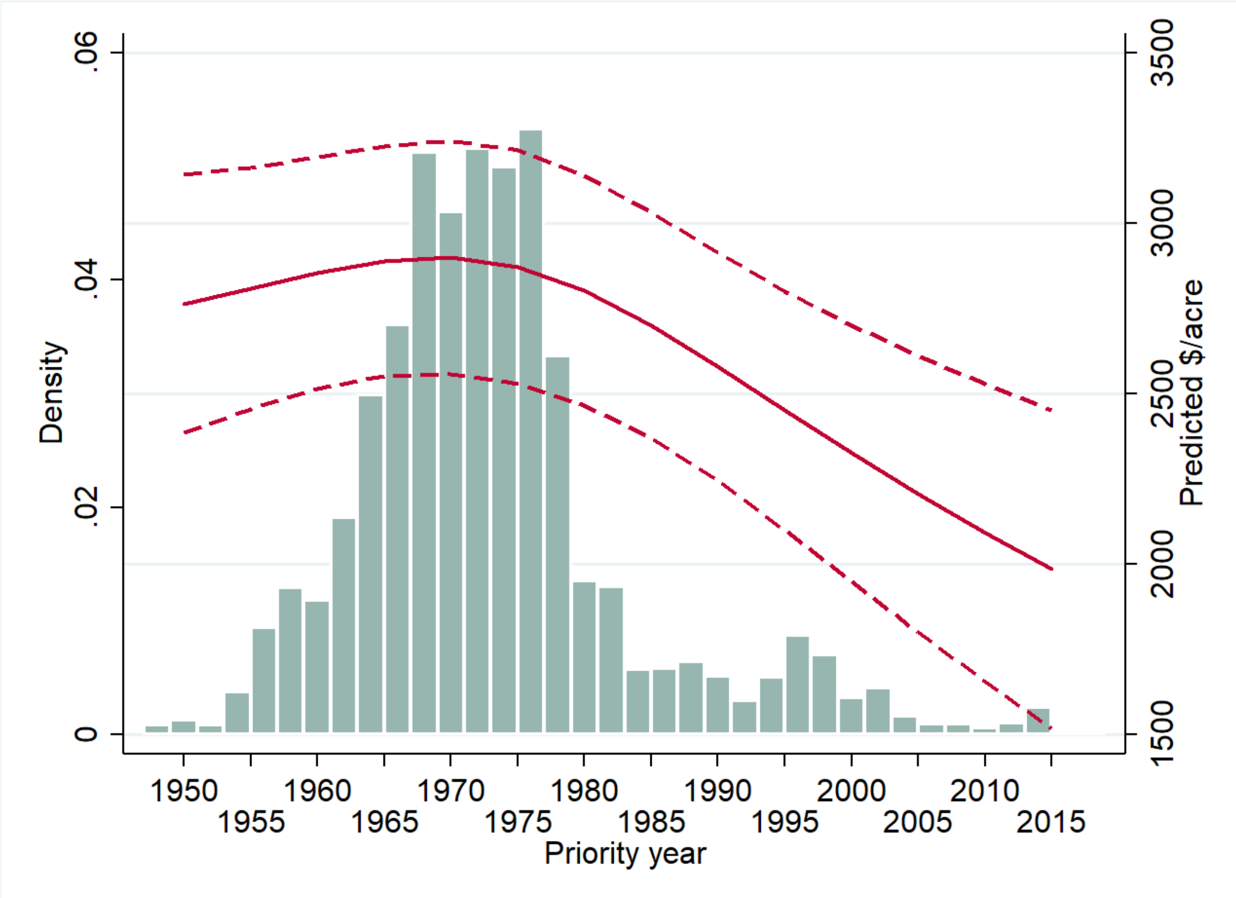

Figure 3 – Predicted irrigated farmland values for different priority years.

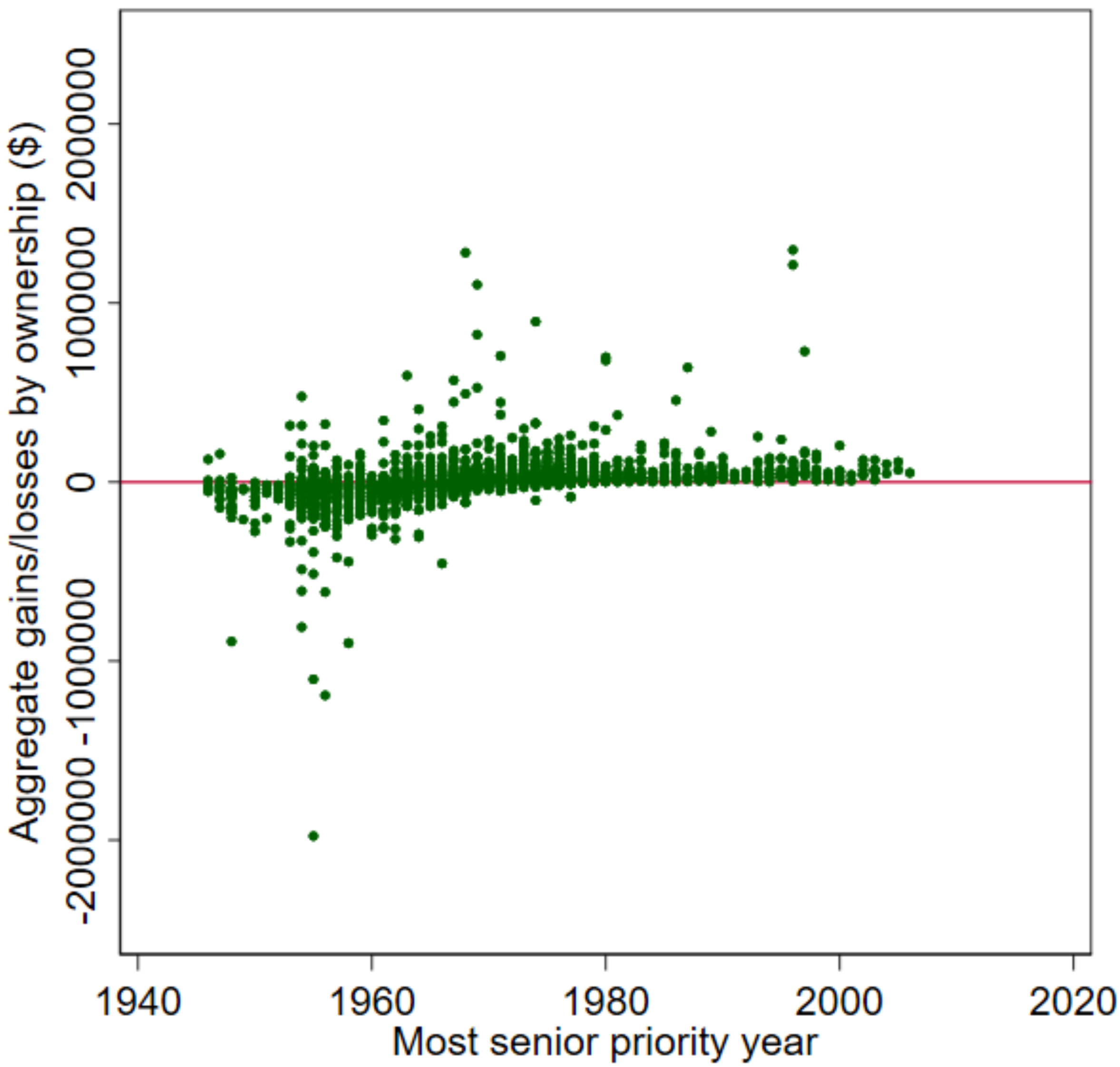

Figure 4 – Distribution of gains and losses from a fixed priority date by irrigator.

