Division of Economics and Business
Working Paper Series

The Relative Economic Merits of Alternative Water Rights

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Working Paper 2019-08
`http://econbus-papers.mines.edu/working-papers/wp201908.pdf`

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December 2019

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The Relative Economic Merits of Alternative Water Rights*

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ABSTRACT

How natural resources are measured and bounded within a property rights structure can influence their development and productivity. This is especially true for surface water given its fluid, fungible, and stochastic nature. Two alternatives have emerged: The prior appropriation doctrine provides absolute quantities to water allocated based on first use while proportional water rights distribute a set percentage of total water to owners. While theoretical differences have been identified, empirical tests are lacking due to the endogenous choice of water rights. I identify and utilize a natural experiment where acequias (Hispanic-rooted irrigation ditches) developed in Territorial New Mexico are later divided by the formation of Colorado, exogenously forcing that subset to be subject to the priority system while those in New Mexico continue to practice proportional division today. Drawing on a broad collection of archival, administrative, satellite, hydrological, and survey data, I find priority rights provide greater certainty to earlier arrivals, inducing more investment, but that the marginal product of water is generally lower under that right structure. This research is pertinent to understanding how distinct property right systems may react to changing conditions and influence the development of newer resources, such as wind.

JEL **classifications: P48, K11, Q15, Q25.**
Keywords: property rights, irrigation, *acequias*.

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*I acknowledge NSF Grant BCS-1115009 and USDA-AFRI Grant 67023-29421 for providing the impetus and support for this research. Additional financial support was also provided by the Graduate School at the University of Colorado for the completion of analysis and writing. I am in debt to Michael E. Cox for sharing the remote sensing data he gathered for Taos and Costilla Counties. I thank Lee J. Alston, Krister Andersson, Nick Flores, Charles Howe, Jonathan Hughes, Mark Kanazawa, Bryan Leonard, and Gary Libecap for their insightful comments. Research assistance was ably provided by Diana Schoder and Emilio Castillo. Additional thanks to participants of the CU Environmental and Resource Economics Workshop, Workshop on the Workshop, Bloomington IN, and the International Association for the Study of the Commons, Lima, Peru. All remaining errors are, of course, my own.

1 Introduction

Economists have long recognized that the development and allocation of natural resources are closely related to the underlying property right structure (Gordon 1954, Coase 1960, Demsetz 1967, Alchian & Demsetz 1973, Bromley 1991). Better defined and enforced rights are expected to contribute to the economy by reducing externalities, spurring investment, and/or expanding markets (Alston et al. 1996, Besley & Ghatak 2010, Hornbeck 2010). Evidence of rent dissipation amidst incomplete rights exists for land (Anderson & Hill 1975), timber (Mendelsohn 1994), oil (Libecap & Wiggins 1984), fisheries (Costello et al. 2008), wind (Kaffine & Worley 2010), and water – both surface and ground (Rosegrant & Binswanger 1994, Pfieffer & Lin 2012). Additionally, attention has been given to who owns the rights with particularly efforts to demonstrate communal and government ownership are not inherently inferior to individual rights (Ostrom 1990, Schlager & Ostrom 1992, Sjaastad & Bromley 1997). Less attention, however, has been given to implications of the particulars of how natural resources are measured and bounded within the right structure. The effects can be large, impacting the development and productivity of the resource, the transaction costs of trading the resource, and the proclivity for disputes over the resource, all independent of the security of the rights (Libecap & Lueck 2011).[1]

The bounding and definition of surface water rights is perhaps the most studied. Because irrigation ditches are highly asset-specific (Bretsen & Hill 2007), secure and predictable land rights (Alston & Smith 2019) and water rights (Leonard & Libecap 2019) are important to incentivize investment.[2] Accordingly, many arid regions departed from the common-law riparian doctrine, which grants vague correlative (but not quantified) water rights to riparian land owners and adopted one of two broad types of quantified water rights in its place: 1) Priority rights, where fixed amounts of water are allocated in turn based on an ordering (often based on time of first use), and 2) proportional rights, where the supply in a given year is allocated to users as a quantified share of the total. Priority rights dominate the arid portions of the United States, adopted in some form by the 17 Western states. Meanwhile other regions, such as Australia,

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[1] A related but distinct literature is that of contract choice and its relationship to risk and production (e.g. Cheung 1968, Umbeck 1977, Alston et al. 1984, Allen & Lueck 1992, Hayami & Otsuka 1993, Corts & Singh 2004, Fischer 2013)

[2] See Leonard & Libecap (2019) for a formal model.

Chile, China, and Mexico, employ proportional rights (Grafton & Horne 2014; Rosegrant & Gazmuri 1995; Chen et al. 2005).

The bounding of rights as fixed amounts versus fixed shares of a stochastic flow have implications for investment and production choices as well as trading. Leonard & Libecap (2019) demonstrate that quantification was essential to incentivizing and coordinating investment. Proportional rights, as will be shown in the theory below, could provide a similar effect, but will produce excess and stranded investment as later arrivals erode the amount of water earlier investors will continue to have available. This paper will empirically demonstrate the extent to which these systems differ on investment across the sequential arrival of irrigators.

Most of the literature, however, has focused on the subsequent allocation of water, setting aside the development issues. Bennet et al. (2000) argue that efficient division of water depend on hydrological and economic conditions, but that percentage-based shares provide greater net-benefits compared to fixed compacts across many circumstances. The intuition is that priority rights often allocate the marginal unit of water to a single user experiencing diminishing productivity while more junior users – currently getting no water – could deploy that unit at a higher marginal gain. But even in years of abundance when all claims are satisfied, homogenous irrigators, having developed heterogeneous diversion structures, will have unequal marginal products of water (Burness & Quirk 1979). Under these conditions, and for a fixed aggregate diversion capacity, equal sharing – a specific proportional share – of water is the most efficient allocation. This paper will evaluate this distinction as well, estimating the marginal productivity of water in both systems and how they differ on average and across irrigators.[3]

Innefficient allocations in either system could be ameliorated by water right trading (Chong & Sunding 2006), but relatively few water trades are observed in practice (Brewer et al. 2007, Grafton et al. 2011, Smith 2019). Meanwhile, the underlying rights themselves can impact the transaction costs and subsequently explain various levels market activity. Generally, proportional rights (and their relative homogeneity) are predicted to perform better (Frederick 1986, Howe et

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[3] The empirical setting well suited to testing this among homogenous irrigators, but it should be noted that amid heterogenous production, priority rights do allow for the procurement different degrees of supply reliability, protecting any investments from extreme losses during droughts. Similar certainty under a proportional system would require those users to hold excess rights in "normal" years (Howe et al. 1986).

al. 1986, Rosegrant & Gazmuri 1995, Howe & Goemans 2003, Grafton & Horne 2014). This view is not universal as priority rights can reduce the number of necessary transactions and permit risk mitigation among heterogenous producers (Freebarin & Quiggin 2006, Lefebvre et al. 2012).

While comparisons across distinct water rights systems have aided in our understanding of how these different rights impact development, production, and trade (e.g. Grafton et al. 2011), formal empirical testing of priority rights vis-à-vis proportional rights has been challenging because their adoption, like other property rights, are endogenous to local or regional factors such as hydrological conditions and cultural factors that also impact irrigated agriculture outcomes (Demsetz 1967, Carey & Sunding 2001, Leonard & Libecap 2019). In this paper I address this empirical challenge by drawing on the US's acquisition of the Southwest from Mexico in 1848 and the subsequent downstream impacts on water rights as a natural experiment. Hispanic irrigators developed northern New Mexico with irrigation systems known as *acequias,* but a small subset was subsequently separated by a political subdivision when Colorado Territory was formed, resulting in an exogenous change in water law. The analysis considers the development and investment as well as the performance and robustness of *acequias* in Taos county, New Mexico, where proportional sharing of water still persists, to that of *acequias* in Costilla county, Colorado, the adjacent county to the north where priority water rights are enforced.[4] These systems are but 50 miles apart; both draw upon snowmelt from the Sangre de Cristo Mountains, grow similar crops, share a cultural heritage, and, according to a recent analysis, have similar internal rules and practices (Cody 2019).

Perhaps the research closest to that pursued here is Ji & Cobourn (2018), who also look at the implications of proportional rights vis-à-vis priority rights. They utilize the fact that many irrigation districts are large and internally divide water on a proportional system to compare agriculture choices within irrigation districts to those outside who are subject only to the priority right system. They find those within irrigation districts have welfare gains through their ability to choose more water intensive and profitable crops. While the empirical design provides

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[4] The analysis is limited to investment and production, as the empirical setting does not permit the exploration of water trades.

credibility that the internal proportional rights cause these welfare improvements, irrigation districts are distinct as organizations in other ways (Bretsen & Hill 2007, Smith 2018) while their creation and borders are also endogenously determined. By using the change in territorial borders, my study of the *acequias* in Taos and Costilla isolates impacts of the water right structure on irrigation development, investment, and performance on otherwise similar systems and irrigators. The results are complementary to Ji & Coburn's (2018) results.

With the empirical setting in mind, I first develop a theoretical model in order to provide intuition and a number of testable predictions. This builds from the model used to critique the priority system in Burness & Quirk (1979), henceforth BQ. To test the predictions, I conduct two analyses based on distinct and unique data sets. First, I draw upon irrigation enterprise census records from 1930, hand collected from the National Archives, to test for impacts on development and investment related to irrigation. Second, I utilize satellite imagery measuring NDVI (Normalized Difference Vegetation Index) to create an aggregate proxy for annual production from 1984 to 2011 and explore the marginal productivity of another unit of water in each system. And finally, a third data set from field surveys of 31 *acequias* conducted in 2013 provides insights into recent adaptations and future concerns within the alternative water right regimes. Broadly, the analysis finds that the priority system does protect investment, skewing the distribution towards more senior water rights. Meanwhile, the marginal productivity of water is typically higher, and uniformly so, within the proportional system.[5]

In the next section I present a model based on the empirical setting, formally establishing testable predictions. In Section 3 I layout the natural experiment in greater detail. The data, methods, and results for the investment, production, and survey analyses are provided in sections 4, 5, and 6 respectively. The paper then concludes with section 7.

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[5] The data limits the analysis to separate investigations of the investment costs and marginal productivity. Therefore, it is not possible to ascertain whether the relative cost efficiency gains in the priority system offset the relative production inefficiencies and how the profits between the two systems compare.

2 Model

2.1 Water rights in the American West

The prior appropriation doctrine adopted in the western US during the latter half of the 19th century is in stark contrast to the riparian doctrine which guides water law in more humid east. Prior appropriation is distinct in that water rights are severable from the adjacent land rights, creating a separate usufruct property right (the water itself is owned by the state). Often described as “first in time, first in right,” water rights are established by first possession. In order to establish the right, you must divert water from its natural course and put it to beneficial use. Often this is defined as some consumptive use, and can extend beyond agriculture to manufacturing and domestic uses. The legal ownership of the right is defined by the original date of diversion, diversion location, use location, and approved beneficial use (Getches, 2009). In times of water shortage, senior appropriators, those with the earlier diversion dates, are provided all of their water first. Only once their rights have been filled do more junior rights receive water.

In contrast, settlers of *Nuevo México* began irrigating based on communal institutions, namely *acequias*. Like the priority system, the water can be diverted and applied to non-riparian land, but water shortages (and surpluses) are shared based on norms and customs. Resulting from the Law of Indies, division is guided by the principle that water is sacred and all living beings have a right of access. In practice, this system produces a proportional water right, with many *acequias* along a stream formalizing the shares (Cox & Ross 2011). The *acequias* have persisted for centuries, with many in modern day New Mexico dating back to the 17th century and the bulk of them originating in the 19th century.

2.2 Assumptions

The base model to be used makes the same assumptions as BQ, but presents an alternative for how water delivery is determined. Rather than only applying priority, I allow everyone to receive a proportion of flow based on diversion structures regardless of entry order as an alternative. Borrowing BQ’s notation for simplicity, the model assumptions are as follows:

1) x=acre-feet of streamflow which is a random variable with a known probability function, $f(x)$.

2) $f(x) \geq 0$ for $x \geq 0$ and $f(x) = 0$ for $x < 0$
3) The cumulative distribution function is defined $F(x) = \int_0^x f(c)dc$. I assume $F(0) = 0$ and $\lim_{x \to \infty} F(x) = 1$.
4) Letting a_i be the water available to appropriator i, and $\bar{a}_i$is the diversion capacity constructed by the ith appropriator, the profit function is dependent on these two elements: $\pi^i(a_i, \bar{a}_i)$ subject to the restriction that $a_i \leq \bar{a}_i$.
5) The derivatives of the profit function are as follows:
    a. $\pi_1^i \equiv \partial\pi^i/\partial a_i > 0$ for $0 \leq a_i \leq \bar{a}_i$ and $\pi_1^i = 0$ otherwise. This means the marginal profit from water is positive, but water beyond the diversion capacity offers no additional value.
    b. $\pi_{11}^i \equiv \partial^2\pi^i/\partial {a_i}^2 < 0$. There are decreasing marginal profits to water as an input.
    c. $\pi_2^i \equiv \partial\pi^i/\partial\bar{a}_i < 0$ for $\bar{a}_i \geq 0$. Marginal profit decreases as capacity increases due to the cost of construction and increased maintenance.
    d. $\pi_{22}^i \equiv \partial^2\pi^i/\partial{\bar{a}_i}^2 < 0$ for $\bar{a}_i \geq {\bar{a}_i}^*$ and $\pi_{22}^i = \partial^2\pi^i/\partial{\bar{a}_i}^2 > 0$ for $\bar{a}_i < {\bar{a}_i}^*$ where ${\bar{a}_i}^*$ is the diversion capacity where problems of coordination overwhelm the economies of scale associated with diversion construction. Typically it is assumed that operation occurs in the $\bar{a}_i > {\bar{a}_i}^*$ so that the marginal cost of adding diversion is increasing.
    e. Also assume that depreciation is due only to time, not due to use, so $\pi_{12}^i \equiv \partial\pi^i/\partial a_i\partial\bar{a}_i = 0$. This permits the profit function to be separable: $\pi^i(a_i, \bar{a}_i) = R^i(a_i) - C^i(\bar{a}_i)$ where R^i and C^i are the revenue and cost functions for the ith appropriator.
6) Further, assume homogenous farmers in production capability. That is $\pi^i(a_i, \bar{a}_i) = \pi(a_i, \bar{a}_i)$.
7) As a matter of notation, let $A_i \equiv \sum_{j=1}^{i} \bar{a}_j$. In other words, A_i is the aggregate diversion capacity constructed by firms 1 through i. $A_0 = 0$. Under the priority system, it also represents the amount of water rights senior to firm $i + 1$.

2.2.1 Priority system:

Under the priority system, irrigators receive water sequentially. Specifically, assume that the water available to firm i is given as

8) $a_i = 0$ if $x < A_{i-1}$, $a_i = x - A_{i-1}$ if $A_{i-1} \leq x < A_i$, $a_i = \bar{a}_i$ if $x \geq A_i$

With this, we can write down the expected profit of firm i when choosing how much diversion capacity to build. Specifically,

$$E^{pa}(\pi^i) = F(A_{i-1})\pi(0, \bar{a}_i) + \int_{A_{i-1}}^{A_i} \pi(x - A_{i-1}, \bar{a}_i) f(x)dx + [1 - F(A_i)]\pi(\bar{a}_i, \bar{a}_i)$$

The pa refers to prior appropriation and is used to distinguish from communal sharing (cs) derived below.

2.2.2 Communal sharing (proportional rights)

Rather than assuming an irrigator receives water in a given priority, assume they receive water proportional to their share of the aggregate diversion structure. In particular, the amount of water available to farmer i is given as:

9) $a_i = \frac{\bar{a}_i}{A_N} x$ when $x < A_N$ and $a_i = \bar{a}_i$ when $x \geq A_N$.

In words, when the flow of the river is less than the aggregate capacity, then water available is in proportion based on i's proportion of total capacity. If the flow is greater than this, all appropriators divert up to their capacity. Therefore, maintaining all assumptions but 5e from above, the expected profit function under proportional sharing is given as the following:[6]

$$E^{cs}(\pi^i) = \int_0^{A_N} \pi\left(\frac{\bar{a}_i}{A_N} x, \bar{a}_i\right) f(x)dx + [1 - F(A_N)]\pi(\bar{a}_i, \bar{a}_i)$$

The important differences between E^{pa} and E^{cs} are threefold. First, in communal sharing there is no longer the term for which receiving no water is an option. Second, the middle term is now more complicated and includes a wider range of stream flow and is determined by the aggregate

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[6] Assumption 5e above can no longer hold by construction. While the spirit remains in the sense that maintenance is independent of use, constructed capacity now directly determines the amount of water received by irrigator i, meaning the cross derivative is no longer zero.

diversion built by all N appropriators. In this regard, expected profit can be altered by future diversion whereas in E^{pa} this is not possible. This immediately suggests there may be some inefficiency when this model is used at the outset as early firms may build too large of diversions for the final allocation. Third, the last term is similar in both cases, but the communal regime is influenced by future diversions. If we presume the ith appropriator is not forward looking and that no more diversion will occur after they enter, we can replace A_N with A_i when choosing their capacity.

2.3 Model Results[7]

The overarching result of the BQ analysis is that the priority system is not efficient when a market is lacking. The inefficiencies appear along at least two dimensions. First, more diversion capacity will be constructed than should be given the expected flow of the stream. Second, and more apparent, is that allocative efficiency will not be achieved as the senior water right holder will receive more water in shortages and sufficient flows, meaning marginal benefits are never equated across irrigators. BQ show that equal sharing is the efficient outcome. Here I expand BQ's model to consider the alternative distribution rule which more closely mimics the practice of the Hispanic irrigators.

Proposition 1: *Given a particular amount of diversion already constructed, the next entrant under the communal sharing will build a larger diversion structure than one under prior appropriation:* $\bar{a}_i^{cs} \geq \bar{a}_i^{pa}$ *for a given* A_{i-1} *with strict inequality if* $i>1$.

