Economic Analysis of Property Rights: First Possession of Water in the American West*

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Abstract

We analyze the economic determinants and long-run effects of prior appropriation surface water rights from 1852 to 2013 and show how formal property rights developed to generate the discovery of new information and serve as a coordinating institution for investment under uncertainty. The prior appropriation doctrine (first in time, first in right) replaced the existing, share-based riparian water rights doctrine over an area of 1,808,584 mi^2 on the Western Frontier within 40 years—a rare and dramatic shift that suggests large economic benefits. We develop a model to demonstrate that when information about resources is costly, prior appropriation facilitates socially valuable search, coordination, and investment by reducing uncertainty about resource conditions and the threat of new entry. We derive testable hypotheses about the behavior of claimants under these conditions and test our hypotheses using a novel dataset that includes the location, date, and size of water claims along with measures of infrastructure investment, irrigated acreage, crops, topography, stream flow, soil quality, precipitation, and drought in eastern Colorado. We confront challenges to identification using the dynamic estimator proposed by Wooldridge (2005) to trace the evolution of water claims in the presence of unobserved heterogeneity and find that search effort and infrastructure investment generated positive externalities for subsequent claimants by lowering claiming costs. We show that secure property rights facilitated coordination by reducing uncertainty and heterogeneity, doubling average infrastructure investment. This coordinated investment led to long-run gains of over $100 per-acre. We estimate that prior appropriation contributed between 3.5 and 20% of state income in 1930. Importantly, economic returns were lower in areas where pre-existing sharing norms dominated legal prior appropriation claims. Our analysis extends the literatures on institutional change, property rights, and first possession and informs the debate over the efficiency of prior appropriation and the costs of proposed water rights reforms.

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1 Introduction

Property rights are fundamental to economic decisions and outcomes. Property rights contribute to long-run economic growth (Acemoglu et al., 2001, 2005; Mehlum et al., 2006), facilitate greater investment when returns are uncertain or delayed (Besley, 1995; Jacoby et al., 2002; Galiani and Schargrodsky, 2010), allow for the development of markets (Greif et al., 1994; Dixit, 2009), and reduce rent dissipation associated with common pool resources (Libecap and Wiggins, 1984; Gordon, 1954). Despite the importance of property rights in shaping economic outcomes, the determinants of how property rights emerge initially and the resulting path-dependent effects on long-run outcomes are not well understood.[1]

In this paper we shed light on the factors that determine the structure of property rights and the resulting long-run economic outcomes by examining the emergence and path-dependence of water rights in the Western United States that developed as first possession rights and became the basis for large-scale investment in irrigated agriculture and the subsequent economic development of the West. The westward expansion of American settlers into the unclaimed frontier is an excellent setting to study the development and long-term implications of property rights regimes. Settlers moved west ahead of formal state and territorial governments, bringing with them basic legal norms but confronting unfamiliar conditions that required new institutional arrangements for successful economic development. These institutional arrangements appeared spontaneously via local collective action and persist today, molding contemporary markets.[2]

[1]Demsetz (1967), Anderson and Hill (1975), and Barzel (1997) emphasize that property rights emerge when the marginal benefit of creating, defining, and enforcing those rights exceed the marginal costs of doing so, but this leaves open the question of which forms property rights take in different settings and why.Cheung (1968, 1969, 1970) Barzel (1997), and others discuss how transactions costs determine the efficient choice of contractual forms, but this analysis does not examine the emergence whole systems for defining legal rights to property.

[2]Frontier lands—opened by the Homestead and other Acts—required irrigation to be productive, and claimants jointly sought land and water that often had to be moved from streams to farm sites (Gates et al., 1968; Allen, 1991; Romero, 2002; Getches, 2009). As with western land, minerals, and timber, diversion sites to claim and divert water for irrigation were allocated through first possession. First possession assigns ownership based on the timing of claims and typically requires claimants to demonstrate beneficial use of the resource to retain possession (Epstein, 1978; Rose, 1985, 1990; Ellickson, 1993; Lueck, 1995, 1998).Economists have tended to dismiss first possession as a rent-dissipating rights allocation mechanism. Barzel (1968) and Haddock (1986) describe rent losses when the resource is homogeneous in quality and the agents are homogeneous in search costs and large in number relative to resource size. Under this setting, claimants race to capture resource rents and in so doing fully dissipate rents. Rent dissipation, however, is reduced if the agents are heterogeneous in search costs (Barzel, 1994; Lueck, 1995, 1998; Leonard and Libecap, 2015). First possession could also lead to waste, if not complete dissipation, in the rule of capture if the costs of bounding and controlling entry to the resource stock are very high. Homogeneous parties then race to compete for units of the flow, rather than the resource stock as in the case of open-access fisheries (Lueck, 1995, 1998). The legal scholarship on first possession is more favorable, being less concerned with dissipation and more on