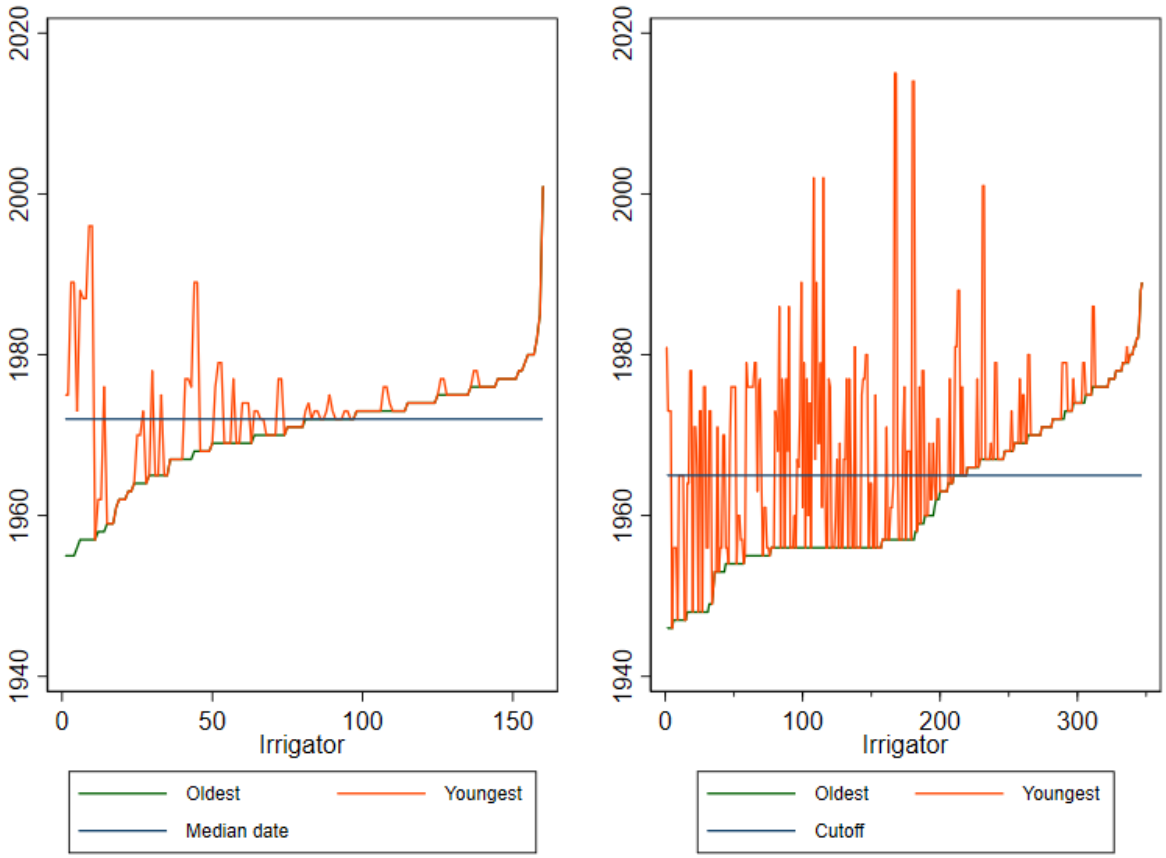

Figure 5 – Distribution of seniority dates for water rights held by irrigators in the Sheridan LEMA (left) and Walnut Creek IGUCA (right).

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Supplementary Appendix

Discussion of Results for Other Covariates

In this section we briefly discuss estimates of additional covariates from equations (1) and (2). Full model output from estimation of equations (1) and (2) are summarized in Tables A1 and A2, respectively. Farmland values are increasing in saturated thickness for those farms with irrigation access rights. A 10-foot increase in saturated thickness is estimated to increase irrigated farmland values by about $15/acre (Table A1). Farms overlying the aquifer without rights to irrigate do not see a statistically significant relationship between saturated thickness and farmland value, indicating that groundwater availability affects farmland values only on farms with irrigation access rights. When the analysis is restricted to only irrigated transactions, the marginal value of a 10-foot increase in saturated thickness ranges from approximately $14 to $21 (Table A2).

With respect to other model covariates from estimation of equation (1), we find that detrimental heat exposure and water deficits detract from farmland values, with no evidence of differential impacts to irrigated and non-irrigated farmland. The effect of one additional degree day over 34°C has approximately the same magnitude as one additional inch of allocation in the water right. Beneficial heat contributes positively to farmland values, with the effect being slightly larger on non-irrigated farmland. Better soil quality, as measured by soil organic carbon, contributes to farmland values. Better soil hydraulic conductivity is found to benefit irrigated farmland values but have no effect on non-irrigated farmland values. Slope detracts from farmland values, which is consistent with sloped lands having excess erosion and lower crop potential. Bundling multiple parcels together in a transaction tends to lower the per-acre transaction value. Finally, we observe negative but not statistically significant coefficients on the distance to town variables.

When restricting the analysis to only irrigated transactions, we see that water deficit detracts from farmland values (Table A2). Somewhat surprisingly, beneficial heat is estimated with a negative coefficient, though the magnitude is small and the effect is only significant at the 0.10 level in most specifications.

Supplementary Tables

Table A1 – Regression results for irrigated and non-irrigated transactions

	(1)	(2)
Proportion with irrigation access rights	1.024***	1.092***
	(0.371)	(0.386)
Access right x Authorized depth (inches)	0.006**	0.005*
	(0.003)	(0.003)
Access right x Priority date (years)	-0.005***	-0.005***
	(0.001)	(0.001)
Access right x Water right count	0.002	0.002
	(0.004)	(0.004)
Access right x Vested status	-0.013	-0.024
	(0.052)	(0.048)
Access right x Surface water source	0.103	0.102
	(0.162)	(0.168)
Saturated thickness (100s of feet)	0.004	0.015
	(0.034)	(0.034)
Square of saturated thickness (100s of feet)	0.017	0.004
	(0.011)	(0.011)
Degree days over 34 Celsius (10s)	-0.077**	-0.055
	(0.034)	(0.040)
Degree days between 10 and 34 Celsius (10s)	0.005**	0.005*
	(0.002)	(0.003)
Water deficit	-0.031***	-0.024***
	(0.006)	(0.007)
Soil hydraulic conductivity	-0.001	-0.001
	(0.001)	(0.001)
Soil organic carbon	0.009***	0.009***
	(0.002)	(0.002)
Basic soils	0.018	0.017
	(0.013)	(0.013)
Slope	-0.055***	-0.055***
	(0.004)	(0.004)
Number of parcels in transaction	-0.010**	-0.011**
	(0.005)	(0.005)
Distance to population 100 (10s of km)	-0.019	-0.026
	(0.018)	(0.018)
Distance to population 1,000 (10s of km)	-0.004	-0.006
	(0.015)	(0.015)

Distance to population 10,000 (10s of km)	-0.021	-0.019
	(0.013)	(0.013)
Other variables interacted with Access right		
Saturated thickness (100s of feet)	0.049	0.068
	(0.047)	(0.045)
Square of saturated thickness (100s of feet)	0.001	-0.008
	(0.012)	(0.012)
Degree days over 34 Celsius (10s)	0.021	0.071
	(0.052)	(0.055)
Degree days between 10 and 34 Celsius (10s)	-0.003*	-0.004**
	(0.002)	(0.002)
Water deficit	-0.008	-0.006
	(0.005)	(0.005)
Soil hydraulic conductivity	0.004***	0.004***
	(0.001)	(0.001)
Spatial Controls	Township (919)	Township (919)
Temporal Controls	Year	GMD-Year
Observations	15,703	15,703
Irrigation average effect	1002.15***	1019.41***
Authorized depth average marginal effect (at 100% irrigated)	10.30**	9.28**
	(4.66)	(4.70)
Priority date average marginal effect (at 100% irrigated)	-8.10***	-8.27***
	(2.06)	(2.07)
Saturated thickness average marginal effect (100s of feet, at 100% irrigated)	151.08***	146.29***
	(57.92)	(55.41)
Saturated thickness average marginal effect (100s of feet, at 0% irrigated)	27.54	20.14
	(22.60)	(21.92)