Intuitively, the larger infrastructure nets more water (of any flow) under the *cs* system, justifying the extra cost of construction. More diversion under prior appropriation nets more water for only a specific range of stream flow, decreasing the odds of enjoying the gain. It is easy to assume that this implies that communal sharing will then build even more diversion structure, making worse the excess capacity found in BQ, but this proposition neither sufficient nor necessary. In these parallel worlds, the third appropriator does not face the same value of prior diversion in their constraint. Yet, once entrance is no longer expected to be profitable under the priority system, it remains so under the communal sharing system. A formal proof is provided in the appendix, but omitted here since it does not deliver a testable prediction in the empirical setting.

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[7] Proofs of propositions are included in Appendix A.

Since BQ suggested over capitalization under the priority system, the issue is exacerbated under the proportional sharing rule. This underscores the merits of the priority system in curbing rent dissipation of initial development in open access situations.[8]

Setting aside the open-access entry issue, for a set aggregate capacity and number of irrigators, BQ show that equal sharing of the available flow is the most efficient. Let $\pi^{cs}(x)$ and $\pi^{pa}(x)$ be the aggregate profit for communal sharing and prior appropriation respectively.

Proposition 2: *For N>1, irrigators with equal diversion capacity,* $\pi^{cs}(x) > \pi^{pa}(x)$ *for all x.*

Corollary 1: *The expected marginal product of water is greater under communal sharing;* $E\{\pi_1^{cs}(x)\} > E\{\pi_1^{pa}(x)\}$

However, this corollary does not extend to $\pi_1^{cs}(x) > \pi_1^{pa}(x)$ for all *x,* only in expectation. This is because a given marginal unit of water under the priority system may be the first unit of water for a junior irrigator depending on the realization of flow that year. The marginal gain in that instance will be large, though concentrated on only the one marginal user.

Proposition 3: $\pi_1^{cs}(x) > \pi_1^{pa}(x)$ *if* $F\left(\bar{a}(i-1)\left(\frac{N}{N-1}\right)\right) < 0.5$ *for* $A_{i-1} \leq x < A_i$ *on average.*

Corollary 2: *Gains in production due to increased flows are uniformly distributed under communal sharing. Under prior appropriation, junior diverters are expected to do worse, yet more likely to experience large variation in marginal gains.*

The marginal gain expected while $A_{i-1} \leq x < A_i$ will be higher under the seniority system if *i* is relatively large and *N* is relatively small. Another way to look at it is if $\frac{\text{Others}' \text{ Water(pa)}}{\text{Others}' \text{ Water Capicity}} < \frac{\text{i}'\text{s water(pa)}}{\text{i}'\text{s Capacity}}$, the gain under the communal sharing system will be larger. Notably, because the priority system's marginal gain is due only to the marginal irrigator, it becomes apparent that production should be expected to be non-uniform under the priority system. Below I map these propositions to testable predictions given the empirical setting.

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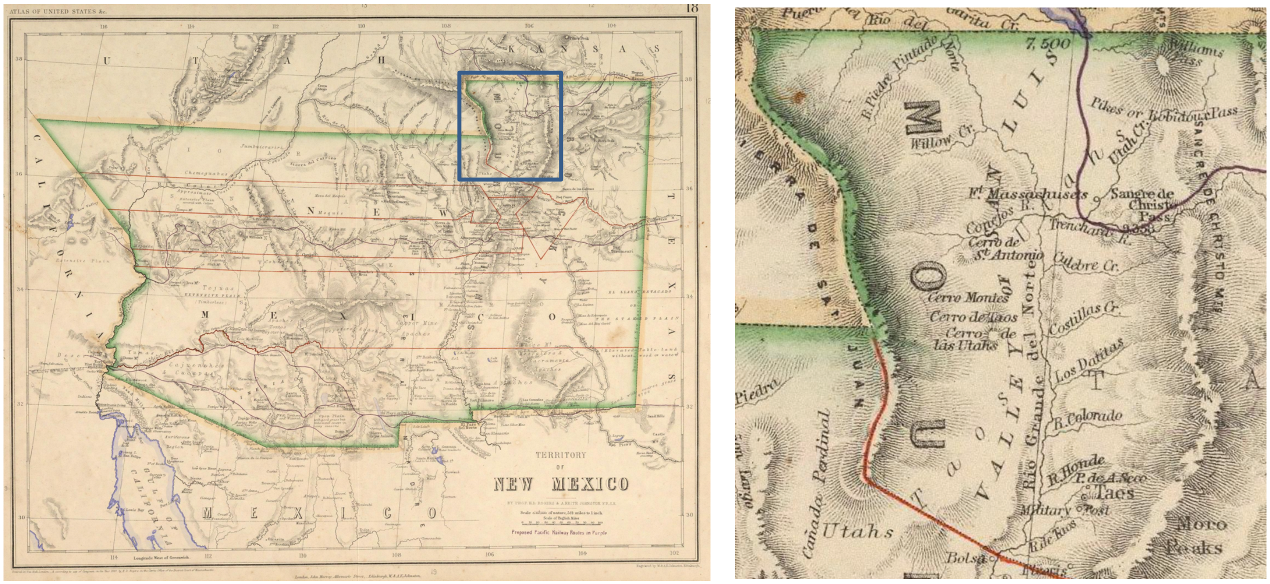
[8] If we allow for more sophisticated economic agents that are forward looking and anticipate the final entrant, the equilibrium investment will be equal across all agents, but still individually excessive and, hence, in aggregate, too much capacity. The intuition is that one would prefer to maintain equal capacity but of smaller scale, but doing so as an individual would allow for later arrivals to build larger systems and claim a larger proportion of the stream. Hence, building large enough to ensure others cannot profitably increase their share creates the equilibrium.

3 Empirical Setting and Strategy

In order to test the model, I draw upon a natural experiment with *acequias* in the southwest. One group of *acequias* is in Taos County, New Mexico and the other group is in the adjacent Costilla County, Colorado. The *acequias* are within 50 miles of one another and both regions are steeped with Hispanic roots, but due to historic developments beyond the *acequias'* control, the New Mexico *acequias* practice proportional sharing whereas the Colorado *acequias* are subject to the priority system. Figure 1 provides a spatial overview with historical context. Taken from an 1857 atlas, it shows the proximity of the streams explored and that in 1857, what is now Costilla county fell within the Territory of New Mexico. Only after the discovery of gold and silver in 1859 was the Colorado Territory carved out.

Figure 1
Map of territorial New Mexico, 1857



Notes: The left panel shows the entirety of the New Mexico Territory, including parts of modern-day Nevada, Arizona, Colorado and New Mexico. The right panel displays more detailed inset of the empirical area, most importantly showing that Costilla Creek and Culebra Creek (as well as the entire modern-day Costilla County) was within New Mexico territory as of 1857. Figure C1 in the appendix further shows that this region now in Colorado was also in Taos County at this time of initial settlement. Figure C2 shows modern political boundaries relative to the *acequias*.
Sources: Rogers & Johnston, 1857.

3.1 New Mexico Settlement and Water Law

European settlement of what is now New Mexico began with the Spanish colonization of *La Provincia del Nuevo México* in 1598. After a brief expulsion by native populations, colonization resumed in full force in 1695 and on through Mexico's independence in 1821. The settlements were guided by the Laws of the Indies issued by the Spanish crown, stating access to water as essential for the formation of a community. Therefore, unlike most of the West, irrigation and water law was not a vacuum upon the United States' acquisition of the region. Instead, a unique set of water laws being employed by many irrigation ditches (*acequias*) was inherited.

The Kearny Code, proclaimed in 1846 upon the United States' occupation stated, "laws heretofore in force concerning water courses, stock marks, and brands, horses, enclosures, commons and arbitrations shall continue in force" (Victory, 1897: p. 90). This protection was confirmed by the Treaty of Guadalupe Hidalgo in 1848, which officially passed the region to US sovereignty from Mexico; "property of every kind now belonging to Mexicans now established there, shall be inviolably respected" (Victory, 1897: p. 31). The *acequias* were provided further protection when the first territorial laws were passed in 1851 and 1852. The statutes, many still on the books, codified the customs and norms. The customary division of water follows *repartiemento,* by which water surpluses and shortages are shared across ditches in proportion (Rodríguez, 2006). This amounts to a proportional system, with around half of the Taos systems reporting formal agreements and the others relying on unwritten agreements (Cox & Ross 2011). As non-Hispanic settlers gained in number, however, they also gained representation in the territorial legislature and water laws slowly converged to those being deployed through the rest of the West, but with important residuals of these earlier rules (see Smith 2014 for more details).

Spurred by the federal formation of Reclamation Service in 1903, the New Mexico Territorial Legislature drafted and passed an expansive water code in 1905 (House Bill number 98 of the 36th Territorial Legislature). The new water code had many implications, but two critical: 1) it adopted the prior appropriation doctrine as the guiding water code for the territory; and 2) created the Office of the Territorial Engineer (now the State Engineer) to centrally administer the private water rights. Both marked a departure from *acequia* tradition in creating priority rights, rather than communal rights, while simultaneously moving water administration further from the local users. The new priority system came at odds with the historic practice of sharing shortages among all *acequias* on a single stream in many regions.

The process of implementing the new water code has been long and drawn out. The adjudication process, by which individual water rights are determined, is ongoing with many regions underway while many others have not even begun. The process in Taos began in 1968 with a hydrological survey and a partial decree was finally issued just in 2015. The complicated process of litigation, general opposition to the priority system, and distinctive history has presented New Mexico with unique solutions. Many basins have chosen to develop settlements among themselves rather than conducting adversarial litigation (Richards, 2008). For *acequias* in Taos, this has allowed them to agree on maintaining their sharing agreements and operate outside of the priority system. The agreement allows the region to maintain their customs and norms with the parties agreeing to refrain from priority calls (Richards, 2008).[9] According to Rodríguez (2006), no *acequia* user interviewed in Taos recalls anyone ever placing a call, i.e. exercising their priority right, on their water. The decentralized water allocation mechanism has worked just as well as more centralized allocation mechanisms that displaced *acequia* governance in other portions of New Mexico (Smith, 2018).

3.2 Colorado Settlement and Water Law

San Luis de la Culebra is the oldest town in Colorado, settled just 50 miles north of Taos by Hispanics in 1852. Just four years after the Treaty of Guadalupe Hidalgo, settlement of the area was also nine years prior to Colorado Territory being carved out of Kansas, Utah, and New Mexico Territories. This area was part of New Mexico Territory – specifically, Taos County (Simmons, 1999) – meaning many of the irrigation ditches were dug under the same codified customs governing the Taos *acequias* at the time. But after 1861 this region found itself in the new Colorado Territory where the adoption and implementation of the prior appropriation occurred quickly and efficiently. Formally stated in the 1876 Colorado State Constitution, the implications were judicially confirmed when the Colorado Supreme Court's decision in *Coffins v. Left Hand Ditch Co.* (1882) recognized the right to divert water from its natural course and confirmed protection of that use from the interference of any new users.

The San Luis People's Ditch, dug by the Hispanic settlers in 1852 on the Culebra Creek, hails as the oldest water right in Colorado. Established after 1848, the Treaty of Guadalupe Hidalgo offers no protection even though the region was under same New Mexico Territory laws as the Taos *acequias* at the time. Ultimately, this timing causes these *acequias* in Colorado to now operate in a very different institutional context, locked into the priority system.[10] Daily, the state

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[9] In meeting Rio Grande Compact demands due to Texas, the priority system may come into play in determining curtailment of water.

[10] Once water is within the *acequia*, division to the individual irrigators is internally determined. Among *acequias,* in both New Mexico and Colorado, the process is typically based on sharing. Often the priority dates are the exact

engineer measures the flow of water and then employs state commissioners to open and close head gates to ensure only those in priority receive water. Under the priority appropriation doctrine, rights can be lost due to non-use. Therefore, even if a senior ditch wishes to take only half their water in order to share some water with junior ditches, they may not due to the risk that the state would view this as non-use and put that portion of their right at risk to abandonment (in which case the right to use that portion of the water is loss). Furthermore, unless the water is meant for the ditch next in priority, they have no legal mechanism to force the intermediate rights to refrain from extracting the water. [11]

While over time the *acequias* here have adapted to the new system, overall there remains the cultural desire to share shortages. Hicks & Peña (2003) recount a story of sharing during the 2002 drought. While they could not legally put water in the junior ditches, a senior right holder permitted some farmers with land on a junior *acequia* to sharecrop a portion of the senior's land. This permitted the shortage to be shared by circumventing the priority system. Illustrative of their frustration with their struggle to exercise their culture and norms, Costilla County, perhaps a bit tongue-in-cheek, petitioned they leave Colorado and become part of New Mexico in 1973 (Simmons, 1999). Indeed, Costilla county was never divided in squares by the Public Land Survey System due to its prior settlement under long lots. These anecdotal points suggest they value their Spanish/Mexican heritage and still desire to allocate water similarly to their New Mexican counterparts, but are much more constrained by the priority-based property regime enforced in Colorado. Besides water rights, both Taos County and Costilla County engage in similar agriculture production, using water to grow mostly forage. In Taos, 95% of the acres are for this purpose and 75% in Costilla (USDA, 2013). Furthermore, in a more rigorous analysis based on extensive irrigation ditch surveys collected by the author in 2013, the *acequias* in Costilla county were found to be distinct in their organization and characteristics from other (Anglo) irrigation ditches in San Luis Valley, Colorado and more similar to the *acequias* in Taos

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same as these are based on diversion and the *acequia* users share the initial diversion, precluding the use of internal priority. Newer mutual irrigation companies in Colorado may maintain seniority if the rights pre-date the formation of the company, but this is not the case for the *acequias* in question.

[11] In 2009 Colorado passed the "Acequia Recognition Law" (Colorado Revised Statutes § 7-42-101.5) which now provides a mechanism for *acequias* founded prior to Colorado Statehood to afford legal protection of communal traditions. The process of implementing this remains ongoing.

(Cody 2019). All told, these two sets of *acequias* provide a compelling natural experiment to isolate the relative impacts of proportional and priority water rights on homogenous irrigators.

3.3 Empirically Testable Hypotheses

Given the empirical setting and the predictions of the model, these are the testable hypotheses:

> H1: Conditional on existing investment/capacity, new diverters in New Mexico will invest more relative to Colorado diverters (Proposition 1)
>
> H2a: New Mexico has a higher aggregate marginal product of stream flow on average across time (Corollary 1)
>
> H2b: Colorado's aggregate marginal product is not highly correlated with stream flow across time (Proposition 1)
>
> H3a: Junior diverters in Colorado will perform relatively worse on average (Corollary 2)
>
> H3b: Junior diverters in Colorado will experience relatively greater temporal variation in performance than would be juniors in New Mexico (Corollary 2)

In order to test these hypotheses, I construct and analyze two distinct data sets. The first, utilized to test predictions related to the irrigation investment predictions, is comprised of cross-sectional information hand-collected from the original 1930 irrigation census schedules held at the National Archives. The second, used to analyze the relationship between available water and production, is a panel data set primarily comprised of USGS stream gauge data and values of "greenness" derived from satellite imagery.

4 Investment and Capacity

4.1 1930 Census Data

As part of the 1930 Decennial Census effort, each irrigation enterprise in the 19 western states filled out a short questionnaire, providing information on the 1929 irrigation season. The responses are tabulated and readily available at county and state levels for the 1930 report (US Bureau of the Census, 1932). But, the original schedules have also been preserved and are at the National Archives in Washington D.C. (US Bureau of the Census 1930, Record Group 29.8.3), providing a cross-section of the ditches themselves. In 2015, I collected the data for Taos County and returned in 2016 to collect data for Costilla County.[12] For the sample, only the smaller systems are considered, dropping larger irrigation districts and commercial enterprises (three from each county, all developed in the 20th century). For analysis, I consider the variables that indicate investment or capacity. Most directly related to the theoretical model is the flow capacity as measured as cubic feet per second. I also consider measures of ditch length, acreage served, capital investment, and maintenance expenditures.[13] The summary statistics, by county, are provided in Table 1.

These means provide some suggestive evidence that *acequias* in New Mexico did tend to be larger: capacity, acreage, and length all tend to be larger in New Mexico. However, Colorado tends to have invested more capital. But these averages mask the relationship across early and late arrivals and may be related to differences of irrigation suitability and water supply across the basins. Therefore, I turn to a regression analysis to estimate the response to pre-existing investment across the two regions. By using the construction start date, the order of arrival can be ascertained and the pre-existing capacity (or investment) in each watershed can be calculated.

TABLE 1

1930 Analysis Summary Statistics

	Taos (New Mexico)			**Costilla (Colorado)**			**Difference**
Variable	Obs	Mean	Std. Dev.	Obs	Mean	Std. Dev.	
Capacity (CFS)	59	10.73	13.77	39	10.30	15.86	0.43
Original Acres	62	492.10	906.07	85	256.66	376.06	235.44
Length (Miles)	59	2.50	2.38	39	1.95	1.20	0.54
Capital ($)	62	1243.71	3405.60	85	1800.06	6316.48	-556.35
Capital per Acre ($)	62	3.90	4.86	85	3.99	4.48	-0.10
Maintenance Costs ($)	58	220.59	376.34	39	134.03	242.72	86.56
Construction Start Year	62	1841.77	53.92	85	1884.98	15.01	-43.20

Note: Descriptive Statistics for irrigation enterprises from the 1930 census by county. See Appendix B for a full description of the variables.

4.2 Empirical Analysis

Using the 1930 Census data, I test H1 (Colorado investment and capacity are more sensitive to pre-existing investment and capacity). I utilize the following equation to test these predictions:

$$Y_{ibr} = \alpha_1 + \alpha_2 \times Col_r + \alpha_3 \times A_{i-1,br} + \alpha_4 \times A_{i-1,br} \times Col_r + \boldsymbol{\tau}'_b + \boldsymbol{v}'_i + e_{irb} \quad (1)$$

---

[12] An example form is provided in Appendix B, figure B1 and B2.

[13] See the Appendix B for an explanation of each variable.