Standard errors clustered at townships in parenthesis

Marginal effects are computed at average characteristics for irrigated transactions

*** p<0.01, ** p<0.05, * p<0.10

Table A2 – Regression results for irrigated transactions

	(1)	(2)	(3)	(4)	(5)
Authorized depth (inches)	0.006***	0.011**	-0.007***	0.007***	0.007***
	(0.002)	(0.005)	(0.002)	(0.002)	(0.002)
Priority date (years)	-0.004***	-0.003*	-0.004***	0.001	-0.002
	(0.001)	(0.002)	(0.001)	(0.001)	(0.001)
Water right count	0.002		0.002	0.002	0.002
	(0.003)		(0.003)	(0.003)	(0.003)
Vested status	-0.033	0.030	-0.031	-0.015	-0.017
	(0.048)	(0.156)	(0.048)	(0.048)	(0.047)
Surface water source	-0.167		-0.193	-0.167	-0.152
	(0.158)		(0.151)	(0.163)	(0.159)
Saturated thickness (100s of feet)	0.117*	0.183*	0.119*	0.128*	0.122*
	(0.070)	(0.095)	(0.069)	(0.071)	(0.070)
Square of saturated thickness (100s of feet)	0.002	-0.039	0.003	-0.001	0.001
	(0.021)	(0.026)	(0.021)	(0.021)	(0.021)
Degree days over 34 Celsius (10s)	0.115	-0.081	0.060	0.120	0.116
	(0.096)	(0.150)	(0.094)	(0.095)	(0.095)
Degree days between 10 and 34 Celsius (10s)	-0.009*	0.003	-0.012**	-0.009*	-0.009*
	(0.005)	(0.009)	(0.005)	(0.005)	(0.005)
Water deficit (inches)	-0.038***	-0.019		-0.039***	-0.038***
	(0.015)	(0.018)		(0.014)	(0.015)
Soil hydraulic conductivity	-0.001	0.000	-0.001	-0.001	-0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Soil organic carbon	-0.001	0.009	-0.001	-0.001	-0.001
	(0.001)	(0.013)	(0.006)	(0.006)	(0.006)
Basic soils	0.043	-0.010	0.044	0.044	0.046
	(0.034)	(0.059)	(0.034)	(0.034)	(0.033)
Slope	-0.004	-0.005	-0.003	-0.006	-0.004

	(0.008)	(0.014)	(0.008)	(0.008)	(0.008)
Number of parcels in transaction	-0.007	0.024	-0.007	-0.007	-0.007
	(0.009)	(0.029)	(0.009)	(0.009)	(0.009)
Distance to population 100 (10s of km)	-0.031	0.047	-0.037	-0.028	-0.029
	(0.045)	(0.038)	(0.045)	(0.045)	(0.045)
Distance to population 1,000 (10s of km)	0.005	-0.016	0.002	0.003	0.004
	(0.036)	(0.022)	(0.035)	(0.036)	(0.036)
Distance to population 10,000 (10s of km)	-0.022	-0.008	-0.032	-0.017	-0.019
	(0.037)	(0.021)	(0.037)	(0.037)	(0.037)
Spatial Controls	Township (525)	County (36)	Township (525)	Township (525)	Township (525)
Temporal Controls	Year	Year	Year	Year	Year
Observations	2,626	520	2,626	2,626	2,626
Authorized depth average marginal effect	10.30***	18.57**	11.83***	10.95***	10.47***
	(3.70)	(8.52)	(3.79)	(3.76)	(3.75)
Priority date average marginal effect	-5.97***	-4.90*	-6.25***	0.02	-2.65
	(2.28)	(3.00)	(2.34)	(1.68)	(1.63)
Irrigated saturated thickness average marginal effect (100s of feet)	192.50***	136.55*	207.29***	200.52***	196.16***
	(48.08)	(81.45)	(50.93)	(48.52)	(47.65)

Standard errors clustered at township (columns 1, 3-5) and county (column 2) in parenthesis

Marginal effects are computed at average characteristics for irrigated transactions

*** p<0.01, ** p<0.05, * p<0.10

Table A3 – Regression results for GMD-specific irrigated transactions

GMD	1	2	3	4	5
Authorized depth average marginal effect	14.43**	27.40	7.26	23.45***	-2.75
	(6.78)	(19.60)	(5.42)	(5.19)	(10.45)
Priority date average marginal effect	-2.32	-8.08*	-6.04*	1.00	-9.17**
	(10.53)	(4.56)	(3.47)	(3.00)	(4.48)
Spatial Controls	County (5)	County (4)	County (12)	County (10)	County (9)
Temporal Controls	Year	Year	Year	Year	Year
Observations	153	124	1,239	460	591

Standard errors clustered at counties in parenthesis

Marginal effects are computed at average characteristics for irrigated transactions

*** p<0.01, ** p<0.05, * p<0.10

Table A4 – Regression results for irrigated transactions using county-level controls

	(1)	(2)	(3)	(4)
Authorized depth (inches)	0.005**	0.007***	0.006**	0.006**
	(0.002)	(0.002)	(0.003)	(0.003)
Priority date (years)	-0.005***	-0.005***	-0.002**	-0.002***
	(0.001)	(0.001)	(0.001)	(0.001)
Water right count	-0.001	-0.001	-0.003	-0.000
	(0.003)	(0.003)	(0.004)	(0.003)
Vested status	-0.041	-0.044	-0.024	-0.012
	(0.041)	(0.041)	(0.042)	(0.040)
Surface water source	0.027	-0.003	0.042	0.046
	(0.085)	(0.069)	(0.085)	(0.095)
Saturated thickness (100s of feet)	0.111***	0.111***	0.128***	0.124***
	(0.036)	(0.035)	(0.037)	(0.036)
Square of saturated thickness (100s of feet)	-0.009	-0.009	-0.015*	-0.014*
	(0.008)	(0.008)	(0.008)	(0.008)
Degree days over 34 Celsius (10s)	0.060	0.004	0.068	0.066
	(0.051)	(0.053)	(0.052)	(0.053)
Degree days between 10 and 34 Celsius (10s)	-0.007*	-0.008**	-0.008**	-0.008**
	(0.004)	(0.004)	(0.004)	(0.004)
Water deficit (inches)	-0.035***	-0.037***	-0.033***	-0.033***
	(0.010)	(0.010)	(0.010)	(0.010)
Soil hydraulic conductivity	0.001	0.001	0.001	0.001
	(0.001)	(0.001)	(0.001)	(0.001)
Soil organic carbon	0.004	0.004	0.004	0.004
	(0.005)	(0.005)	(0.005)	(0.005)
Basic soils	0.029	0.027	0.033	0.034
	(0.032)	(0.033)	(0.033)	(0.034)
Slope	-0.007	-0.007	-0.009	-0.008

	(0.006)	(0.006)	(0.007)	(0.006)
Number of parcels in transaction	0.003	0.003	0.003	0.002
	(0.007)	(0.007)	(0.007)	(0.007)
Distance to population 100 (10s of km)	-0.025	-0.032	-0.025	-0.025
	(0.023)	(0.022)	(0.023)	(0.023)
Distance to population 1,000 (10s of km)	0.009	0.007	0.008	0.007
	(0.018)	(0.018)	(0.018)	(0.018)
Distance to population 10,000 (10s of km)	-0.018	-0.023**	-0.017	-0.017
	(0.011)	(0.012)	(0.011)	(0.011)
Spatial Controls	County (36)	County (36)	County (36)	County (36)
Temporal Controls	Year	Year	Year	Year
Observations	2,626	2,626	2,626	2,626
Authorized depth average marginal effect	8.59**	10.64***	9.38**	9.21**
	(3.97)	(3.78)	(4.06)	(4.12)
Priority date average marginal effect	-8.35***	-7.92***	-3.44**	-4.03***
	(2.09)	(2.17)	(1.74)	(1.45)
Irrigated saturated thickness average marginal effect (100s of feet)	134.53***	138.78***	135.64***	132.49***
	(35.78)	(34.43)	(35.88)	(35.82)

Standard errors clustered at counties in parenthesis
Marginal effects are computed at average characteristics for irrigated transactions
Column 2 defines depth as the difference between authorized depth and the water deficit
Column 3 uses the oldest water right in the transaction
Column 4 uses the most junior water right in the transaction
*** p<0.01, ** p<0.05, * p<0.10

Supplementary Figures

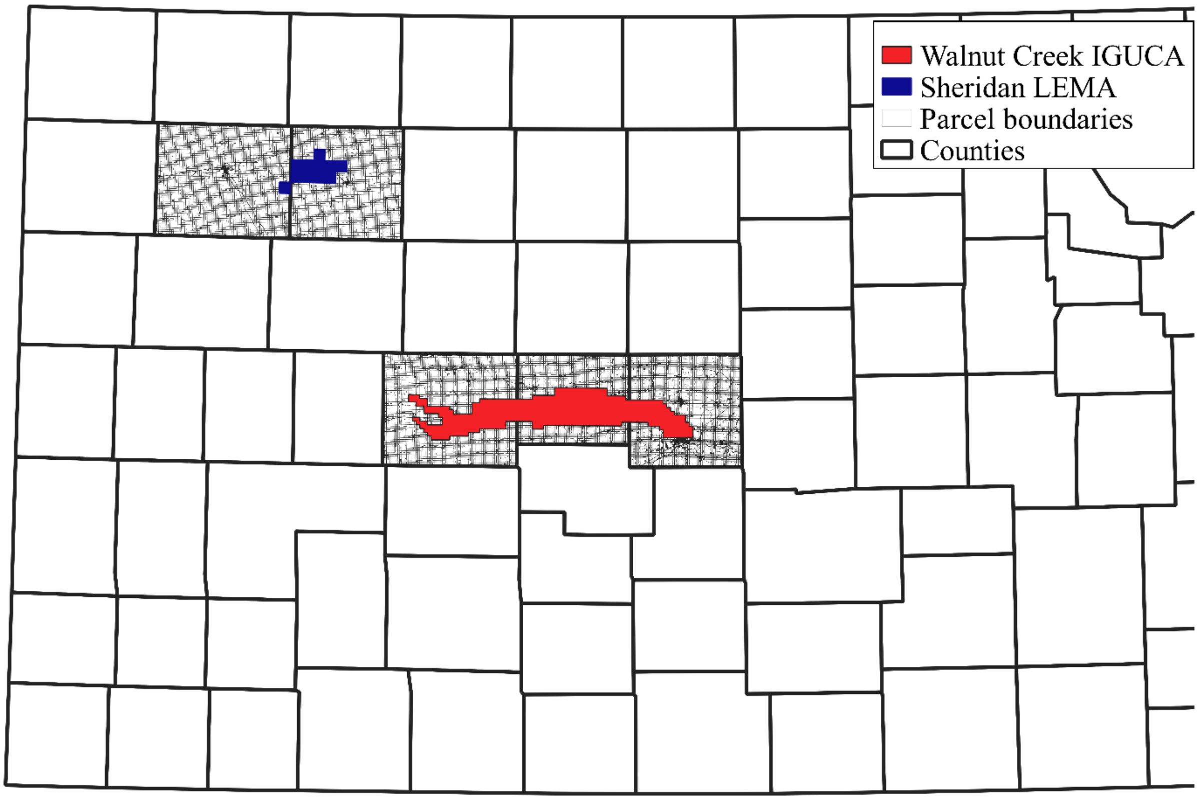

Figure A1 – Location of Sheridan LEMA and Walnut Creek IGUCA.

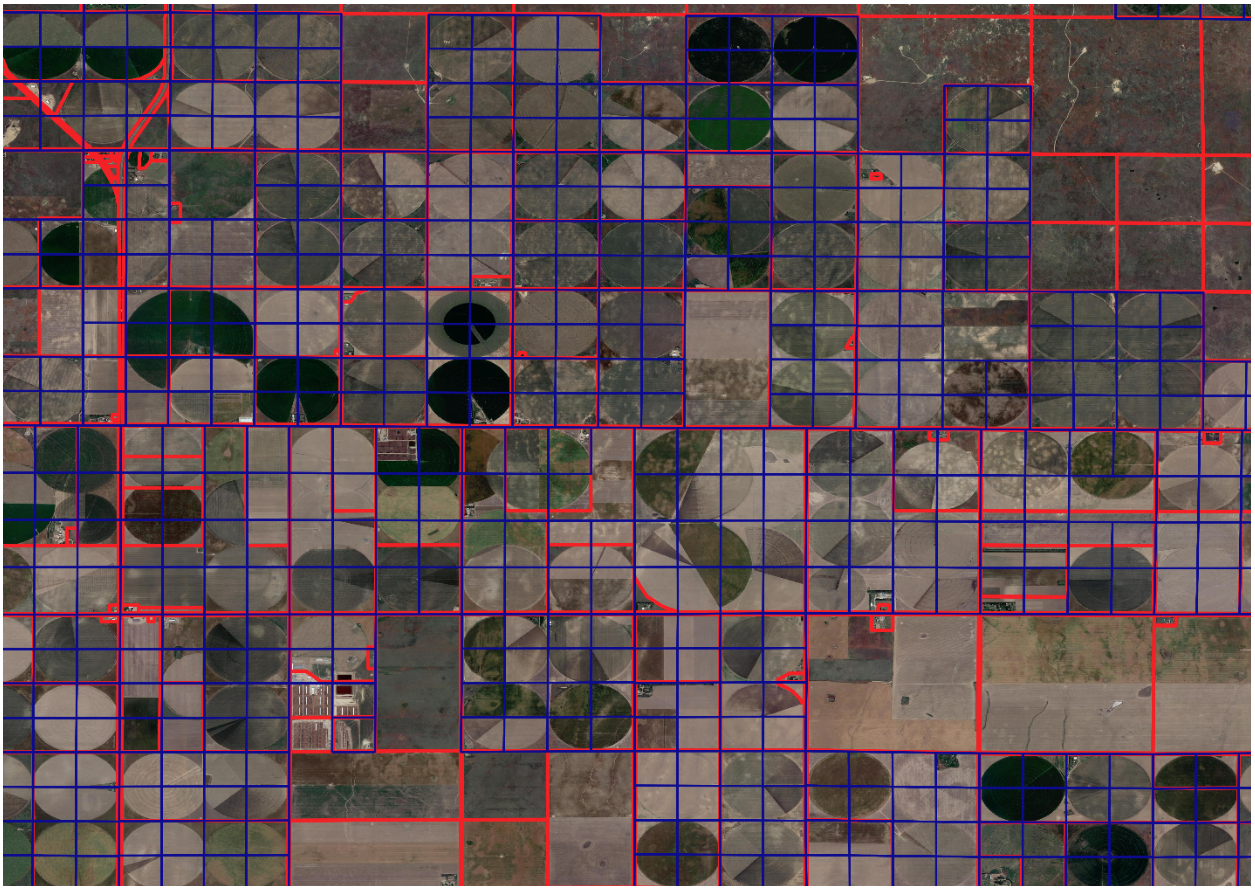

Figure A2 – Parcel boundaries (red line) and WIMAS place of use boundaries (blue line) in Finney County.