Y_{ibr} is one of the measures of investment or capacity for ditch *i* in basin *b,* region *r* (either Colorado or New Mexico). Following the notation from the theoretical section, $A_{i-1,br}$ is the capacity already existing in basin *b* when ditch *i* was first built. This is interacted with an indicator for Colorado to allow for a differential effect. To account for heterogenous watersheds may tend to attract more investment due to unobserved reasons, $\boldsymbol{\tau}_b'$ is a vector of basin level fixed effects and their coefficients so that identification comes from within a watershed. Finally, to address the fact that a ditch built in 1710 is likely different in character than a ditch constructed in 1852 independent of the pre-existing capacity in the basin, I include $\boldsymbol{v}_i'$, a vector of construction year indicator variables and their coefficients. There are insufficient observations for year fixed effects, so the indicators capture 25-year periods (e.g. 1701-1725). Standard errors are clustered at the basin level for the primary analysis. Regressions include only basins with more than one ditch reporting.

I capture pre-existing capacity or investment ($A_{i-1,br}$) in two ways for the main results. First, I utilize the dependent variable directly, i.e. $A_{i-1,br} = Y_{i-1,br}$. Second, I use acreage for a proxy of existing capacity across all outcomes. Cubic feet per second would be preferable, but with many ditches not reporting this value, it creates measurement error in the existing capacity. The correlation between acreage and capacity is positive in all basins and overall 0.512 and robustness checks using CFS do provide similar results.[14] Results are provided in Table 2.

In New Mexico, there is no evidence that development or capacity is curtailed by later arrival and in fact, many point estimates are positive. In comparison, those that arrive facing more pre-existing capacity in Colorado do tend to build smaller and invest less relative to their counterparts in New Mexico: they divert less, irrigate fewer acres, dig shorter ditches, invest less capital (total and per acre) and even expend less on annual maintenance. This is true whether existing capacity is proxied by the dependent variable being analyzed or simply acreage.[15] Taken together, the evidence is supportive of H1 and consistent with results from Leonard & Libecap (2019).

---

[14] A robustness check using CFS is provided in the appendix, table C1.

[15] Additional robustness checks for the inclusion/exclusion of the basin and start of construction fixed effects are provided in the appendix, table C2. In addition, a specification clustering errors by start of construction bins. Results are similar across all specifications.

TABLE 2

1930 Investment Regression Results

VARIABLES	(1) Capacity (CFS)	(2) Original Acres	(3) Length (Miles)	(4) Capital ($)	(5) Capital per Acre ($)	(6) Maintenance Costs ($)
Panel A: Dependent Variable						
Existing Dependent Var	0.144***	-0.0203	0.173***	0.278***	0.0538	0.184**
	(0.0276)	(0.0237)	(0.0474)	(0.0235)	(0.0574)	(0.0822)
Existing Dependent Var x Colorado	-0.279***	-0.0600*	-0.199***	-0.536***	-0.104*	-0.318**
	(0.0340)	(0.0322)	(0.0542)	(0.0223)	(0.0555)	(0.112)
Observations	98	147	98	147	147	97
R-squared	0.477	0.446	0.461	0.385	0.347	0.421
Panel B: Acreage						
Existing Acreage	0.00213***	-0.0203	0.000329***	0.742***	-0.000325	-0.00120
	(0.000398)	(0.0237)	(6.45e-05)	(0.0934)	(0.000281)	(0.00790)
Existing Acreage x Colorado	-0.00419***	-0.0600*	-0.000393***	-1.808***	-0.000176	-0.0357***
	(0.000476)	(0.0322)	(7.56e-05)	(0.138)	(0.000246)	(0.0117)
Observations	98	147	98	147	147	97
R-squared	0.490	0.446	0.439	0.401	0.370	0.402

Regression results for various measures (see data section) of irrigation investment and existing capacity for ditches in Costilla and Taos counties. Panel A utilizes existing basin level investment measured by the dependent variable. Panel B utilizes existing capacity (acres) across all columns. Fixed effects for construction start by 25 year intervals and basin level fixed effects are included in all regressions. Robust standard errors, clustered by basin, in parentheses.

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

5 Water and Production

5.1 Production and Water Data

Analysis of stream flow and production focus on four streams, two from each state: the Rio Culebra and Rio Costilla in Colorado and the Rio Hondo and Rio Lucero in New Mexico.[16] Data on production, stream flow, and priority ranking (order of arrival in New Mexico) are constructed to analyze the relationships between the three. For production, I utilize the Normalized Vegetation Difference Index (NDVI). Derived from Landsat Satellite imagery (USGS 2013a), NDVI is an ecological metric capturing the extent of healthy vegetation present in area providing a reliable proxy for crop production, particularly in arid regions and has been utilized in this context (Cox & Ross, 2011; Smith, 2016; Cody, 2018).

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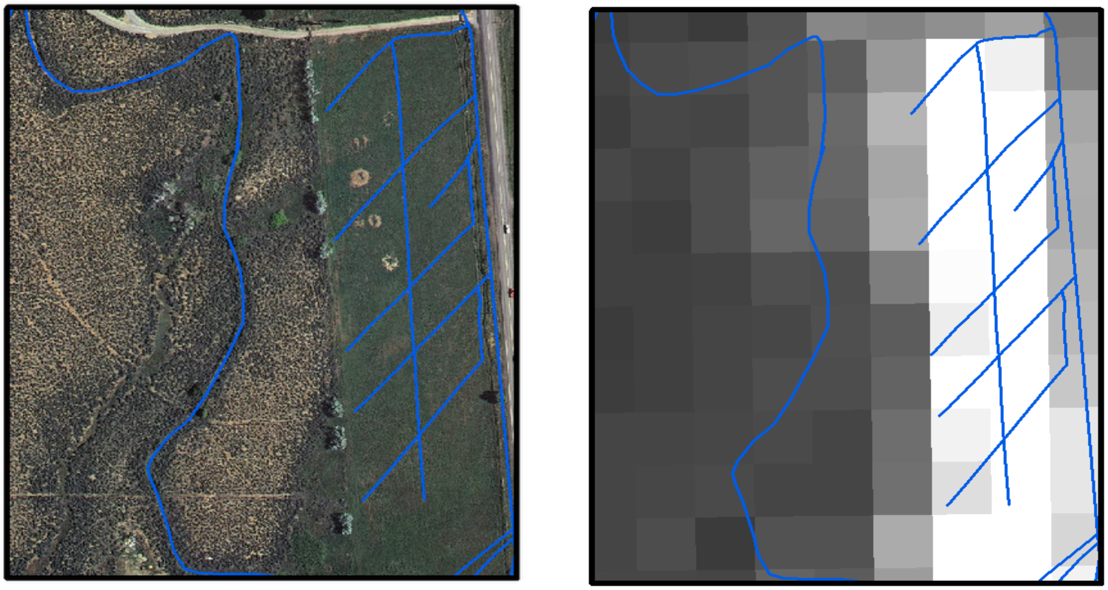
[16] These are the primary streams in Colorado. Furthermore, stream gauge data (and priority date in New Mexico) are limited for the other streams.

The measure itself is based on two wavelengths: NIR measures the extent that Near-infrared wavelengths are reflected back and RED measures the red wavelengths in the electromagnetic spectrum reflected back. With healthy vegetation absorbing RED and reflecting NIR, NDVI is constructed such that values closer to 1 indicate abundant healthy vegetation and values closer to -1 indicate more barren ground.

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

To provide some physical context, NDVI values are contrasted to the greenness of a field in Figure 2. The raw data are gathered for each growing season from 1984-2011. The images provide 30x30 meters pixels. To match pixels to *acequias,* GIS information is utilized from Colorado’s and New Mexico’s Office of the State Engineer that indicate service area of the ditches (CDSS, 2013; OSE, 2009). NDVI (spatial) averages are calculated each year for each ditch and averages across the aggregation of all land serviced by a given stream.

FIGURE 2
ILLUSTRATION OF “GREENNESS” AND NDVI VALUES



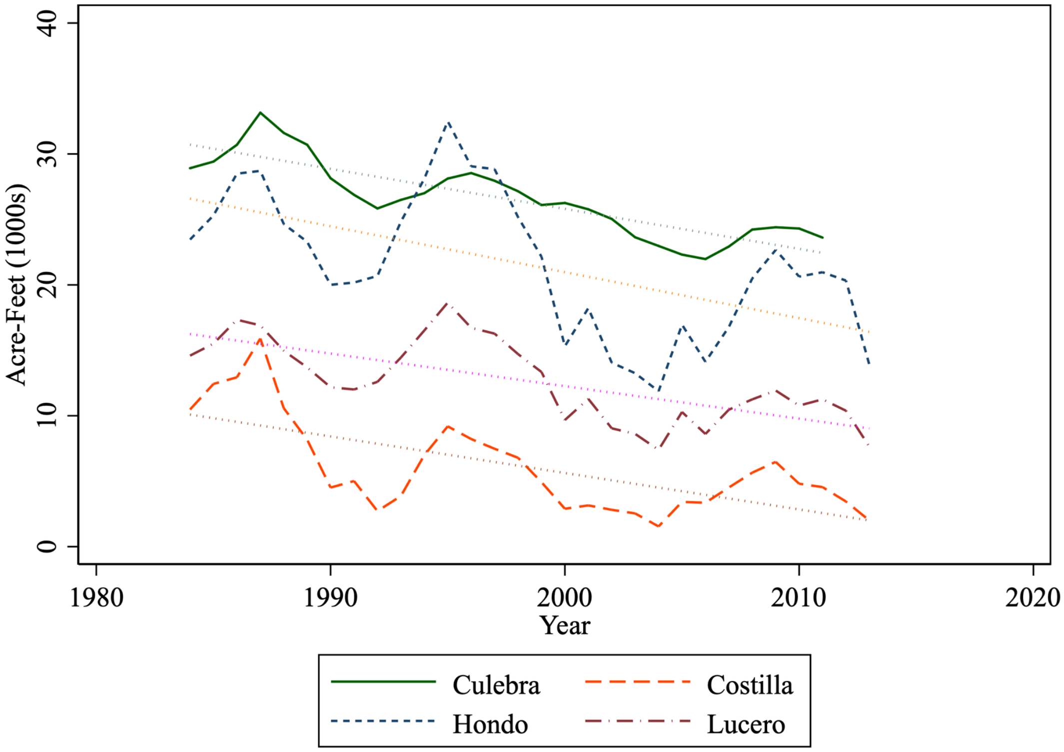
Aerial

NDVI

Notes: The images show a portion of an *acequia* (canals in blue) and irrigated land in New Mexico. The left panel shows aerial image while the right provides the 30x30 meter NDVI pixels, with whiter values being closer to 1.
Sources: Rendering from using GIS Data on ditch location (OSE 2009) and NDVI measures (USGS 2013a).

For water supply, I utilize flow data from the United States Geological Survey (USGS, 2013b).[17] The gauges gather daily readings throughout the year. Like many snowmelt systems, all four see considerable increases around April, peaking in June or July, before returning to low stable flows by October (see Figure C3 in the Appendix). To create an annual measure, I first convert the daily cubic feet per second to a volume of water delivered over the entire day, measured in Acre-Feet.[18] Dropping the winter months, I then sum up total annual water volume during the growing season. Figure 3 provides a rolling five-year average for the streams, revealing three patterns. First, the Culebra generally has the most water, followed by the Hondo, Lucero, and then the Costilla. Second, the streams are generally correlated with one another through time. And third, since 1983, all four streams have experienced a downward trend in annual water volume.

FIGURE 3
TRENDS IN WATER VOLUME BY STREAM, 1983-2011



Notes: Five year rolling averages of the annual volume of water during the growing season (April-October) on each stream. Linear trends are also plotted for each time series.
Sources: Authors' rendering of USGS (2013b) stream flow data.

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[17] The Gauges used are as follows: Culebra, USGS Gauge 08250000; Costilla, USGS Gauge 08261000; Hondo, USGS Gauge 08267500; Lucero, USGS Gauge 08271000 for the Rio Lucero. Flow is available as far back as 1913, though records are complete for all four streams from the 1960s.

[18] The volume of water needed to cover one acre in one foot of water or about 325,851 gallons of water.

TABLE 3

1984-2011 Analysis Summary Statistics

VARIABLES	Observation Type	No. Obs	Mean	Std. Dev.	Min	Max
Panel A: Culebra						
NDVI	Stream-Year	28	0.478	0.053	0.339	0.559
Acre Feet (1000s)	Stream-Year	29	26.449	4.286	18.736	34.866
NDVI	Acequia-Year	196	0.507	0.085	0.266	0.658
Temporal S.D. NDVI	Acequia	7	0.068	0.011	0.056	0.085
Priority Year	Acequia	7	1862.571	13.138	1852.000	1882.000
Acres	Acequia	7	1345.296	1169.125	57.600	3158.224
Precipitation (mm)	Acequia-Year	196	29.999	10.787	8.625	68.210
Temperature (Celsius)	Acequia-Year	196	12.094	1.136	8.901	14.761
Panel B: Costilla						
NDVI	Stream-Year	28	0.307	0.050	0.223	0.412
Acre Feet (1000s)	Stream-Year	29	6.341	6.798	0.118	27.344
NDVI	Acequia-Year	140	0.261	0.080	0.136	0.478
Temporal S.D. NDVI	Acequia	5	0.052	0.021	0.033	0.086
Priority Year	Acequia	5	1859.800	7.950	1853.000	1873.000
Acres	Acequia	5	256.554	317.385	34.916	770.597
Precipitation (mm)	Acequia-Year	140	27.005	9.260	8.018	49.905
Temperature (Celsius)	Acequia-Year	140	12.762	0.838	10.921	14.823
Panel C: Hondo						
NDVI	Stream-Year	28	0.402	0.068	0.224	0.539
Acre Feet (1000s)	Stream-Year	29	21.825	9.790	3.896	41.002
NDVI	Acequia-Year	196	0.442	0.113	0.153	0.684
Temporal S.D. NDVI	Acequia	7	0.069	0.008	0.057	0.078
Priority Year	Acequia	7	1817.143	6.466	1808.000	1828.000
Acres	Acequia	7	387.316	308.690	48.037	868.451
Precipitation (mm)	Acequia-Year	196	30.486	10.894	11.853	61.380
Temperature (Celsius)	Acequia-Year	196	13.610	0.967	11.274	16.036
Panel D: Lucero						
NDVI	Stream-Year	28	0.516	0.094	0.270	0.623
Acre Feet (1000s)	Stream-Year	29	12.799	5.267	2.156	22.775
NDVI	Acequia-Year	168	0.447	0.122	0.153	0.637
Temporal S.D. NDVI	Acequia	6	0.089	0.018	0.057	0.110
Priority Year	Acequia	6	1827.333	45.320	1747.000	1865.000
Acres	Acequia	6	653.173	432.384	261.314	1375.955
Precipitation (mm)	Acequia-Year	168	29.438	10.673	12.053	61.380
Temperature (Celsius)	Acequia-Year	168	14.160	0.960	11.274	16.203

Note: Summary statistics.

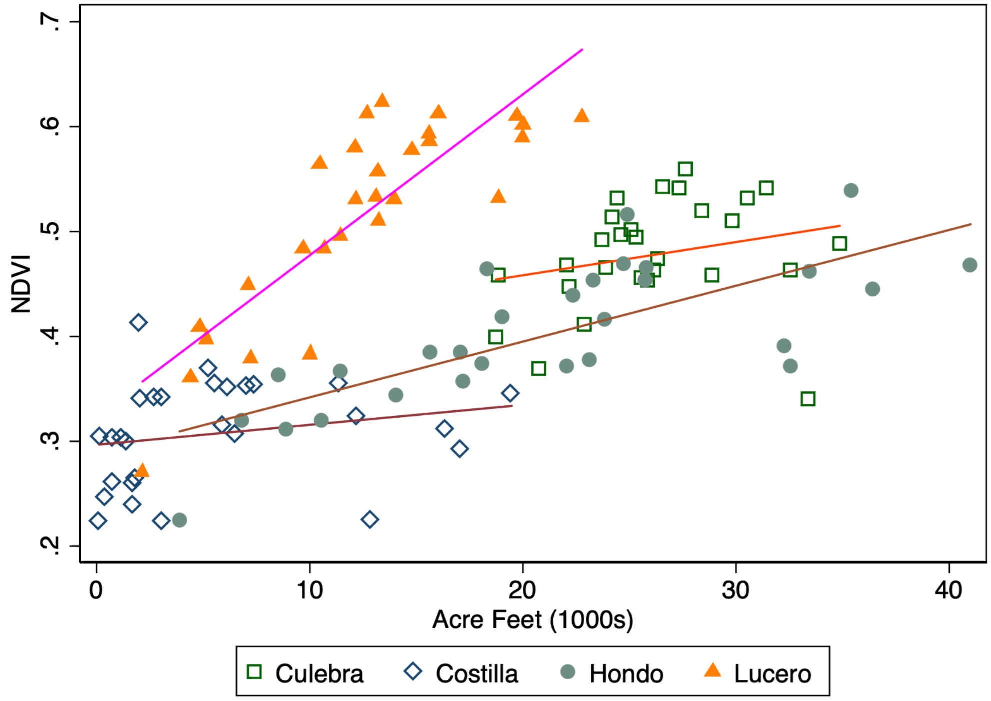
For *acequia* level analysis, the priority or order of arrival is ascertained. In Colorado, ditches are given a priority based on formal state records (CDWR, 2012). In New Mexico, where there is no priority system, I construct it based on construction dates compiled by Dos Rio Consultants (1996). Finally, while the regions are close and experience similar weather shocks, additional precision is attained by calculating growing season average temperature and total precipitation from spatially sensitive weather data (PRISM 2004).

A summary of the panel data, separated by stream, is provided in Table 3. For the *acequia*-level analysis, only the most senior *acequias* in Colorado are considered, those that are widely considered as the major irrigators and entering prior to 1882 (Peña, 1999). The sample in New Mexico are constrained to those with for which a date of beginning is available.[19]

5.2 Stream-Level Results

In this section I use the stream level aggregations to test H2, which has two parts: First, whether New Mexico has, on average, a higher marginal productivity of water. And second, whether that relationship is stronger in New Mexico. Before turning to the regression, a scatter plot of the raw NDVI and surface water availability is provided in Figure 4.