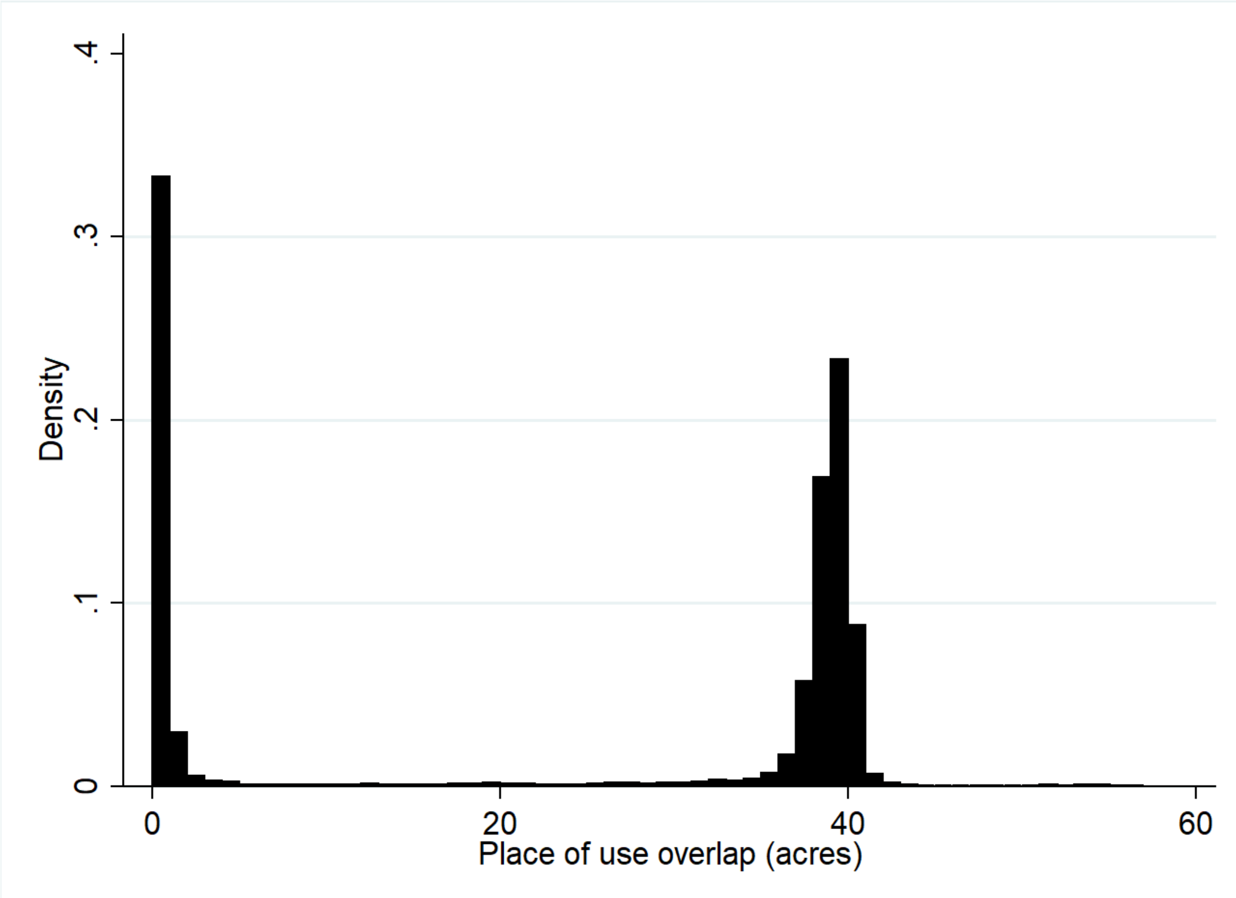

Figure A3 – Summary spatial overlap between place of use and parcel boundary.

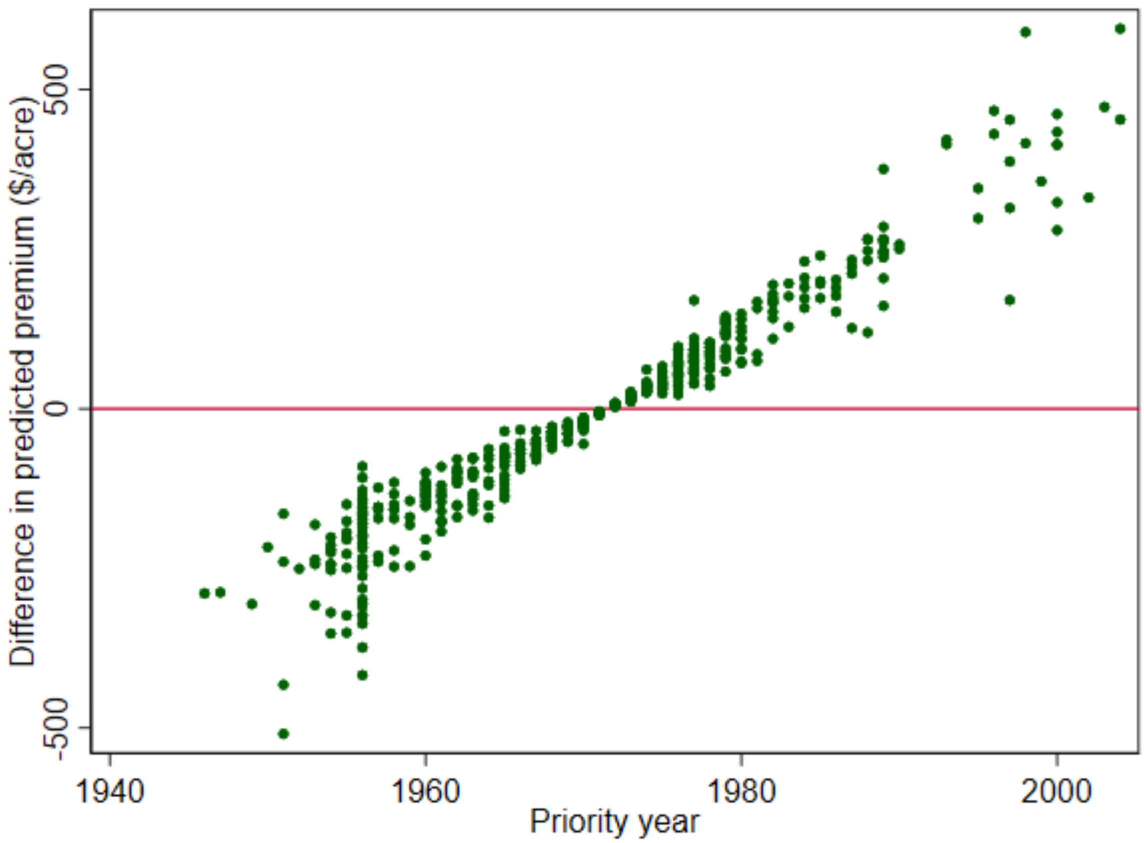

Figure A4 – Distribution of gains and losses of a uniform priority date outside of the GMDs.

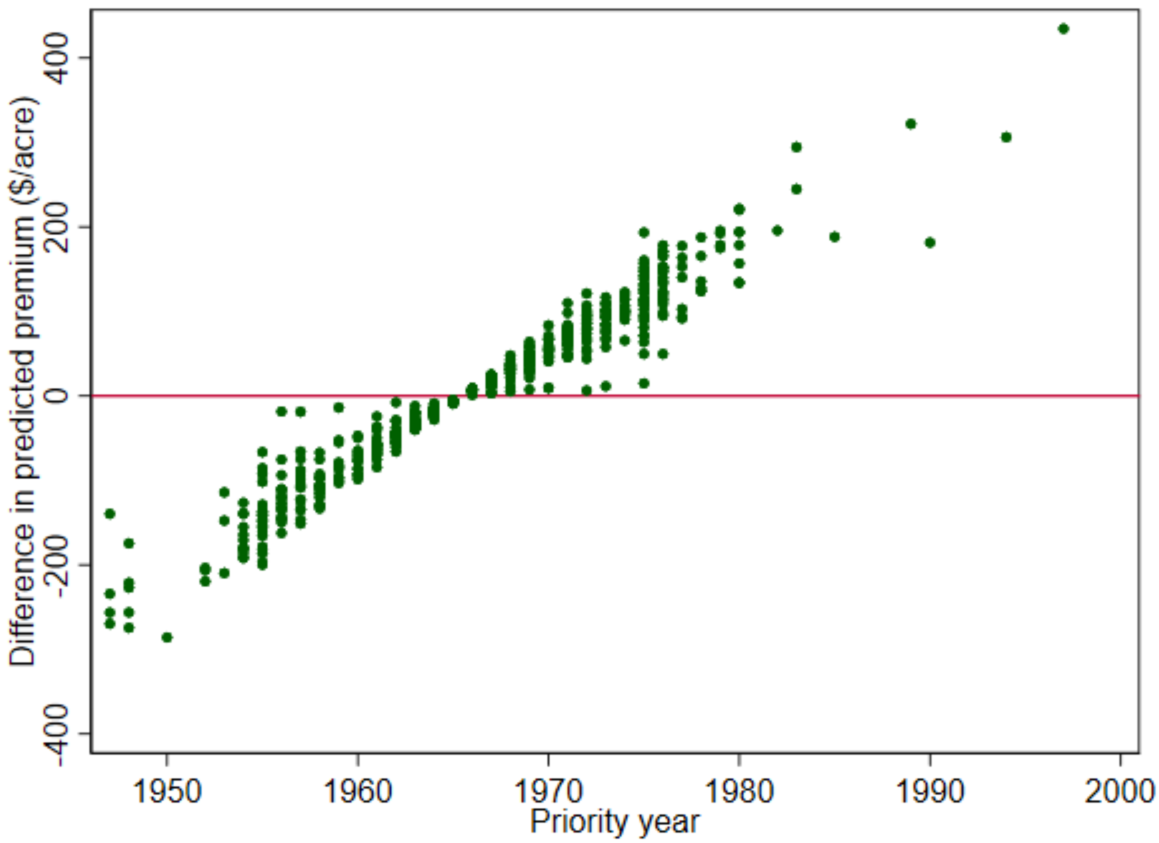

Figure A5 – Distribution of gains and losses of a uniform priority date in GMD 1.

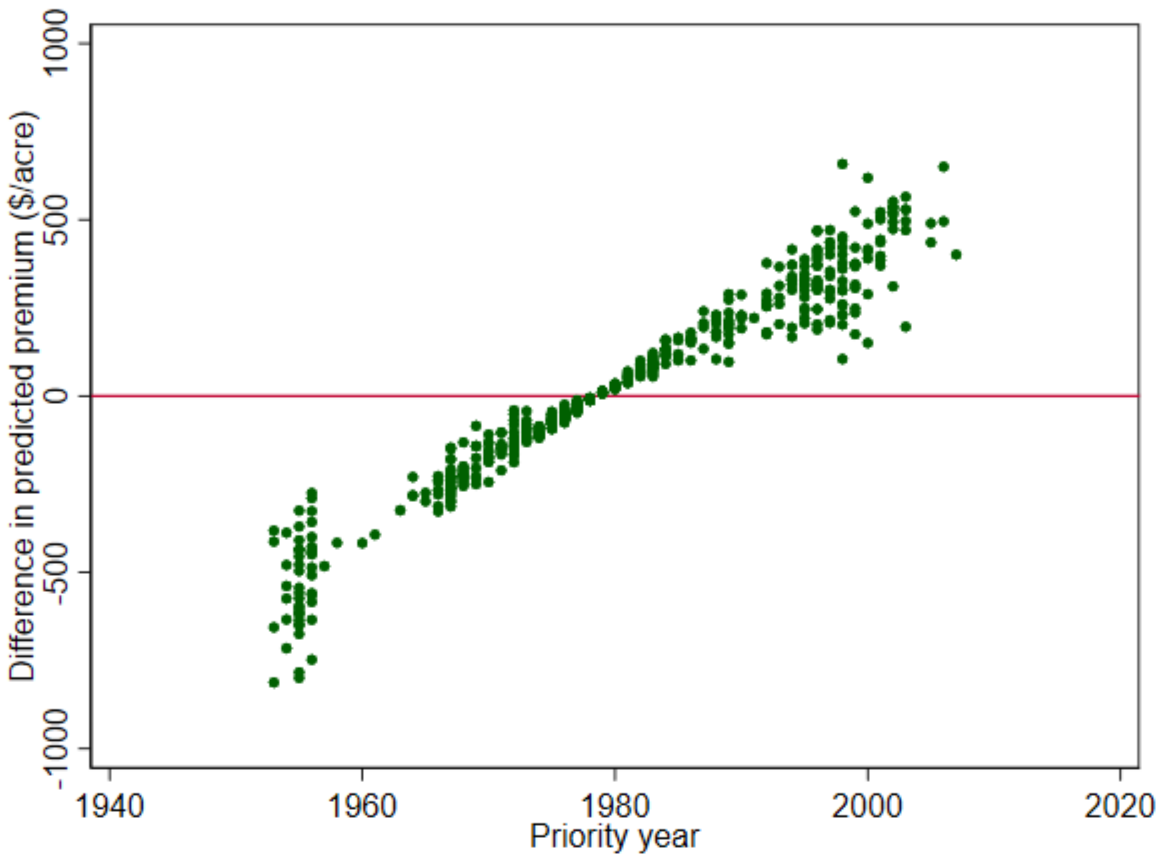

Figure A6 – Distribution of gains and losses of a uniform priority date in GMD 2.