FIGURE 4
ANNUAL NDVI AND STREAM VOLUME BY STREAM, 1984-2011



Notes: Scatter plot of annual (growing season) stream volume and stream level average NDVI. Linear fit lines are provided.
Sources: Authors' rendering of USGS (2013a and 2013b) data.

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[19] In New Mexico, 4 *acequias* are removed due to missing dates, whereas in Colorado 12 are removed, 11 on the Culebra. One additional *acequia* on the Costilla is removed because it 1) has diverters in both States and 2) access to a storage reservoir. The *acequia*-level analyses with the full sample are quite similar, but the later systems in Colorado have no direct comparison to ditches in New Mexico.

Each stream does exhibit a positive correlation between stream flow and NDVI. Furthermore, the slope for both streams in New Mexico are steeper than those in Colorado. And last, the observations for the streams in New Mexico stay closer to their fitted lines than those in Colorado.

In order to test these relationships more rigorously, I run the following regression:

$$NDVI_{sy} = \beta_1 + \beta_2 \times AF_{sy} + \beta_3 \times AF_{sy-1} + \beta_4 \times Year_{sy} + \beta_5 \times ppt_{sy} + \beta_6 \times temp_{sy} + e_{sy} \tag{2}$$

The dependent variable ($NDVI_{sy}$) is the spatial mean. Subscript y refers to the year while s designates the stream. AF_{sy} captures the annual acre-feet in the stream while $Year_{sy}$ adjusts for the downward trend present in stream flow and any trend present in production. Weather variables (ppt_{sy} and $temp_{sy}$) that may also impact NDVI are included, averaged from the *acequia* level data for the stream. A separate regression is run on each of the four streams followed by a pooled regression with stream-level fixed effects and variables interacted with a Colorado indicator to identify statistically distinct relationships between water and NDVI under the two water right regimes.

The estimates are provided in Table 4. Across all the streams, the coefficient on acre-feet is positive, but tends to be larger and more significant in New Mexico. Furthermore, last year's water supply has no predictive power for this year's production, consistent with the fact that the region has little in the way of storage and that production this year depends highly on the randomly available snowmelt. Somewhat related, it is worth noting that the Breusch-Godfrey test fails to reject that there is no auto-correlation in the error terms. Related to H2b, the model fit is considerably higher in the two New Mexico streams as indicated by the respective r-squared values. In the pooled regression, presented in column (5), the results confirm that New Mexico does have a statistically distinct and higher marginal productivity of water on average.[20]

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[20] It may not necessarily be higher because of the water rights; for instance, the Culebra receives more water on average, which might mean the marginal value of water is lower due to diminishing returns. Looking back at Figure 4, this concern is minimized to some extent since the Lucero and Costilla have similar amounts of water while the Hondo and Culebra also exhibit similar amounts.

TABLE 4

Stream Level NDVI

VARIABLES	(1) Mean NDVI	(2) Mean NDVI	(3) Mean NDVI	(4) Mean NDVI	(5) Mean NDVI
Acre Feet (1000s)	0.00211	0.00282*	0.00356***	0.0100***	0.00516***
	(0.00341)	(0.00145)	(0.000678)	(0.00199)	(0.000951)
Acre Feet (1000s) = L,	0.000112	-0.00112	0.000176	0.000110	1.93e-05
	(0.00383)	(0.00149)	(0.000531)	(0.00207)	(0.000648)
Year	0.000599	0.00108	-0.00272***	-0.00251*	-0.00301***
	(0.00138)	(0.00107)	(0.000827)	(0.00139)	(0.000910)
Colorado Interactions					
Acre Feet (1000s)					-0.00323**
					(0.00142)
Acre Feet (1000s) = L,					-0.00117
					(0.00175)
Year					0.00393***
					(0.00129)
Observations	28	28	28	28	112
R-squared	0.061	0.088	0.704	0.741	0.772
Breush-Godfrey p-value	0.959	0.826	0.686	0.354	
Stream	Culebra	Costilla	Hondo	Lucero	All
State	Colorado		New Mexico		Both

Note: Average NDVI is the dependent variable. Acre Feet is the total volume of water on the stream from April to October. Precipitation and temperature are additional, unreported controls. Each Column presents a separate regression for the stream indicated. The final column pools the observations, includes stream fixed effects, and allows the coefficients to vary across states. Robust standard errors in parantheses.
*** p<0.01, ** p<0.05, * p<0.1

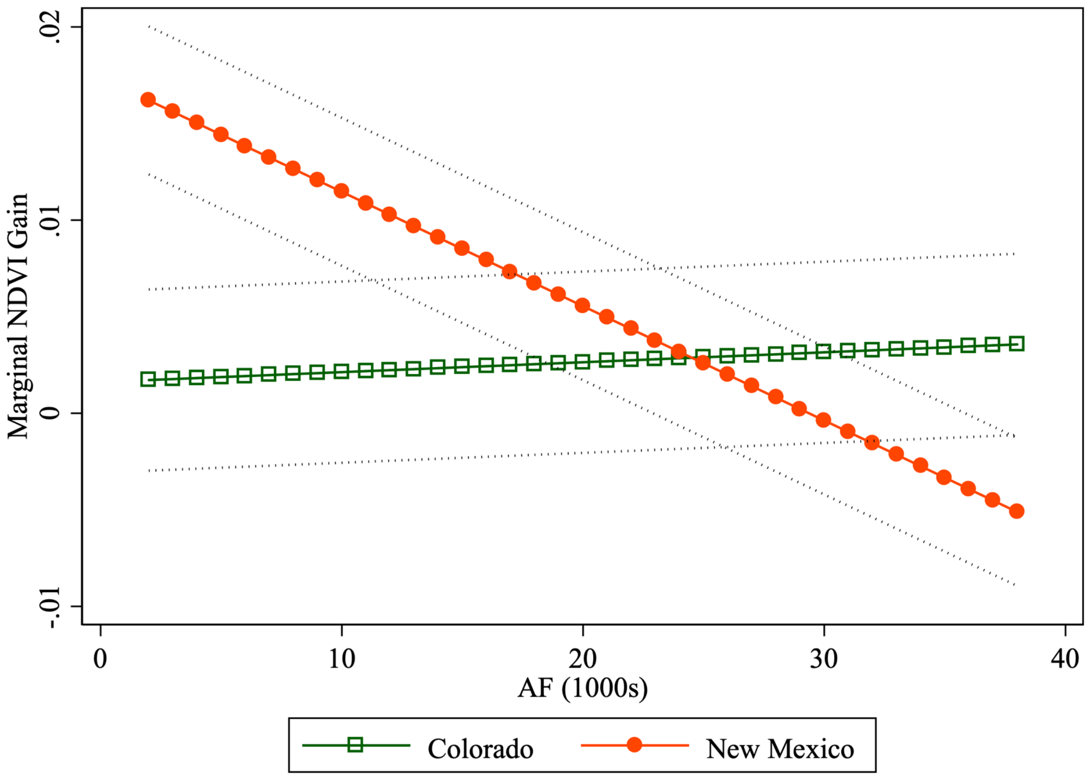
A series of robustness checks are reported in Table C3 of the appendix. Results are not particularly sensitive to the inclusion of the year trend, lagged water supply, year trend, weather variables, lagged dependent variable, or the exclusion of 1984 – which has a notably lower NDVI in Colorado despite a higher water supply. Furthermore, calculating NDVI on the most senior streams only or running the regression on the *acequia* observations as a pooled-OLS does not alter the results appreciably.[21] Finally, the results are robust to allowing the water supply to enter the regression in a non-linear fashion. In Figure 5, I plot the estimated marginal gain in

---

[21] Regression using acequia level NDVI are similar, as the independent variables are the same and the dependent variable are nearly the same, differing slightly as the stream level analysis essentially takes a weighted (by area) average of the *acequias* mean while the *acequia* level analysis ignores the weighting, giving equal weight to each *acequia*.

NDVI due to another AF of water with water supply entering as a second-order polynomial.[22] Even in the non-linear specification, the marginal gain in Colorado is not distinguishable from zero while New Mexico shows a positive marginal gain initially and subsequent diminishing marginal gains.

FIGURE 5
ESTIMATED MARGINAL NDVI OF STREAM WATER



Notes: Coefficient estimates of the marginal increase in NDVI due to another 1000 acre-feet of water in the stream. Values are calculated from a quadratic regression of stream volume (see Table C4 in the Appendix). Dashed lines provide the 95th percentile confidence interval
Sources: Authors' estimates, see text.

5.3 Acequia-Level Results

Underlying the model's prediction is that dividing the water equally across ditches means the equimarginal principle is being met and the water is being used efficiently, at least when water is the sole input to production. To better support the model, I consider the production across the various priorities within the streams. First, I regress a version of equation (2) at the *acequia* level (d) and allow the marginal product of stream supply to vary by rank (r):

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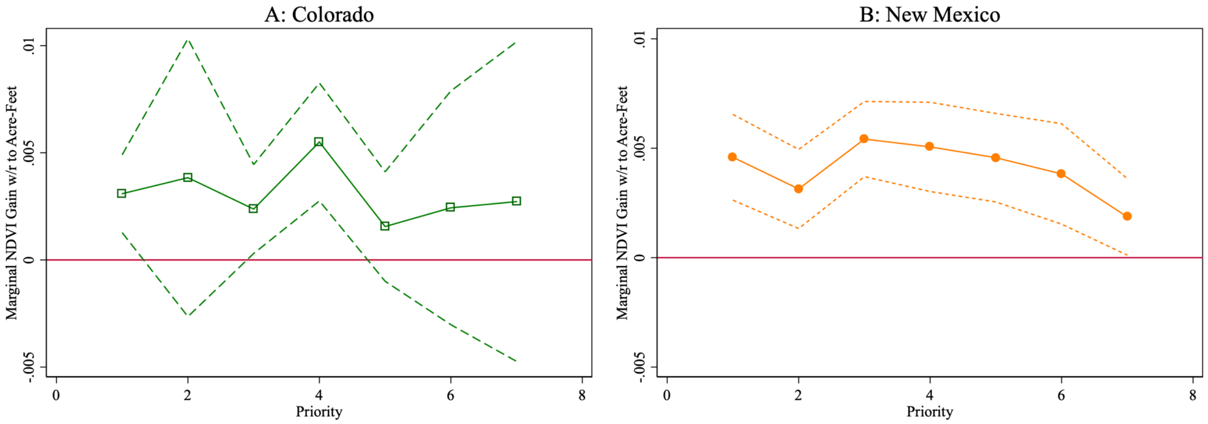
[22] Coefficient estimates of this pooled-regression are provided in Table C4 of Appendix C.

$$NDVI_{dsry} = \alpha_1 + \sum_r (\alpha_{2r} \times r_{ds}) \times AF_{sy} + \sum_r (\alpha_{3r} \times r_{ds}) \times AF_{sy-1} + \alpha_4 \times ppt_{dsry} + \alpha_5 \times temp_{dsry} + \boldsymbol{\mu_d} + e_{dsry} \quad (3)$$

The coefficient estimates are shown in Figure 6 (full results are provided in Table C5 in the appendix).[23] While all point estimates are positive, the estimates in Colorado across priorities is considerably noisier with only two (priorities 1 and 4) being statistically distinct from zero. In contrast, across all priorities in New Mexico additional water in stream has a statistically positive effect on production. When estimated for each stream separately, each *acequia* in New Mexico has a statistically positive marginal value of stream water with a 99th percentile confidence interval; in Colorado, none on the on the Culebra do and only two on the Costilla do. Furthermore, though not always statistically distinct, the marginal value of a given rank is higher in New Mexico other than priority 7. Collectively, this lends more support to the model that the higher marginal productivity across the stream in New Mexico stems, at least in part, from the equimarginal principle being achieved through proportional water sharing.

FIGURE 6
ESTIMATED MARGINAL NDVI OF STREAM WATER BY WATER RIGHT REGIME AND PRIORITY RANK



Notes: Coefficient estimates of the marginal increase in NDVI due to another 1000 acre-feet of water in the stream for individual *acequias* based on priority rank. Full results for the regressions are available in the Appendix (see Table C5). Dashed lines provide the 95th percentile confidence interval
Sources: Authors' estimates, see text.

Given the priority system's effect, it is suggestive that we should expect junior ditches in Colorado to be less productive on average (H4a) and subject to larger temporal variation (H4b). To test this, I use a cross-sectional regression framework:

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[23] Figure C4 includes the more junior ditches in Colorado as well. Most of which do not exhibit a statistically significant gain in NDVI due to more water in the stream either.

$$NDVI_{dr} = \gamma_1 + \gamma_2 \times Col_r + \gamma_3 \times Priority_{dr} + \gamma_4 \times Priority_{dr} \times Col_r + e_{dy} \qquad (4)$$

First, using the temporal average NDVI for the outcome (Panel A of Table 5), there is little support that later *acequias* produce less on average. In fact, there is no detectable decline in Colorado and some evidence of increased production for later *acequias* in New Mexico. This could be driven by other factors not controlled for (topography, soil quality, etc.), and indicative of other endogenous adjustments to variable water supply.[24] However, presented in Panel B, the temporal standard deviation for NDVI is lower for early ditches in Colorado but increases for ditches with lower priority in Colorado, providing support for H3b that these more junior ditches in Colorado experience greater inter-annual volatility.

TABLE 5

Acequia Cross-Sectional Regressions

VARIABLES	(1)	(2)	(3)	(4)	(5)
Panel A: Temporal Average NDVI					
Priority	0.00931	0.0258*	0.0317**	0.00234	0.0199*
	(0.00808)	(0.0118)	(0.0122)	(0.0184)	(0.0105)
Priority x Colorado					-0.00153
					(0.0247)
Colorado					-0.0367
					(0.117)
Constant	0.469***	0.163**	0.315***	0.439***	0.369***
	(0.0412)	(0.0396)	(0.0480)	(0.0740)	(0.0499)
Observations	7	5	7	6	25
R-squared	0.129	0.572	0.496	0.002	0.133
Stream	Culebra	Costilla	Hondo	Lucero	All
Panel B: Temporal Standard Deviation NDVI					
Priority	0.00378***	0.00687	-0.00215	0.00315	-0.000820
	(0.000931)	(0.00503)	(0.00120)	(0.00340)	(0.00253)
Priority x Colorado					0.00587*
					(0.00298)
Colorado					-0.0396***
					(0.0122)
Constant	0.0528***	0.0259	0.0771***	0.0780***	0.0811***
	(0.00325)	(0.0173)	(0.00426)	(0.0183)	(0.0101)
Observations	7	5	7	6	25
R-squared	0.602	0.405	0.322	0.108	0.349
Stream	Culebra	Costilla	Hondo	Lucero	All

Coefficient estimates are from the cross-section regression of equaiton (4) in the text. Panel (A) considers the temporal average NDVI of the *acequia* while panel (B) considers the temporal standard deviation of NDVI for the *acequia*. No other controls are included. Robust standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

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[24] These results are robust to the inclusion of average temperature, precipitation, and total acreage. See Table C6 in the Appendix.

6 Supplementary Survey Support

The empirical evidence is largely supportive of the theoretical model. This section augments the analysis with *acequia* manager surveys that were conducted in both Taos and Costilla Counties in 2013, providing additional context how ditches in the two water right regimes are experiencing and adapting to climate change. The surveys were conducted face-to-face with each interview lasting about an hour. The survey instrument was wide ranging and focused largely on rules of operation (Anderson et al. 2013: see Cody 2019 and Cody 2018 for analyses), but also included a number of questions of concerns and recent adaptations.[25] In Table 6, I provide a summary and comparison of responses for a subset of questions regarding these concerns and adaptations. The rank coefficient indicates whether there is a statistically significant relationship between that item and the order or priority of the *acequias.* [26]

TABLE 6

Survey Variables

		Colorado			**New Mexico**			**Difference**
Variable	Type	Obs	Mean	Rank Coefficient	Obs	Mean	Rank Coefficient	
Concerns								
Water Availability Change 15 years	Categorial (1-5, 5 increasing)	13	1.46		17	1.53		-0.07
Water Availability Change 5 years	Categorial (1-5, 5 increasing)	13	1.54	(-)	18	1.67		-0.13
Drought Concern	Categorial (1-5, 5 greater)	13	4.69		18	4.39		0.30
Water Quality Concern	Categorial (1-5, 5 greater)	11	2.55		18	2.28		0.27
Infrastructure Concern	Categorial (1-5, 5 greater)	13	2.38		18	2.56		-0.17
Snowmelt Timing Concern	Categorial (1-5, 5 increasing)	13	2.69		18	2.67		0.03
Average Concern (water)	Continuous	13	2.33		18	3.11		-0.78
Average Concern (all 15)	Continuous	13	3.38		18	2.10		1.28
Adaptation								
Crop Change 15 years	Binary	13	0.15		17	0.47		-0.32*
Crop Change 5 years	Binary	12	0.17		16	0.38		-0.21
Irrigation Technology Change 15 Years	Binary	13	0.31		11	0.36	(+)	-0.06
Irrigation Technology Change 5 Years	Binary	13	0.08		9	0.67		-0.59***
Irrigated Acres Change 15 years	Categorial (1-5, 5 increasing)	13	2.38	(-)	17	2.12		0.27
Irrigated Acres Change 5 years	Categorial (1-5, 5 increasing)	13	2.15	(-)	17	2.24		-0.08

Note: Descriptive Statistics. Rank Coefficient indicates the sign of coefficient estimates on the priority or order of arrival of the *acequias*. Only those statistically significant at the 10 percent level or higher are indicated. Continous measures are estimated by OLS regressions. Binary measures apply logit estimation. Categorical measures utilize ordered logit regression. Statistically distinct differences in means are indicated by: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Across both regions, *acequias* perceive that the overall water availability has decreased with high levels of concern over future droughts. This, by far, was the greatest concern; water quality and

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[25] The entire survey instrument is available upon request from the author.