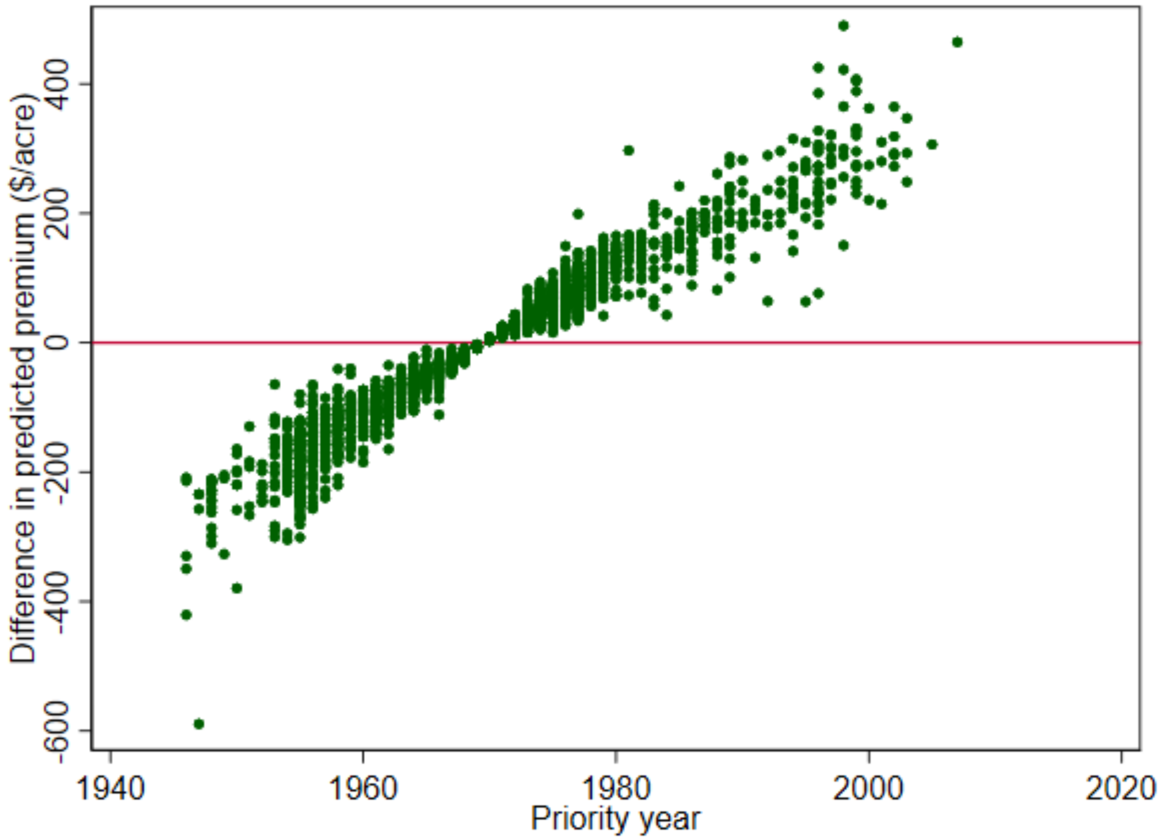

Figure A7 – Distribution of gains and losses of a uniform priority date in GMD 3.

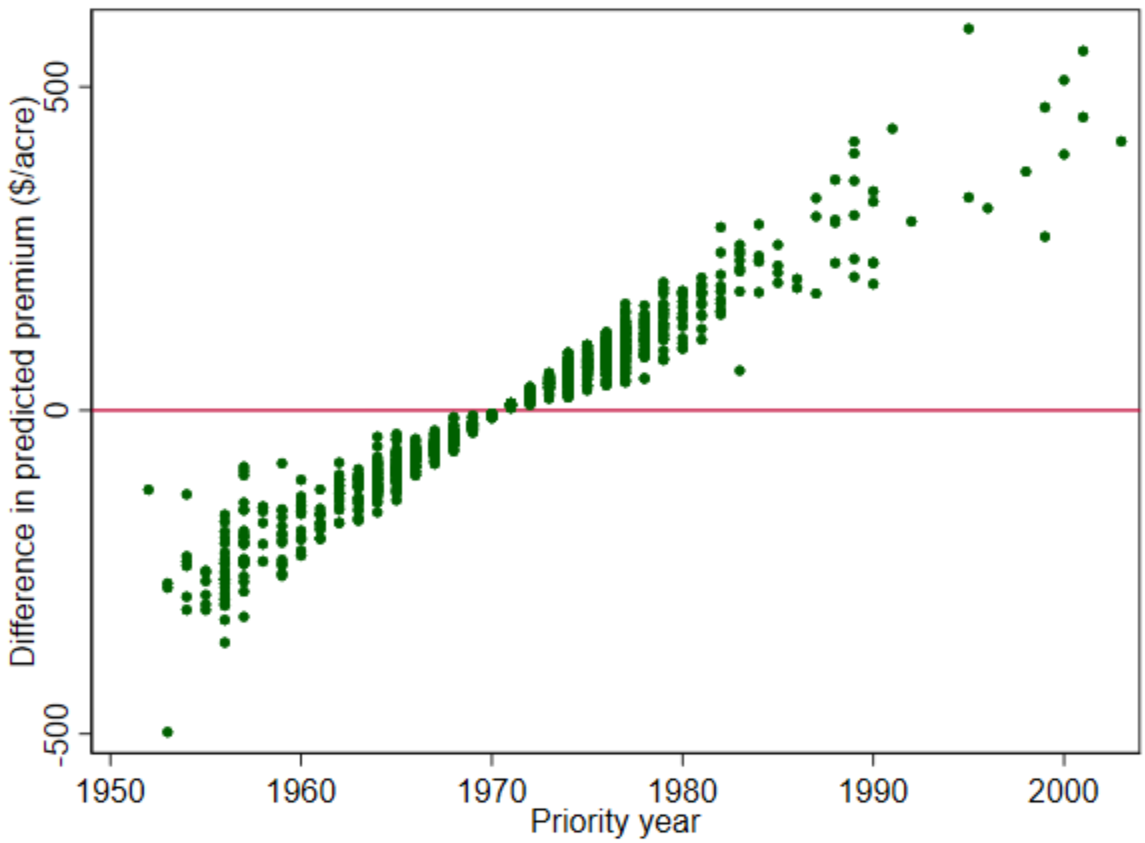

Figure A8 – Distribution of gains and losses of a uniform priority date in GMD 4.

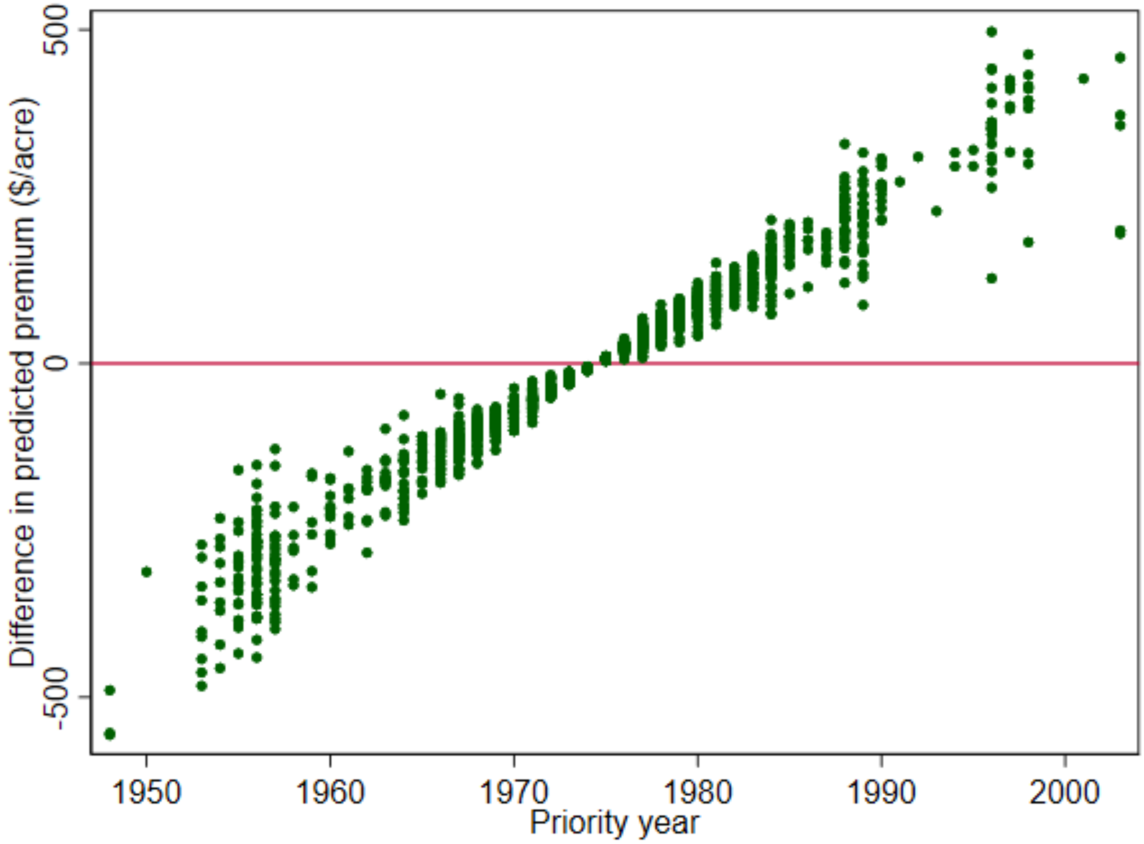

Figure A9 – Distribution of gains and losses of a uniform priority date in GMD 5.

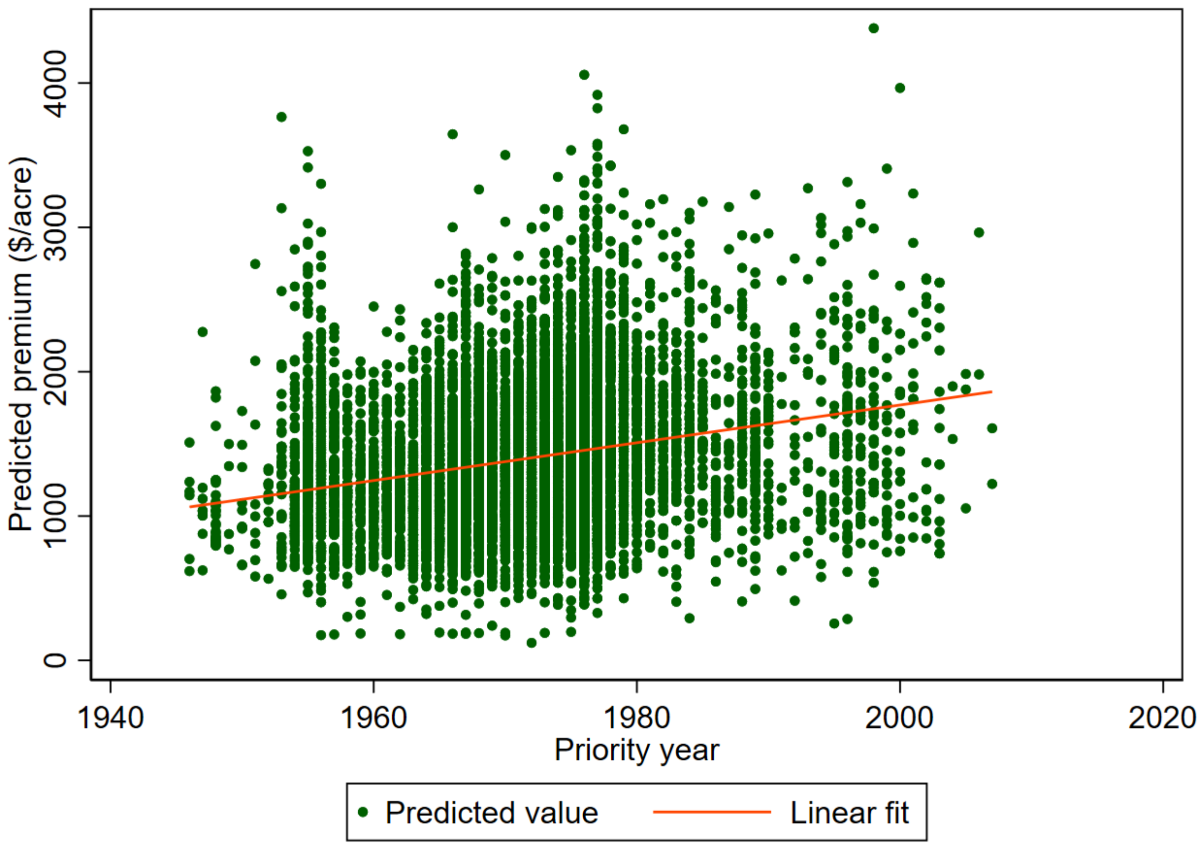

Figure A10 – Predicted irrigation premium for water right groups and linear fit to the prediction.

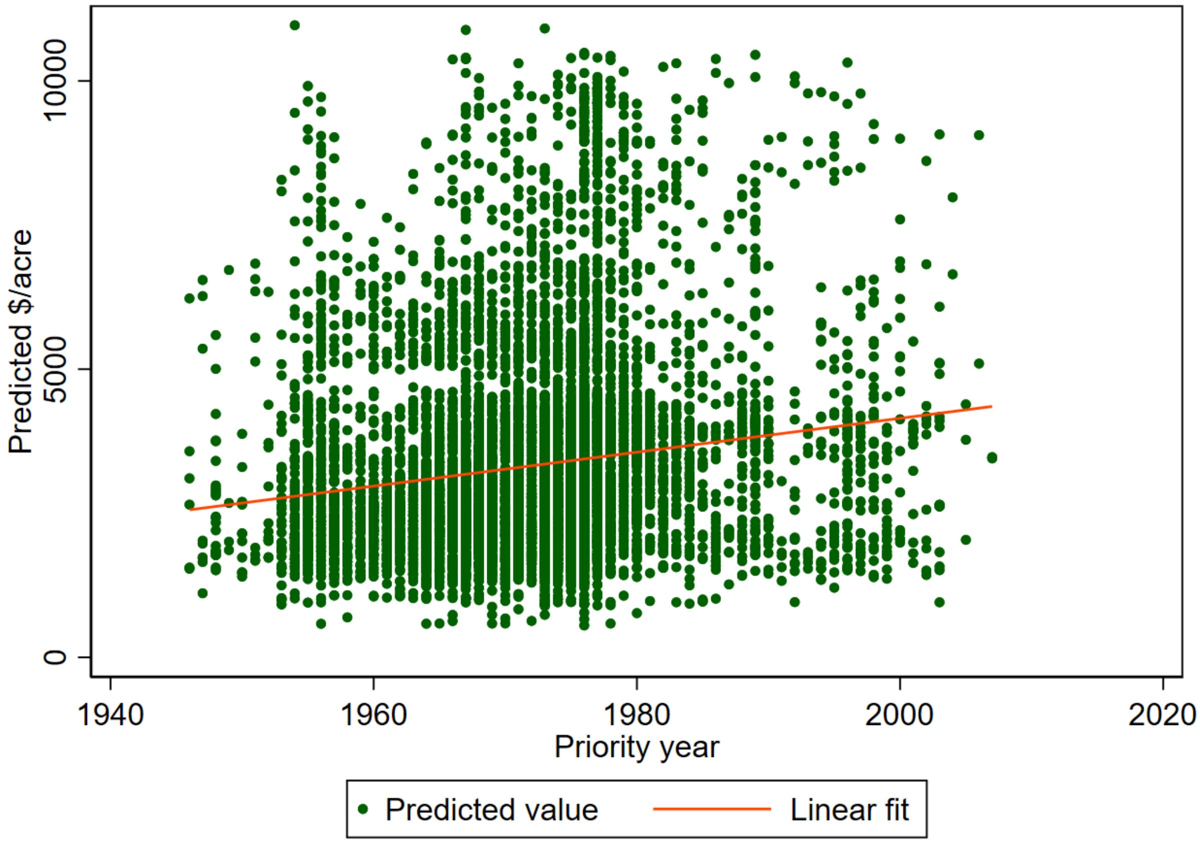

Figure A11 – Predicted price per acre for water right groups and linear fit to the prediction.