[26] For continuous variables, the regressions are estimated by ordinary least squares. For binary variables, regressions are estimated by logit models. And for categorical variables, an ordered logit model is utilized. For the concerns, the average level of concern across all 15 categories for the respondent is included to calibrate to overall subjective concern levels. Note that there was no convergence of the model for Colorado with drought because all but one *acequia* responding with a 5. Point estimates for all are provided in Table C7 of the appendix.

snowmelt timing concerns were secondary. The perceived decline in water availability has no relationship to order in New Mexico but later *acequias* in Colorado perceive greater declines in water availability. This confirms that the appropriation system is being followed and more junior systems face disproportionately greater risk amid weather variability.

In terms of adaptions, nearly half of the New Mexico *acequias* reported changes in cropping patterns over the prior 15 years. This average rate is statistically distinct from the 15 percent of *acequias* in Colorado reporting a similar change. Similarly, ditches in New Mexico were (statistically) more likely to adopt new irrigation technology. Both regions report similar declines in irrigated acreage over the 5- and 15-year time horizons. But in terms of the distribution of these acres, according to the regressions, the decline is more severe for Colorado *acequias* lower in priority.

Overall, the survey results are consistent with the model and preceding empirics. Drought is a major concern going forward, but the decline in water availability appears greater for those with junior rights in the priority system. Colorado has responded more by reducing irrigated acreage, while systems in New Mexico are reducing acreage, changing crops, and altering irrigation techniques. Whether it is preferable to have all ditches adjust in such a manner verses the priority system in which there are fewer changes but some ditches are compelled to reduce irrigated acreage more acutely, depends on the production and social objective function.

7 Conclusion

Property rights to natural resources can be defined and bound in different ways, having impact on the resource's development and use. In arid areas, both proportional rights and priority rights have emerged and scholars have considered the distinct impact of each on waters use and trades. Direct empirical comparison, however, remains lacking due to the endogenous nature of property rights – particularly for the impact on initial investment in the resource. This paper fills this gap by using exogenous historical events which left two groups of irrigation ditches in different water right regimes despite their proximity and shared attributes. Evidence is gathered from three distinct data sets and is generally supportive of the predictions generated by the model. Within a proportional sharing system, later arrivals are not incentivized to curtail capacity and investment, suggesting over capitalization in a proportional system could occur absent other mechanisms to address the investment decision. However, water maintains a higher marginal product in the proportional system, seemingly from the equal division of the water.

The empirical analysis improves our understanding of the underlying performance of distinctly bounded water right alternatives. This is increasingly important as water supplies are altered by climate change (Ficklin et al. 2015, Williams et al. 2015, Rodell et al. 2018) and calls to shift from one system to the other grow (e.g. Young 2014). Convincing senior appropriators to make this adjustment in property rights, however, is a tall order and it remains that in other settings with heterogenous drought-sensitive investments the priority system may yet offer necessary security (and higher production). But the results are not only applicable to water and as new demands for resources emerge, these findings can also help inform the implications of distinct bounding of property rights. Most relevant is the similarly stochastic and variable flows of wind for which property rights are not yet established.

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Appendix A: Mathematical Proofs

Proof for diversion for a given amount of prior capacity (Proposition 1):

If the ith appropriator assumes they will be the final, then when deciding how much capacity to build they will choose $\bar{a}_i^{cs}$ to maximize expected profit given A_{i-1}.

$$\max_{\bar{a}_i^{cs}} E^{cs}(\pi^i) = \int_0^{A_i^{cs}} \pi\left(\frac{\bar{a}_i^{cs}}{A_i^{cs}}\, x, \bar{a}_i^{cs}\right) f(x)dx + [1 - F(A_i^{cs})]\pi(\bar{a}_i^{cs}, \bar{a}_i^{cs})$$

Taking the derivative we obtain the first order condition as follows:

$$\begin{aligned}[1 - F(A_i^{cs})][\pi_1(\bar{a}_i^{cs}, \bar{a}_i^{cs}) + \pi_2(\bar{a}_i^{cs}, \bar{a}_i^{cs})] \\ + \int_0^{A_i^{cs}} \left[\frac{x}{A_i^{cs}} - \frac{\bar{a}_i^{cs}}{(A_i^{cs})^2}\, x\right] \pi_1\left(\frac{\bar{a}_i^{cs}}{A_i^{cs}}\, x, \bar{a}_i^{cs}\right) f(x)dx \\ + \int_0^{A_i^{cs}} \pi_2\left(\frac{\bar{a}_i^{cs}}{A_i^{cs}}\, x, \bar{a}_i^{cs}\right) f(x)dx = 0\end{aligned}$$

In the prior appropriation world, the appropriator is also maximizing their expected profit. BQ find the condition to be:

$$\pi_2(\bar{a}_i^{pa}) + [1 - F(A_i^{pa})]\pi_1(\bar{a}_i^{pa}) = 0$$

Therefore, the two conditions are equal to one another because they are both set equal to zero. Furthermore, iff the profit function remained separable, $\pi_2(z, w) = \pi_2(w)$ and $\pi_2(w) = -C'(w)$, as pointed out by BQ for the pa world. Here, this cannot be done, but we can note that $\pi_2(z, w) = \frac{z}{A_i^{cs}} R'(z) - C'(w) > \pi_2(w)$. Therefore, we can write:

$$\pi_2(\bar{a}_i^{cs}) + [1 - F(A_i^{cs})]\pi_1(\bar{a}_i^{cs}) + \int_0^{A_i^{cs}} \left[\frac{x}{A_i^{cs}} - \frac{\bar{a}_i^{cs}}{(A_i^{cs})^2}\, x\right] \pi_1\left(\frac{\bar{a}_i^{cs}}{A_i^{cs}}\, x, \bar{a}_i^{cs}\right) f(x)dx < 0$$

Furthermore, because $\left[\frac{x}{A_i^{cs}} - \frac{\bar{a}_i^{cs}}{(A_i^{cs})^2}\, x\right] > 0$

$$\int_0^{A_i^{cs}} \left[\frac{x}{A_i^{cs}} - \frac{\bar{a}_i^{cs}}{(A_i^{cs})^2}\, x\right] \pi_1\left(\frac{\bar{a}_i^{cs}}{A_i^{cs}}\, x, \bar{a}_i^{cs}\right) f(x)dx > 0$$

It must be the case that

$$\pi_2(\bar{a}_i^{cs}) + [1 - F(A_i^{cs})]\pi_1(\bar{a}_i^{cs}) < \pi_2(\bar{a}_i^{pa}) + [1 - F(A_i^{pa})]\pi_1(\bar{a}_i^{pa})$$

Now assume that $\bar{a}_i^{cs} \leq \bar{a}_i^{pa}$. This implies two things: 1) $A_i^{cs} \leq A_i^{pa}$, meaning that $F(A_i^{cs}) \leq F(A_i^{pa})$ and $[1 - F(A_i^{cs})] \geq [1 - F(A_i^{pa})]$ and 2) $\pi_2(\bar{a}_i^{cs}) \geq \pi_2(\bar{a}_i^{pa})$ assuming we are choosing diversion capacity where $\bar{a}_i > \bar{a}_i^*$ such that marginal costs are increasing. From these two implications, in order for the above inequality to hold we have that:

$$\pi_1(\bar{a}_i^{cs}) \leq \pi_1(\bar{a}_i^{pa})$$

However, given that $\bar{a}_i^{cs} \leq \bar{a}_i^{pa}$, and that $\pi_{11}^i < 0$ due to decreasing marginal returns to water, we have that:

$$\pi_1(\bar{a}_i^{cs}) > \pi_1(\bar{a}_i^{pa})$$

Hence, we have found a contradiction, meaning our assumption cannot be true that $\bar{a}_i^{cs} \leq \bar{a}_i^{pa}$, meaning that instead, $\bar{a}_i^{cs} > \bar{a}_i^{pa}$. In other words, given the same amount of prior diversion structure constructed, the next entrant will construct larger capacity in a world where division is based on proportional sharing than where it is a strict prior appropriation system. Not only does this yield over capitalization for individual i, their construction also decreases the profits of everyone that entered before them, leading to greater inefficiency in aggregate diversions.

Proof for Regional Profit (Proposition 2):

As is indicated by proposition 5 in BQ, the inefficient division of water in the priority system results in a lower expected profit at the regional level than with the communal sharing. To derive comparisons, we will assume a fixed capacity and equal diversions and focus only on the division rule. Let. y be the total stream flow and x be the stream flow available to the marginal irrigator under the priority scheme.

$$\pi^{pa}(y) = \sum_{i \le y/\bar{a}} \pi(\bar{a}, \bar{a}) + \pi(x, \bar{a}) + \sum_{i > y/\bar{a}+1} \pi(0, \bar{a})$$

And

$$\pi^{cs}(y) = \sum_{i \le y/\bar{a}} \pi\left(\frac{1}{N}y, \bar{a}\right) + \pi\left(\frac{1}{N}y, \bar{a}\right) + \sum_{i > y/\bar{a}+1} \pi\left(\frac{1}{N}y, \bar{a}\right) = N\pi\left(\frac{1}{N}y, \bar{a}\right)$$

Let k represent the marginal irrigator under the priority system, in other words, $(k-1)\bar{a} \le y < k\bar{a}$. At this flow, $\pi^{cs}(y) = \pi^{pa}(y) + (k-1)\left[\pi\left(\frac{1}{N}(x+(k-1)\bar{a}), \bar{a}\right) - \pi(\bar{a}, \bar{a})\right] + \left[\pi\left(\frac{1}{N}(x+(k-1)\bar{a}), \bar{a}\right) - \pi(x, \bar{a})\right] + (N-k)\left[\pi\left(\frac{1}{N}(x+(k-1)\bar{a}), \bar{a}\right) - \pi(0, \bar{a})\right]$. Assume $k = 1$.

$$\left[\pi\left(\frac{1}{N}(x), \bar{a}\right) - \pi(x, \bar{a})\right] + (N-1)\left[\pi\left(\frac{1}{N}(x), \bar{a}\right) - \pi(0, \bar{a})\right] \ge 0$$

This implies that for $k = 1$, $\pi^{cs}(y) \ge \pi^{pa}(y)$, with strict inequality so long as , $N > 1$.

When moving from k to $k+1$, the relative profit gains are:

$$\Delta\pi^{pa} = \pi(\bar{a}, \bar{a}) - \pi(0, \bar{a})$$

And

$$\Delta\pi^{cs} = N[\pi\left(\frac{1}{N}(x+k\bar{a}), \bar{a}\right) - \pi\left(\frac{1}{N}(x+(k-1)\bar{a}), \bar{a}\right)]$$

For profits under the priority system to raise above that under the communal sharing, the gain needs to be greater than the communal gain plus the gap already built. We would need to assume that

$\pi(\bar{a}, \bar{a}) - \pi(0, \bar{a}) > N[\pi\left(\frac{1}{N}(x+k\bar{a}), \bar{a}\right) - \pi\left(\frac{1}{N}(x+(k-1)\bar{a}), \bar{a}\right)] + (k-1)\left[\pi\left(\frac{1}{N}(x+(k-1)\bar{a}), \bar{a}\right) - \pi(\bar{a}, \bar{a})\right] + \left[\pi\left(\frac{1}{N}(x+(k-1)\bar{a}), \bar{a}\right) - \pi(x, \bar{a})\right] + (N-k)\left[\pi\left(\frac{1}{N}(x+(k-1)\bar{a}), \bar{a}\right) - \pi(0, \bar{a})\right]$.

If $k = 0$, meaning there is no water whatsoever and $\pi^{cs}(0) = \pi^{pa}(0)$. As shown above, when $k = 1$, $\pi^{cs}(y) > \pi^{pa}(y)$. That implies that that when $k = 0$, moving to $k = 1$,

$$0 \leq N\left[\pi\left(\frac{1}{N}(x + k\bar{a}), \bar{a}\right)\right] - (k)[\pi(\bar{a}, \bar{a})] - \pi(x, \bar{a}) - (N - (k + 1)\pi(0, \bar{a}).$$

Now assume this holds for k, and we need to show it holds for $k + 1$. Begin by assuming opposite:

$$\begin{aligned}&\pi(\bar{a}, \bar{a}) - \pi(0, \bar{a}) \\ &\qquad > N\left[\pi\left(\frac{1}{N}(x + (k + 1)\bar{a}), \bar{a}\right)\right] - (k)[\pi(\bar{a}, \bar{a})] - \pi(x, \bar{a}) - (N - (k + 1))\pi(0, \bar{a})\end{aligned}$$

Which becomes:

$$0 > N\left[\pi\left(\frac{1}{N}(x + (k + 1)\bar{a}), \bar{a}\right)\right] - (k - 1)[\pi(\bar{a}, \bar{a})] - \pi(x, \bar{a}) - (N - (k))\pi(0, \bar{a})$$

Which becomes:

$$\begin{aligned}0 > {} & N\left[\pi\left(\frac{1}{N}(x + (k)\bar{a}), \bar{a}\right)\right] - (k)[\pi(\bar{a}, \bar{a})] - \pi(x, \bar{a}) - \big(N - (k + 1)\big)\pi(0, \bar{a}) \\ &+ N\left[\pi\left(\frac{1}{N}(x + (k + 1)\bar{a}), \bar{a}\right) - \pi\left(\frac{1}{N}(x + (k)\bar{a}), \bar{a}\right)\right] + [\pi(\bar{a}, \bar{a}) - \pi(0, \bar{a})]\end{aligned}$$

From our assumption above, we know $0 \leq N\left[\pi\left(\frac{1}{N}(x + k\bar{a}), \bar{a}\right)\right] - (k)[\pi(\bar{a}, \bar{a})] - \pi(x, \bar{a}) - (N - (k + 1)\pi(0, \bar{a})$. Furthermore, because $\pi_1 > 0$, $N\left[\pi\left(\frac{1}{N}(x + (k + 1)\bar{a}), \bar{a}\right) - \pi\left(\frac{1}{N}(x + (k)\bar{a}), \bar{a}\right)\right] > 0$ and $[\pi(\bar{a}, \bar{a}) - \pi(0, \bar{a})] > 0$. This presents a contradiction, meaning

$$\begin{aligned}&\pi(\bar{a}, \bar{a}) - \pi(0, \bar{a}) \\ &\qquad \leq N\left[\pi\left(\frac{1}{N}(x + (k + 1)\bar{a}), \bar{a}\right)\right] - (k)[\pi(\bar{a}, \bar{a})] - \pi(x, \bar{a}) - (N - (k + 1))\pi(0, \bar{a})\end{aligned}$$

Therefore, $\pi^{cs}(y) \geq \pi^{pa}(y)$ for all y with strict inequality if $N > 1$.

Proof for Regional Marginal Profit (Proposition 3):

Begin with the profit functions:

$$\pi^{pa}(x) = \sum_{i \leq x/\bar{a}} \pi(\bar{a}, \bar{a}) + \pi(x - i \times int(x/\bar{a}), \bar{a}) + \sum_{i > x/\bar{a}+1} \pi(0, \bar{a})$$

And

$$\pi^{cs}(x) = \sum_{i \leq x/\bar{a}} \pi\left(\frac{1}{N}x, \bar{a}\right) + \pi\left(\frac{1}{N}x, \bar{a}\right) + \sum_{i > x/\bar{a}+1} \pi\left(\frac{1}{N}x, \bar{a}\right) = N\pi\left(\frac{1}{N}x, \bar{a}\right)$$

Therefore,

$$\frac{d\pi^{pa}}{dx} = \pi_1(x - A_{i-1}, \bar{a}), \text{for } A_{i-1} \leq x < A_i$$

And

$$\frac{d\pi^{cs}}{dx} = \pi_1(\frac{1}{N}x, \bar{a})$$

At any moment, if $\frac{1}{N}x < x - A_{i-1}$, then $\frac{d\pi^{cs}}{dx} > \frac{d\pi^{pa}}{dx}$ because $\pi_2 < 0$. This condition holds while $A_{i-1} \leq x < A_i$ if $x > a(i-1)\left(\frac{N}{N-1}\right)$. So in expected terms, if $F\left(\bar{a}(i-1)\left(\frac{N}{N-1}\right)\right) < 0.5$, $\frac{d\pi^{cs}}{dx} > \frac{d\pi^{pa}}{dx}$ for $\bar{a}(i-1) \leq x < \bar{a}(i)$. Because $F(x)$ is non-decreasing, this implies the marginal gain under the priority system can be expected to be greater as i increases and N increases relative to the communal sharing system.

Proof for total diversion structure:

An entrant will only enter if $E\left(\pi^{i}\right) > 0$. Assuming risk neutrality, we simply want to see if given a certain capacity of diversions already constructed, does it remain profitable to enter. To begin, assume contrary to the above proof and let $\bar{a}_i{}^{cs} = \bar{a}_i{}^{pa}$. Let us pick irrigator k such that under the priority system,

$$E^{pa}(\pi^{k}) = \int_{0}^{A_{k-1}} \pi(0, \bar{a}_k) f(x)dx + \int_{A_{k-1}}^{A_k} \pi(x - A_{k-1}, \bar{a}_k) f(x)dx + [1 - F(A_k)]\pi(\bar{a}_k, \bar{a}_k) + \varepsilon$$

$$= 0$$

Such that it is just non-profitable to enter, and we can see whether the same irrigator would have under the communal sharing system.

$$E^{cs}(\pi^{k}) = \int_{0}^{A_{k-1}} \pi\left(\frac{\bar{a}_k}{A_k}\, x, \bar{a}_k\right) f(x)dx + \int_{A_{k-1}}^{A_k} \pi\left(\frac{\bar{a}_k}{A_k}\, x, \bar{a}_k\right) f(x)dx + [1 - F(A_k)]\pi(\bar{a}_k, \bar{a}_k)$$

Now consider each term. The final term ($[1 - F(A_k)]\pi(\bar{a}_k, \bar{a}_k)$) is the same for each. Now consider the first term. When $a_k \leq \bar{a}_k$, $\pi_1^k > 0$ by assumption, meaning $\pi\left(\frac{\bar{a}_k}{A_k}\, x, \bar{a}_k\right) > \pi(0, \bar{a}_k)$ for $\forall x$. For the middle term, we begin with the fact that $x \leq A_k$ (or else we would be in the third term). This means $x(\bar{a}_k - A_k) \geq A_k(\bar{a}_k - A_k)$, implying that $x(\frac{\bar{a}_k}{A_k}) \geq (x + \bar{a}_k - A_k)$. Noting that $A_k = A_{k-1} + \bar{a}_k$, we have $x(\frac{\bar{a}_k}{A_k}) \geq (x + \bar{a}_k - A_{k-1} - \bar{a}_k)$, finally establishing that $x(\frac{\bar{a}_k}{A_k}) \geq (x - A_{k-1})$ for $\forall x$. Therefore the middle term is larger in the communal sharing world as well. On net,

$$E^{cs}(\pi^{k}) > E^{pa}(\pi^{k})$$

Therefore, even when it is no longer profitable to enter under the priority system, someone under the communal sharing system would enter. This will result in greater overall diversion capacity constructed under communal sharing. Relaxing the assumption that $\bar{a}_k{}^{cs} = \bar{a}_k{}^{pa}$ maintains the result, as the more profitable decision is to pick $\bar{a}_k{}^{cs} > \bar{a}_k{}^{pa}$, which would only increase $E^{cs}(\pi^{k})$.

Appendix B: Data Appendix

1. *Raw Data Sources:*

Andersson, Krister, Michael E. Cox, Steven M. Smith, and Kelsey C. Cody. 2013. "Manager Questionnaire: Snowmelt dependent systems in the Unites States and Kenya." Collected Summer 2013.

Colorado Division of Water Resources. 2012. "District 24 Call Sheet." Copy obtained during site visit, June 2012.

Colorado's Decision Support System (CDSS). Division 3--rio grande. 2013 [cited 8/24 2013]. Available from http://cdss.state.co.us/GIS/Pages/Division3RioGrande.aspx.

Cox, Michael, Justin M. Ross. 2011 "Robustness and vulnerability of community acequia systems: The case of the Taos valley acequias. *Journal of Environmental and Economic Management.* Vol 61: 254-266

Dos Rios Consultants, Inc. 1996, available: http://bloodhound.tripod.com/ACEQFINL.htm [2012, 5/17].

Office of the State Engineer (OSE). Hydrographic survey maps and reports. 2009 [cited 3/24 2012]. Available from http://www.ose.state.nm.us/legal_ose_hydro_survey_reports_maps.html.

PRISM Climate Group, Oregon State University. 2004, http://prism.oregonstate.edu, created 11 Oct 2014

United States Bureau of the Census. 1930. "Irrigation Schedules". Available at the National Archives, Washington D.C.: Records of the Bureau of the Census, Record Group 29.8.3 "Miscellaneous nonpopulation schedules and supplementary records." Collected May 2016.

United States Geological Survey (USGS). Global Visualization Viewer. Landsat Satellite Images. 2013a https://glovis.usgs.gov (accessed June 15, 2013)

United States Geological Survey (USGS). Streamgage data. 2013b [cited 7/12 2013]. Available from http://waterdata.usgs.gov/nwis/nwisman; (accessed May 13, 2013).

2. *Variable Descriptions:*

2.1. 1930 Irrigation Organization Data

All of the variables are from US Census Irrigation Schedules (United States Bureau of the Census, 1930). Examples of a front side and a backside are provided in figures B1 and B2.

Capacity (CFS): Capacity of the ditch measured in cubic feet per second, Question 16a.

Original Acres: Number of irrigable acres when the project is complete, Question 24.

Length (Miles): Length of the main canals, excluding laterals, Question 16c.

Capital ($): Total irrigation works and equipment, Question 29

Capital per Acre ($): Capital divided by acres (Question 29 and Question 24)

Maintenance Cost ($): Cost of maintenance and operation in 1929, Question 32.

Construction Start Year: Date construction begun, Question 13a.

Lagged (_____): Using the drainage basin (Question 8a) and the Construction Start Year, the order of ditch arrival is determined such that pre-existing measures of each variable above (save for the construction year) can be calculated for each basin.

2.2. NDVI and Stream analysis

NDVI (Stream): Using the ArcGIS Spatial Statistic Tool, the average NDVI raster values (USGS 2013a and Cox & Ross 2011) are calculated for all *acequias* on a given stream using GIS shape files (Colorado: CDSS 2013; New Mexico: OSE 2009). Images draw from a cloudless image within the growing season from 1984 to 2011.

NDVI (Acequia): Using the ArcGIS Spatial Statistic Tool, the average NDVI raster values (USGS 2013a and Cox & Ross 2011) are calculated for each individual *acequia* on a given stream using GIS shape files (Colorado: CDSS 2013; New Mexico: OSE 2009). Images draw from a cloudless image within the growing season from 1984 to 2011.

NDVI (Acequia-Mean): The mean of the annual *NDVI (Acequia)* measure above for 1984 to 2011.

NDVI (Acequia Temporal SD): The standard deviation of the annual *NDVI (Acequia)* measure above for 1984 to 2011.

Acre-Feet: The volume of water flowing past a stream gauge for growing season (April-October). Daily flow is collected from USGS Gauges (2013b) [Culebra, USGS Gauge 08250000; Costilla, USGS Gauge 08261000; Hondo, USGS Gauge 08267500; Lucero, USGS Gauge 08271000]. This measure is in flow (cubic feet per second) and is converted to acre-feet by assuming the flow was constant for the day and aggregating the entire day and then adding up the days from April to October for each year. Data goes back to 1913.

Priority Year: For Colorado ditches, this comes from administrative records that are crosschecked to various other sources, but are taken from the District 24 call sheet (Colorado Division of Water Resources, 2012). For New Mexico, where priority is not practiced, the priority years are taken from Dos Rios Consultants Inc. (1996), which compiled dates for all *acequias* in New Mexico from a wide array of sources.

Priority Rank: Using the priority year, this measure ranks the ditches from earliest to latest on a given water source. Higher ranked (#1) ditches are the earliest and “first in line” under the priority system.

Acres: Size of the of the *acequia* polygons from the GIS files (CDSS 2013, OSE 2009).

Precipitation: Monthly data gathered from PRISM (2004). For each month, the values at the centroid of the *acequia* (CDSS 2013, OSE 2009) are extracted in ArcGIS. Monthly totals from April to July (the latest NDVI measure) are summed up for each year.

Temperature: Monthly data gathered from PRISM (2004). For each month, the values at the centroid of the *acequia* (CDSS 2013, OSE 2009) are extracted in ArcGIS. Monthly average temperature from April to July (the latest NDVI measure) are averaged for each year.

2.3. Survey analysis

All variables are responses to an original survey instrument, available upon request from the author. Surveys were conducted in 2013. The Colorado sample was part of a 64-ditch stratified-random sample across the entire San Luis Valley, CO for which *acequia* status was one dimension targeted. In Taos, New Mexico, where only *acequias* operate the sample was random with some resampling if an *acequia* could not participate.

Water availability Change (X) years: "How have the following changed: Water availability (5 and 15 years)?" (1-greatly decreased, 2-slightly decreased, 3-no change, 4-slightly increased, 5-greatly increased)

Crop Change (X) years: "Did the most important crops to your association change substantially in the past (5 and 15) years?" Yes=1, No=0.

Irrigation Technology Change (X) years: "How have the following changed: irrigation technology (5 and 15 years)?" (1-new adopted, 0-no change)

Irrigate Acres Change (X) years: "How have the following changed: acres irrigated (5 and 15 years)?" (1-greatly decreased, 2-slightly decreased, 3-no change, 4-slightly increased, 5-greatly increased)

The following concerns are used directly from a single table which, among other things: "For the disturbance identified, please fill out each of the subsequent columns: For each of the threat, identify the extent to which the threat is problematic for your association, rating this from 1 to 5 (5=very problematic, 1=not very problematic):

Drought: "For the disturbance identified (drought), please fill out each of the subsequent columns: For each of the threat, identify the extent to which the threat is problematic for your association, rating this from 1 to 5 (5=very problematic, 1=not very problematic)

Water Quality: "For the disturbance identified (water quality), please fill out each of the subsequent columns: For each of the threat, identify the extent to which the threat is problematic for your association, rating this from 1 to 5 (5=very problematic, 1=not very problematic)

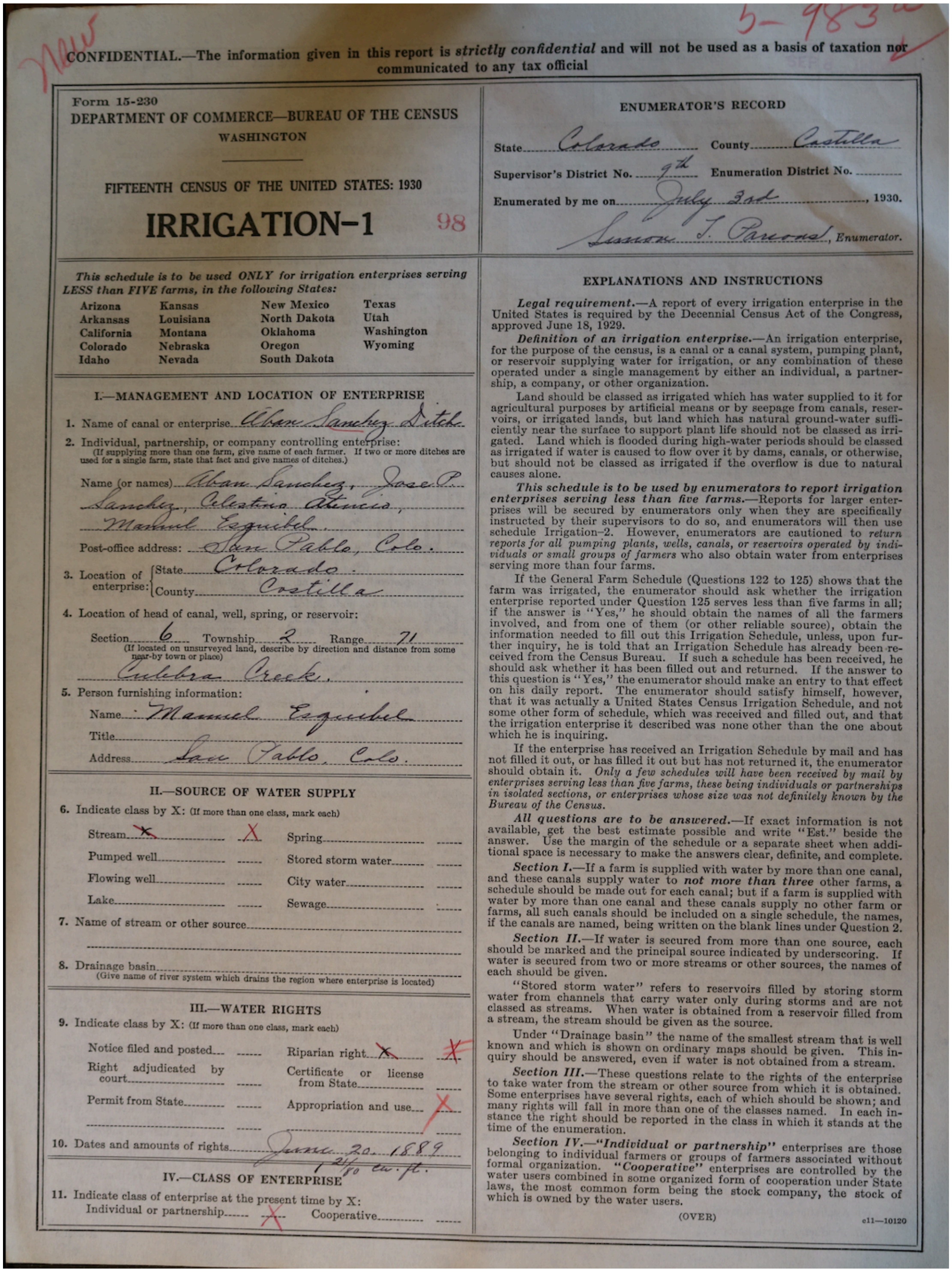
Snowmelt Timing: "For the disturbance identified (snowmelt timing), please fill out each of the subsequent columns: For each of the threat, identify the extent to which the threat is problematic for your association, rating this from 1 to 5 (5=very problematic, 1=not very problematic)

Infrastructure: "For the disturbance identified (infrastructure), please fill out each of the subsequent columns: For each of the threat, identify the extent to which the threat is problematic for your association, rating this from 1 to 5 (5=very problematic, 1=not very problematic)

Average Concern (water): Averages the first 3 concerns listed above (drought, water quality, snowmelt timing) price of water and municipal exports.

Average Concern (all 15): Average of the 3 water concerns and the 12 others: infrastructure, fire, soil fertility, price of agriculture inputs, price of water, municipal (water) exports, availability of land, regulatory changes, agricultural commodity prices, access to capital, environmental groups, urban encroachment

FIGURE B1
FRONT SIDE OF THE 1930 IRRIGATION SCHEDULE



New

5-983

CONFIDENTIAL.—The information given in this report is *strictly confidential* and will not be used as a basis of taxation nor communicated to any tax official

Form 15-230
DEPARTMENT OF COMMERCE—BUREAU OF THE CENSUS
WASHINGTON

FIFTEENTH CENSUS OF THE UNITED STATES: 1930

IRRIGATION-1

98

This schedule is to be used ONLY for irrigation enterprises serving LESS than FIVE farms, in the following States:

Arizona	Kansas	New Mexico	Texas
Arkansas	Louisiana	North Dakota	Utah
California	Montana	Oklahoma	Washington
Colorado	Nebraska	Oregon	Wyoming
Idaho	Nevada	South Dakota	

I.—MANAGEMENT AND LOCATION OF ENTERPRISE

1. Name of canal or enterprise Alban Sanchez Ditch
2. Individual, partnership, or company controlling enterprise: (If supplying more than one farm, give name of each farmer. If two or more ditches are used for a single farm, state that fact and give names of ditches.)

Name (or names) Alban Sanchez, Jose P. Sanchez, Celestino Atencio, Manuel Esquibel.
Post-office address: San Pablo, Colo.

3. Location of enterprise: State Colorado. County Costilla
4. Location of head of canal, well, spring, or reservoir:

Section 6 Township 2 Range 71
(If located on unsurveyed land, describe by direction and distance from some near-by town or place)
Culebra Creek.

5. Person furnishing information:

Name Manuel Esquibel
Title
Address San Pablo, Colo.

II.—SOURCE OF WATER SUPPLY

6. Indicate class by X: (If more than one class, mark each)

Stream X	X	Spring	
Pumped well		Stored storm water	
Flowing well		City water	
Lake		Sewage	

7. Name of stream or other source
8. Drainage basin
(Give name of river system which drains the region where enterprise is located)

III.—WATER RIGHTS

9. Indicate class by X: (If more than one class, mark each)

Notice filed and posted		Riparian right X	X
Right adjudicated by court		Certificate or license from State	
Permit from State		Appropriation and use	X

10. Dates and amounts of rights June 20. 1889
1 24/80 cu. ft.

IV.—CLASS OF ENTERPRISE

11. Indicate class of enterprise at the present time by X:
Individual or partnership X Cooperative

ENUMERATOR'S RECORD

State Colorado County Castilla
Supervisor's District No. 9th Enumeration District No.
Enumerated by me on July 3rd, 1930.
Simon T. Parsons, Enumerator.

EXPLANATIONS AND INSTRUCTIONS

Legal requirement.—A report of every irrigation enterprise in the United States is required by the Decennial Census Act of the Congress, approved June 18, 1929.

Definition of an irrigation enterprise.—An irrigation enterprise, for the purpose of the census, is a canal or a canal system, pumping plant, or reservoir supplying water for irrigation, or any combination of these operated under a single management by either an individual, a partnership, a company, or other organization.

Land should be classed as irrigated which has water supplied to it for agricultural purposes by artificial means or by seepage from canals, reservoirs, or irrigated lands, but land which has natural ground-water sufficiently near the surface to support plant life should not be classed as irrigated. Land which is flooded during high-water periods should be classed as irrigated if water is caused to flow over it by dams, canals, or otherwise, but should not be classed as irrigated if the overflow is due to natural causes alone.

This schedule is to be used by enumerators to report irrigation enterprises serving less than five farms.—Reports for larger enterprises will be secured by enumerators only when they are specifically instructed by their supervisors to do so, and enumerators will then use schedule Irrigation-2. However, enumerators are cautioned to *return reports for all pumping plants, wells, canals, or reservoirs operated by individuals or small groups of farmers* who also obtain water from enterprises serving more than four farms.

If the General Farm Schedule (Questions 122 to 125) shows that the farm was irrigated, the enumerator should ask whether the irrigation enterprise reported under Question 125 serves less than five farms in all; if the answer is "Yes," he should obtain the names of all the farmers involved, and from one of them (or other reliable source), obtain the information needed to fill out this Irrigation Schedule, unless, upon further inquiry, he is told that an Irrigation Schedule has already been received from the Census Bureau. If such a schedule has been received, he should ask whether it has been filled out and returned. If the answer to this question is "Yes," the enumerator should make an entry to that effect on his daily report. The enumerator should satisfy himself, however, that it was actually a United States Census Irrigation Schedule, and not some other form of schedule, which was received and filled out, and that the irrigation enterprise it described was none other than the one about which he is inquiring.

If the enterprise has received an Irrigation Schedule by mail and has not filled it out, or has filled it out but has not returned it, the enumerator should obtain it. *Only a few schedules will have been received by mail by enterprises serving less than five farms, these being individuals or partnerships in isolated sections, or enterprises whose size was not definitely known by the Bureau of the Census.*

All questions are to be answered.—If exact information is not available, get the best estimate possible and write "Est." beside the answer. Use the margin of the schedule or a separate sheet when additional space is necessary to make the answers clear, definite, and complete.

Section I.—If a farm is supplied with water by more than one canal, and these canals supply water to ***not more than three*** other farms, a schedule should be made out for each canal; but if a farm is supplied with water by more than one canal and these canals supply no other farm or farms, all such canals should be included on a single schedule, the names, if the canals are named, being written on the blank lines under Question 2.

Section II.—If water is secured from more than one source, each should be marked and the principal source indicated by underscoring. If water is secured from two or more streams or other sources, the names of each should be given.

"Stored storm water" refers to reservoirs filled by storing storm water from channels that carry water only during storms and are not classed as streams. When water is obtained from a reservoir filled from a stream, the stream should be given as the source.

Under "Drainage basin" the name of the smallest stream that is well known and which is shown on ordinary maps should be given. This inquiry should be answered, even if water is not obtained from a stream.

Section III.—These questions relate to the rights of the enterprise to take water from the stream or other source from which it is obtained. Some enterprises have several rights, each of which should be shown; and many rights will fall in more than one of the classes named. In each instance the right should be reported in the class in which it stands at the time of the enumeration.

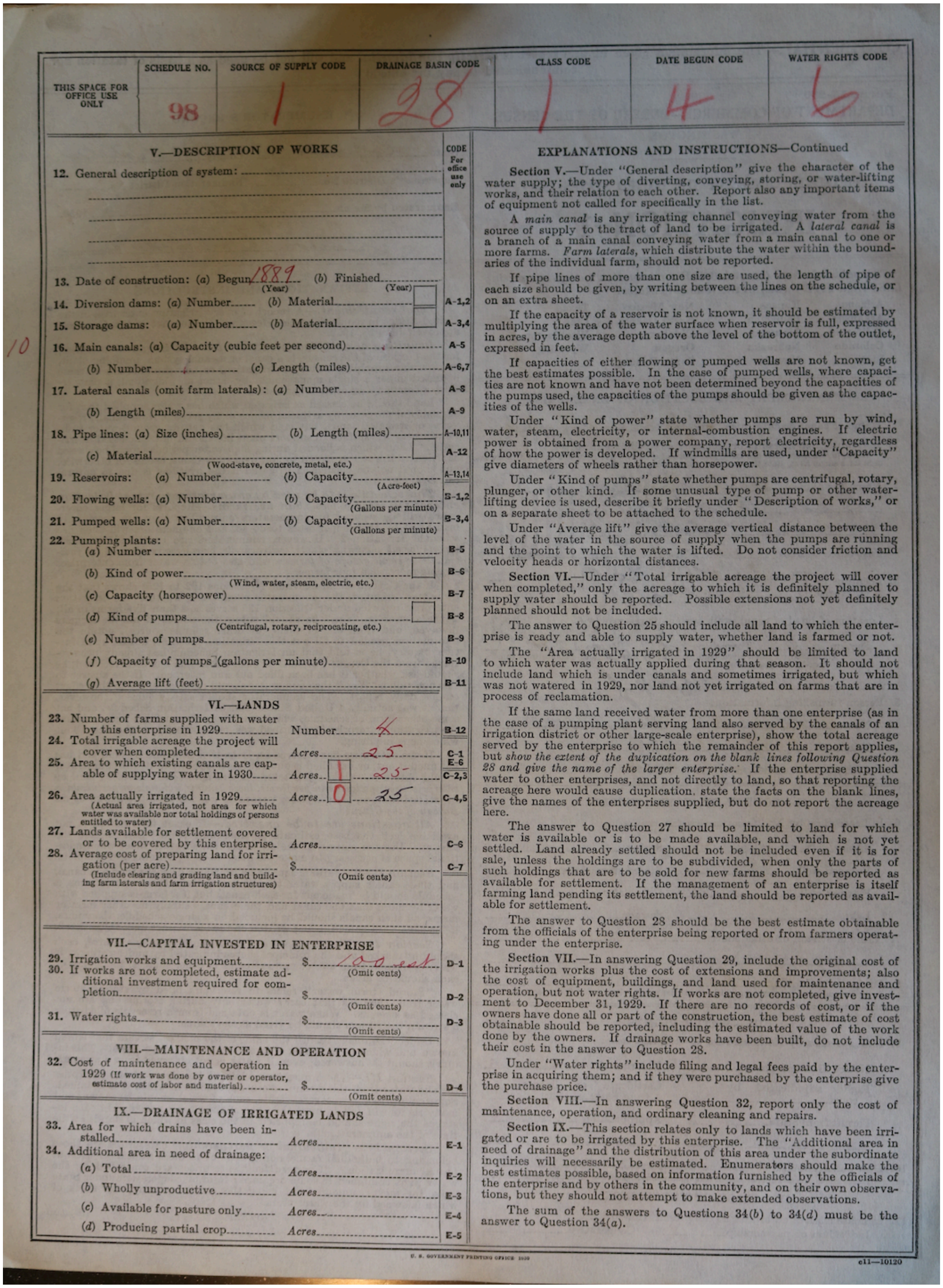
Section IV.—"Individual or partnership" enterprises are those belonging to individual farmers or groups of farmers associated without formal organization. ***"Cooperative"*** enterprises are controlled by the water users combined in some organized form of cooperation under State laws, the most common form being the stock company, the stock of which is owned by the water users.

(OVER)

e11—10120

Notes: Photo of original record captured in 2016.
Sources: National Archives, Record Group 29.8.3 "Miscellaneous nonpopulation schedules and supplementary records."

FIGURE B2
BACK SIDE OF THE 1930 IRRIGATION SCHEDULE



THIS SPACE FOR OFFICE USE ONLY	SCHEDULE NO.	SOURCE OF SUPPLY CODE	DRAINAGE BASIN CODE	CLASS CODE	DATE BEGUN CODE	WATER RIGHTS CODE
	98	1	28	1	4	6

V.—DESCRIPTION OF WORKS

CODE For office use only

12. General description of system:

13. Date of construction: (a) Begun 1889 (Year) (b) Finished (Year)
14. Diversion dams: (a) Number (b) Material ☐ A-1,2
15. Storage dams: (a) Number (b) Material ☐ A-3,4
10 16. Main canals: (a) Capacity (cubic feet per second) A-5
(b) Number (c) Length (miles) A-6,7
17. Lateral canals (omit farm laterals): (a) Number A-8
(b) Length (miles) A-9
18. Pipe lines: (a) Size (inches) (b) Length (miles) A-10,11
(c) Material (Wood-stave, concrete, metal, etc.) ☐ A-12
19. Reservoirs: (a) Number (b) Capacity (Acre-feet) A-13,14
20. Flowing wells: (a) Number (b) Capacity (Gallons per minute) B-1,2
21. Pumped wells: (a) Number (b) Capacity (Gallons per minute) B-3,4
22. Pumping plants:
(a) Number B-5
(b) Kind of power (Wind, water, steam, electric, etc.) ☐ B-6
(c) Capacity (horsepower) B-7
(d) Kind of pumps (Centrifugal, rotary, reciprocating, etc.) ☐ B-8
(e) Number of pumps B-9
(f) Capacity of pumps (gallons per minute) B-10
(g) Average lift (feet) B-11

VI.—LANDS

23. Number of farms supplied with water by this enterprise in 1929 Number 4 B-12
24. Total irrigable acreage the project will cover when completed Acres 25 C-1 E-6
25. Area to which existing canals are capable of supplying water in 1930 Acres 1 25 C-2,3
26. Area actually irrigated in 1929 (Actual area irrigated, not area for which water was available nor total holdings of persons entitled to water) Acres 0 25 C-4,5
27. Lands available for settlement covered or to be covered by this enterprise Acres C-6
28. Average cost of preparing land for irrigation (per acre) (Include clearing and grading land and building farm laterals and farm irrigation structures) $ (Omit cents) C-7

VII.—CAPITAL INVESTED IN ENTERPRISE

29. Irrigation works and equipment $ 100 est (Omit cents) D-1
30. If works are not completed, estimate additional investment required for completion $ (Omit cents) D-2
31. Water rights $ (Omit cents) D-3

VIII.—MAINTENANCE AND OPERATION

32. Cost of maintenance and operation in 1929 (If work was done by owner or operator, estimate cost of labor and material) $ (Omit cents) D-4

IX.—DRAINAGE OF IRRIGATED LANDS

33. Area for which drains have been installed Acres E-1
34. Additional area in need of drainage:
(a) Total Acres E-2
(b) Wholly unproductive Acres E-3
(c) Available for pasture only Acres E-4
(d) Producing partial crop Acres E-5

EXPLANATIONS AND INSTRUCTIONS—Continued

Section V.—Under "General description" give the character of the water supply; the type of diverting, conveying, storing, or water-lifting works, and their relation to each other. Report also any important items of equipment not called for specifically in the list.

A *main canal* is any irrigating channel conveying water from the source of supply to the tract of land to be irrigated. A *lateral canal* is a branch of a main canal conveying water from a main canal to one or more farms. *Farm laterals*, which distribute the water within the boundaries of the individual farm, should not be reported.

If pipe lines of more than one size are used, the length of pipe of each size should be given, by writing between the lines on the schedule, or on an extra sheet.

If the capacity of a reservoir is not known, it should be estimated by multiplying the area of the water surface when reservoir is full, expressed in acres, by the average depth above the level of the bottom of the outlet, expressed in feet.

If capacities of either flowing or pumped wells are not known, get the best estimates possible. In the case of pumped wells, where capacities are not known and have not been determined beyond the capacities of the pumps used, the capacities of the pumps should be given as the capacities of the wells.

Under "Kind of power" state whether pumps are run by wind, water, steam, electricity, or internal-combustion engines. If electric power is obtained from a power company, report electricity, regardless of how the power is developed. If windmills are used, under "Capacity" give diameters of wheels rather than horsepower.

Under "Kind of pumps" state whether pumps are centrifugal, rotary, plunger, or other kind. If some unusual type of pump or other water-lifting device is used, describe it briefly under "Description of works," or on a separate sheet to be attached to the schedule.

Under "Average lift" give the average vertical distance between the level of the water in the source of supply when the pumps are running and the point to which the water is lifted. Do not consider friction and velocity heads or horizontal distances.

Section VI.—Under "Total irrigable acreage the project will cover when completed," only the acreage to which it is definitely planned to supply water should be reported. Possible extensions not yet definitely planned should not be included.

The answer to Question 25 should include all land to which the enterprise is ready and able to supply water, whether land is farmed or not.

The "Area actually irrigated in 1929" should be limited to land to which water was actually applied during that season. It should not include land which is under canals and sometimes irrigated, but which was not watered in 1929, nor land not yet irrigated on farms that are in process of reclamation.

If the same land received water from more than one enterprise (as in the case of a pumping plant serving land also served by the canals of an irrigation district or other large-scale enterprise), show the total acreage served by the enterprise to which the remainder of this report applies, but *show the extent of the duplication on the blank lines following Question 28 and give the name of the larger enterprise.* If the enterprise supplied water to other enterprises, and not directly to land, so that reporting the acreage here would cause duplication, state the facts on the blank lines, give the names of the enterprises supplied, but do not report the acreage here.

The answer to Question 27 should be limited to land for which water is available or is to be made available, and which is not yet settled. Land already settled should not be included even if it is for sale, unless the holdings are to be subdivided, when only the parts of such holdings that are to be sold for new farms should be reported as available for settlement. If the management of an enterprise is itself farming land pending its settlement, the land should be reported as available for settlement.

The answer to Question 28 should be the best estimate obtainable from the officials of the enterprise being reported or from farmers operating under the enterprise.

Section VII.—In answering Question 29, include the original cost of the irrigation works plus the cost of extensions and improvements; also the cost of equipment, buildings, and land used for maintenance and operation, but not water rights. If works are not completed, give investment to December 31, 1929. If there are no records of cost, or if the owners have done all or part of the construction, the best estimate of cost obtainable should be reported, including the estimated value of the work done by the owners. If drainage works have been built, do not include their cost in the answer to Question 28.

Under "Water rights" include filing and legal fees paid by the enterprise in acquiring them; and if they were purchased by the enterprise give the purchase price.

Section VIII.—In answering Question 32, report only the cost of maintenance, operation, and ordinary cleaning and repairs.

Section IX.—This section relates only to lands which have been irrigated or are to be irrigated by this enterprise. The "Additional area in need of drainage" and the distribution of this area under the subordinate inquiries will necessarily be estimated. Enumerators should make the best estimates possible, based on information furnished by the officials of the enterprise and by others in the community, and on their own observations, but they should not attempt to make extended observations.

The sum of the answers to Questions 34(b) to 34(d) must be the answer to Question 34(a).

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Notes: Photo of original record captured in 2016.
Sources: National Archives, Record Group 29.8.3 "Miscellaneous nonpopulation schedules and supplementary records."

Appendix C: Additional Figures and Tables

FIGURE C1
INITIAL DELINEATION OF NEW MEXICO TERRITORY, 1852

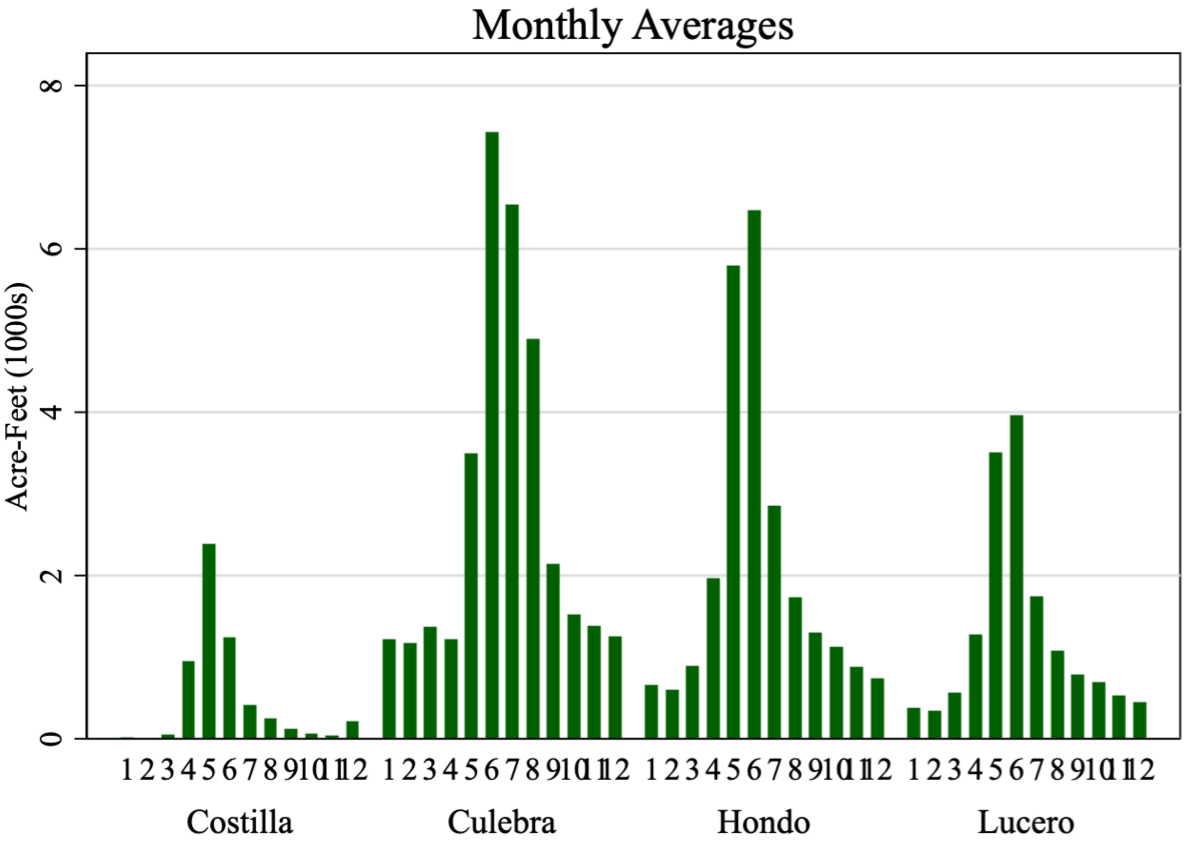
Notes: Original counties are as indicated and subsequent alterations in Territorial/State boundaries are shown
Sources: https://en.wikipedia.org/wiki/File:New_Mexico_Territory,_1852.png#metadata

FIGURE C2
MODERN POLITICAL BOUNDARIES AND TOPOGRAPHY OF *ACEQUIAS*

Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

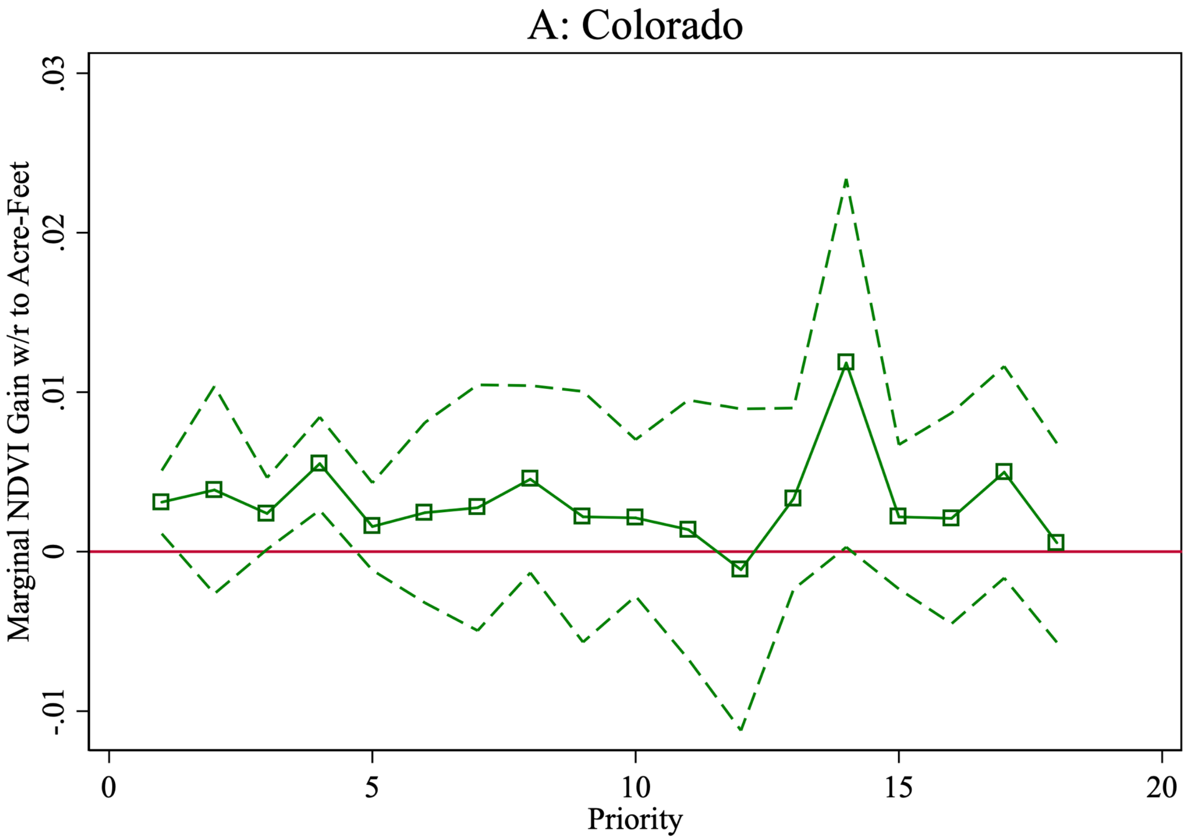
Notes: Overview of the empirical study area showing the location of the *acequias*.
Sources: Authors' rendering of OSE (2009) and CDSS (2013) data.

FIGURE C3
AVERAGE MONTHLY STREAM FLOW, 1983-2011



Notes: For each stream, the average total volume measured by the stream gauge from 1983 to 2011 are plotted.
Sources: Authors' rendering of USGS (2013b) stream gauge data.

FIGURE C4
ESTIMATED MARGINAL NDVI OF STREAM WATER BY PRIORITY FOR ALL COLORADO *ACEQUIAS*



Notes: Coefficient estimates of the marginal increase in NDVI due to another 1000 acre-feet of water in the stream for individual *acequias* based on priority rank in Colorado. Estimates included for *acequias* beyond the primary first 7 ditches. Dashed lines provide the 95th percentile confidence interval

Sources: Authors' estimates, see text.

TABLE C1

1930 Investment Robustness: CFS as Capacity

VARIABLES	(1) Capacity (CFS)	(2) Original Acres	(3) Length (Miles)	(4) Capital ($)	(5) Capital per Acre ($)	(6) Maintenance Costs ($)
Existing CFS	0.144***	-2.983*	0.0251***	49.21***	-0.0160	0.529
	(0.0276)	(1.412)	(0.00655)	(6.751)	(0.0205)	(0.734)
Existing CFS x Colorado	-0.279***	-2.954	-0.0288***	-128.5***	-0.0198	-3.107**
	(0.0340)	(1.917)	(0.00699)	(10.74)	(0.0196)	(1.141)
Observations	98	147	98	147	147	97
R-squared	0.477	0.456	0.442	0.427	0.372	0.407

Regression results for various measures (see data section) of irrigation investment and existing capacity for ditches in Costilla and Taos counties. Regressions utilize existing CFS as the measure of prior investment across all columns. Fixed effects for construction start by 25 year intervals and basin level fixed effects are included in all regressions. Robust standard errors, clustered by basin, in parentheses.

*** p<0.01, ** p<0.05, * p<0.1

TABLE C2

1930 Investment Robustness: Fixed Effects

	(1)	(2)	(3)	(4)	(5)
VARIABLES					
Capacity (CFS)					
Existing Dependent Var	0.0444***	0.0406***	0.0389*	0.144***	0.144***
	(0.0150)	(0.00618)	(0.0183)	(0.0276)	(0.0418)
Existing Dependent Var x Colorado	-0.0162	-0.0114	-0.148***	-0.279***	-0.279***
	(0.0112)	(0.00960)	(0.0331)	(0.0340)	(0.0524)
Observations	98	98	98	98	98
R-squared	0.081	0.187	0.422	0.477	0.477
Original Acres					
Existing Dependent Var	0.0746***	0.0712***	0.0553***	-0.0203	-0.0203
	(0.00376)	(0.00619)	(0.00207)	(0.0237)	(0.122)
Existing Dependent Var x Colorado	-0.0815***	-0.0761***	-0.112***	-0.0600*	-0.0600
	(0.00405)	(0.00634)	(0.00670)	(0.0322)	(0.120)
Observations	147	147	147	147	147
R-squared	0.222	0.311	0.332	0.446	0.446
Length (Miles)					
Existing Dependent Var	0.0420***	0.0327***	-0.0158	0.173***	0.173**
	(0.0115)	(0.0106)	(0.0434)	(0.0474)	(0.0606)
Existing Dependent Var x Colorado	-0.0223	-0.0123	0.00628	-0.199***	-0.199***
	(0.0162)	(0.0123)	(0.0531)	(0.0542)	(0.0572)
Observations	98	98	98	98	98
R-squared	0.085	0.313	0.206	0.461	0.461
Capital ($)					
Existing Dependent Var	0.0329***	0.0368***	0.142***	0.278***	0.278***
	(0.00167)	(0.00540)	(0.0164)	(0.0235)	(0.0615)
Existing Dependent Var x Colorado	-0.0351***	-0.0335***	-0.378***	-0.536***	-0.536***
	(0.00987)	(0.0104)	(0.0186)	(0.0223)	(0.0692)
Observations	147	147	147	147	147
R-squared	0.026	0.089	0.333	0.385	0.385
Capital per Acre ($)					
Existing Dependent Var	0.0212	0.0123	0.00495	0.0538	0.0538
	(0.0282)	(0.0173)	(0.0594)	(0.0574)	(0.0704)
Existing Dependent Var x Colorado	-0.0312	-0.0221	-0.0503	-0.104*	-0.104
	(0.0248)	(0.0191)	(0.0527)	(0.0555)	(0.0910)
Observations	147	147	147	147	147
R-squared	0.018	0.124	0.274	0.347	0.347
Maintenance Costs ($)					
Existing Dependent Var	0.0768**	0.0708	0.134**	0.184**	0.184*
	(0.0350)	(0.0525)	(0.0624)	(0.0822)	(0.0923)
Existing Dependent Var x Colorado	-0.0474	-0.0375	-0.243***	-0.318**	-0.318***
	(0.0303)	(0.0532)	(0.0603)	(0.112)	(0.0720)
Observations	97	97	97	97	97
R-squared	0.106	0.154	0.340	0.421	0.421
Standard Error Clusters	Basin	Basin	Basin	Basin	Start
Construction Start FE	N	Y	N	Y	Y
Basin FE	N	N	Y	Y	Y

Regression results for various measures (see data section) of irrigation investment and existing capacity for ditches in Costilla and Taos counties. Regressions utilize the dependent variable as the measure of prior investment. Each panel presents robustness for investment as measured by the indicated variable. Fixed effects included are as indicated in each column and robust standard errors, clustered by basin or construction start date, are in parentheses.

*** p<0.01, ** p<0.05, * p<0.1

TABLE C3

Stream Level NDVI Specification Robustness

VARIABLES	(1) NDVI	(2) NDVI	(3) NDVI	(4) NDVI	(5) NDVI	(6) NDVI	(7) NDVI	(8) NDVI	(9) NDVI
Panel A: Culebra									
Acre Feet (1000s)	0.00317	0.00320	0.00298	0.00211	0.00301	0.00323	0.00211	0.00324	0.0473
	(0.00330)	(0.00324)	(0.00335)	(0.00341)	(0.00267)	(0.00304)	(0.00344)	(0.00305)	(0.0283)
Acre Feet Squared									-0.000862
									(0.000542)
Lagged Acre Feet			0.000540	0.000112	0.00316	0.00183	-0.000129	0.00173	0.0405
			(0.00405)	(0.00383)	(0.00265)	(0.00292)	(0.00386)	(0.00309)	(0.0453)
Lagged Acre Feet Squared									-0.000728
									(0.000865)
Year Trend		1.94e-05	0.000134	0.000599	0.000836	0.000157	0.000543	0.000165	-0.000236
		(0.00130)	(0.00143)	(0.00138)	(0.00119)	(0.00125)	(0.00139)	(0.00129)	(0.00126)
Lagged NDVI								0.0576	
								(0.161)	
Observations	28	28	28	28	486	27	28	27	28
R-squared	0.060	0.060	0.061	0.190	0.801	0.417	0.183	0.421	0.417
Panel B: Costilla									
Acre Feet (1000s)	0.00190	0.00250*	0.00265*	0.00282*	0.00307***	0.00303*	0.00341***	0.00302*	0.0206***
	(0.00146)	(0.00131)	(0.00138)	(0.00145)	(0.000966)	(0.00151)	(0.000859)	(0.00153)	(0.00538)
Acre Feet Squared									-0.00102***
									(0.000306)
Lagged Acre Feet			-0.000920	-0.00112	0.00117	0.000388	0.000168	0.000203	0.00820**
			(0.00168)	(0.00149)	(0.000944)	(0.00158)	(0.00106)	(0.00178)	(0.00361)
Lagged Acre Feet Squared									-0.000435***
									(0.000138)
Year Trend		0.00113	0.000832	0.00108	0.000923	0.000888	-8.69e-05	0.000800	-0.00144
		(0.00115)	(0.00111)	(0.00107)	(0.000722)	(0.00107)	(0.000731)	(0.00115)	(0.00111)
Lagged NDVI								0.0638	
								(0.231)	
Observations	28	28	28	28	135	27	28	27	28
R-squared	0.045	0.076	0.088	0.177	0.694	0.159	0.489	0.162	0.475
Panel C: Hondo									
Acre Feet (1000s)	0.00532***	0.00444***	0.00443***	0.00356***	0.00348***	0.00347***	0.00355***	0.00347***	0.00866***
	(0.00104)	(0.000901)	(0.000924)	(0.000678)	(0.000647)	(0.000702)	(0.000682)	(0.000730)	(0.00238)
Acre Feet Squared									-0.000111**
									(5.13e-05)
Lagged Acre Feet			0.000206	0.000176	0.000394	0.000300	0.000153	0.000271	-0.000386
			(0.000748)	(0.000531)	(0.000537)	(0.000558)	(0.000535)	(0.00104)	(0.00232)
Lagged Acre Feet Squared									2.10e-05
									(5.19e-05)
Year Trend		-0.00337***	-0.00330***	-0.00272***	-0.00238***	-0.00291***	-0.00275***	-0.00289***	-0.00247***
		(0.000945)	(0.00101)	(0.000827)	(0.000751)	(0.000863)	-0.000838	(0.000944)	(0.000805)
Lagged NDVI								0.00578	
								(0.153)	
Observations	28	28	28	28	216	27	28	27	28
R-squared	0.554	0.703	0.704	0.864	0.906	0.868	0.865	0.868	0.887
Panel D: Lucero									
Acre Feet (1000s)	0.0153***	0.0140***	0.0140***	0.0100***	0.0102***	0.0101***	0.0106***	0.0101***	0.0372***
	(0.00204)	(0.00219)	(0.00221)	(0.00199)	(0.00153)	(0.00202)	(0.00170)	(0.00207)	(0.00511)
Acre Feet Squared									-0.00101***
									(0.000173)
Lagged Acre Feet			-0.000516	0.000110	0.000313	-0.000187	0.000163	-0.000965	0.00554
			(0.00235)	(0.00207)	(0.00135)	(0.00210)	(0.00146)	(0.00382)	(0.00870)
Lagged Acre Feet Squared									-8.93e-05
									(0.000286)
Year Trend		-0.00220*	-0.00234	-0.00251*	-0.00134	-0.00221	-0.00200*	-0.00210	-0.00138
		(0.00120)	(0.00144)	(0.00139)	(0.00122)	(0.00152)	(0.00116)	(0.00166)	(0.00122)
Lagged NDVI								0.0528	
								(0.216)	
Observations	28	28	28	28	243	27	28	27	28
R-squared	0.709	0.740	0.741	0.822	0.845	0.820	0.866	0.821	0.892
1984 Observation	Y	Y	Y	Y	N	N	Y	N	Y
Climate	N	N	N	Y	Y	Y	Y	Y	Y
Acequias Included	All	All	All	All	All	All	First	All	All
Unit	Stream	Stream	Stream	Stream	Acequia	Stream	Stream	Stream	Stream

Note: Average NDVI is the dependent variable. Acre Feet is the total volume of water on the stream from April to October. Column (4) is the main specification from the text. Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

TABLE C4

Stream Level NDVI, Polynomial

VARIABLES	(1) Mean NDVI
Acre Feet (1000s)	0.0174***
	(0.00211)
Acre Feet Squared	-0.000296***
	(5.28e-05)
Lagged Acre Feet	0.000659
	(0.00254)
Lagged Acre Feet Squared	1.16e-05
	(5.99e-05)
Year	-0.00212***
	(0.000698)
Acre Feet (1000s) x Colorado	-0.0158***
	(0.00346)
Acre Feet Squared x Colorado	0.000322***
	(0.000112)
Lagged Acre Feet x Colorado	-0.000349
	(0.00345)
Lagged Acre Feet Squared x Colorado	-6.27e-05
	(0.000109)
Year x Colorado	0.00279**
	(0.00128)
Colorado	-5.617**
	(2.566)
Constant	4.664***
	(1.438)
Observations	112
R-squared	0.849
Stream	All

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

TABLE C5

Acequia Level NDVI and Priority

	(1)	(2)	(3)	(4)	(5)
VARIABLES	NDVI	NDVI	NDVI	NDVI	NDVI
Acre Feet x *Priority*:					
First	0.00167	0.00360**	0.00371***	0.0106***	0.00507***
	(0.00380)	(0.00177)	(0.000789)	(0.00179)	(0.000921)
Second	0.00373		0.00352***	0.00487***	0.00360***
	(0.00380)		(0.000794)	(0.00176)	(0.000818)
Third	0.00360	0.00290	0.00378***	0.0143***	0.00588***
	(0.00379)	(0.00177)	(0.000796)	(0.00176)	(0.000763)
Fourth	0.00611	0.00489***	0.00395***	0.0121***	0.00552***
	(0.00380)	(0.00177)	(0.000794)	(0.00176)	(0.000922)
Fifth	-0.00146	0.00269	0.00432***	0.00840***	0.00504***
	(0.00379)	(0.00177)	(0.000790)	(0.00177)	(0.000930)
Sixth	0.00387	0.00129	0.00237***	0.0120***	0.00432***
	(0.00380)	(0.00177)	(0.000795)	(0.00177)	(0.00110)
Seventh	0.00265		0.00254***		0.00228***
	(0.00380)		(0.000795)		(0.000740)
Colorado x Acre Feet x *Priority*:					
First					-0.00224*
					(0.00121)
Second					-7.24e-05
					(0.00332)
Third					-0.00374***
					(0.00117)
Fourth					-0.000284
					(0.00146)
Fifth					-0.00373**
					(0.00156)
Sixth					-0.00216
					(0.00262)
Seventh					9.72e-05
					(0.00362)
Observations	189	135	189	162	675
R-squared	0.598	0.701	0.907	0.889	0.873
Number of id	7	5	7	6	20
Stream	Culebra	Costilla	Hondo	Lucero	All

Robust Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

TABLE C6

Acequia Cross-Sectional Regressions Robustness

VARIABLES	(1)	(2)	(3)	(4)	(5)
Panel A: Temporal Average NDVI					
Priority	0.0182	0.0492	-0.0253	-0.0245	0.0248*
	(0.0509)	(0.0242)	(0.0294)	(0.0351)	(0.0125)
Priority x Colorado					0.00607
					(0.0244)
Colorado					-0.138
					(0.169)
Constant	-12.99	0.0900	7.495	-4.208	0.662
	(24.94)	(0.731)	(7.130)	(6.819)	(1.593)
Observations	7	5	7	6	25
R-squared	0.554	0.826	0.771	0.529	0.385
Stream	Culebra	Costilla	Hondo	Lucero	All
Panel B: Temporal Standard Deviation NDVI					
Priority	0.00658	0.0165	0.00285	0.0119**	0.000297
	(0.00464)	(0.00921)	(0.00213)	(0.00315)	(0.00228)
Priority x Colorado					0.00790**
					(0.00310)
Colorado					-0.0399
					(0.0240)
Constant	-1.677	-0.181	1.257**	1.941**	-0.0379
	(2.196)	(0.278)	(0.480)	(0.613)	(0.233)
Observations	7	5	7	6	25
R-squared	0.892	0.746	0.915	0.902	0.443
Stream	Culebra	Costilla	Hondo	Lucero	All

Coefficient estimates are from the cross-section regression of equaiton (4) in the text. Panel (A) considers the temporal average NDVI of the *acequia* while panel (B) considers the temporal standard deviation of NDVI for the *acequia.* Average precipitation, temperature, and acres are included as additional controls. Robust standard errors in parentheses.

*** p<0.01, ** p<0.05, * p<0.1

TABLE C7

Survey Measures and Prioirity Regressions

MEASURES	(1) Rank Coefficient	(2) Rank Coefficient
Concerns		
Water Availability Change 15 years	-0.245	-0.111
	(0.195)	(0.155)
Water Availability Change 5 years	-0.427*	-0.0120
	(0.253)	(0.137)
Drought Concern	**No Convergence**	-0.0352
		(0.137)
Water Quality Concern	-0.0715	0.167
	(0.181)	(0.136)
Infrastructure Concern	-0.173	0.00647
	(0.160)	(0.111)
Snowmelt Timing Concern	0.0149	0.111
	(0.159)	(0.156)
Average Concern (water)	0.0934	0.00220
	(0.0952)	(0.0636)
Average Concern (all 15)	0.0404	-0.0113
	(0.0462)	(0.0288)
Adaptation		
Crop Change 15 years	0.713	0.180
	(0.523)	(0.150)
Crop Change 5 years	0.217	0.111
	(0.249)	(0.146)
Irrigation Technology Change 15 Years	-0.134	0.552**
	(0.170)	(0.356)
Irrigation Technology Change 5 Years	-0.275	0.278
	(0.358)	(0.453)
Irrigated Acres Change 15 years	-0.378**	-0.122
	(0.183)	(0.129)
Irrigated Acres Change 5 years	-0.249*	-0.192
	(0.150)	(0.133)
State	CO	NM

Note: Coefficient estimate of "rank" for separate regressions for each of the survey measures in both states. Continous measures are estimated by OLS regressions. Binary measures apply logit estimation. Categorical measures utilize ordered logit regression. Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1