Economists are most familiar with first possession in the context of patent races, which assign ownership of a single asset—typically the right to produce as a monopolist—to a single claimant.[3] Patents provide an incentive for private agents to pursue socially valuable innovations, but the patents may be less socially valuable when follow-on innovations are considered in a dynamic setting with sequential innovations because granting monopoly rights can impair future development (Green and Scotchmer, 1995; Bessen and Maskin, 2009).[4] First possession allocation of natural resources is complicated by the fact that multiple claims can be established to a resource that is partionable, implying potential coordination benefits among claimants. Prior appropriation—the legal doctrine of assigning water rights via first possession—assigns priority to water rights based on timing of claims. Prior appropriation allocates a fixed amount of water that can be separated from the stream and place into beneficial use (Libecap, 2011). In times of drought users with high priority receive their full allocation before more junior users have the right to divert any water.[5]

Prior appropriation was an institutional innovation that abruptly replaced the common-law riparian water rights that had dominated in the eastern United States within 40 years over an immense area of some 1,808,584 mi^2. Property rights to surface water are formally administered under the prior appropriation doctrine in 17 western US states and at least 2 Canadian provinces. Most water rights were established between 1850 and 1920 when water was primarily valued as an input to irrigated agriculture and today 70-80% of western water consumption remains in agriculture (Brewer et al., 2008).[6] Such voluntary, large-scale property rights regime change is unusual empirically and a setting like this has not been analyzed previously.[7]

We develop a model to demonstrate that when information about resources is costly, prior appropriation facilitates socially valuable search, coordination, and investment by reducing uncertainty about resource conditions and the threat of new entry. We derive testable hypotheses about the behavior of claimants under these conditions and test our hypotheses

how the practice encourages valuable discovery and provides a clear, simple way to define ownership that can be equitable (Epstein, 1978; Rose, 1985, 1990; Ellickson, 1993). This literature, however, does not examine why prior appropriation emerged in the first place.

[3]See Dasgupta et al. (1983), Fudenberg et al. (1983), and Harris and Vickers (1987).

[4]But, awarding patents may fail to fully internalize the relevant externalities (Jones and Williams, 1998; Bloom et al., 2013). In contrast, we emphasize the advantages associated with coordination around well-defined and legally secure property rights.

[5]This system is often characterized by the phrase, "first in time, first in right."

[6]Kanazawa (1998) explores the early development of prior appropriation in mining camps, but it developed largely from demands for irrigation in the semi-arid region west of the 100th meridian.

[7]Property regimes more commonly change involuntarily with revolution or military conquest as was the case with the Russian revolution of 1917 or the expansion of the British Empire over native institutions.

using a novel dataset that includes the location, date, and size of water claims along with measures of infrastructure investment, irrigated acreage, crops, topography, stream flow, soil quality, precipitation, and drought in eastern Colorado. We find that i) search effort and infrastructure investment generated positive externalities for subsequent claimants by lowering claiming costs, ii) secure property rights facilitated coordination by reducing uncertainty, iii) coordination led to substantially higher levels of infrastructure investment, which led to iv) long run differences in income-per-acre. We also find that property rights generated lasting economic returns in areas that adhered to the strict legal doctrine of prior appropriation but not in those where pre-existing communal norms dominated. Finally, we provide the first empirical estimates of the contribution irrigated agriculture to economic development in the Western United States in the twentieth century. Our analysis extends the literatures on institutional change, property rights, and first possession and informs the debate over the efficiency of prior appropriation and the costs of proposed water rights reforms.

2 Background

The western frontier was immense and varied in terrain, quality, and potential value, leading to high information and coordination costs for resource claimants. Through most of the 19th century, all natural resources in the American West—farm land, timber land, mineral land, range land, and water—were open for first possession claiming (Kanazawa, 2015; Libecap et al., 2011).[8] Examination of the claiming process for various resources reveals how little early claimants knew about the location of the most promising mineral ore sites, timber stands, or agricultural lands. Most parties had little experience with western resources and many California emigrants, for example, ultimately earned only their opportunity wage.[9]

Settlers sought to establish property rights to resources with very limited information and understanding of the necessary conditions for successful agricultural development. Frontier migrants could observe relatively stable resource characteristics, such as topography, eleva-

[8] The federal government attempted to sell lands early in the century at a floor price of between $1.25 to $2.50/acre, but given the vastness of the area and small size of the US Army, the government could not control or police entry as squatters moved ahead of the government survey and occupied properties under first possession. Kanazawa (1996) discusses the rapid shift from sales and land auctions to first possession in the distribution of federal lands in the early to mid-19th century. Eventually, with enactment of the Preemption Acts of 1830-41, the federal government abandoned sales (Gates et al., 1968). Subsequently, the Homestead Act of 1862 and the Mining Law of 1868 made first possession the primary means of distributing property rights to valuable frontier resources (Gates et al., 1968; Libecap, 2007).

[9] Clay and Jones (2008). Other studies of the relative homogeneity of parties include Umbeck (1977a,b, 1981); Libecap (1978); Libecap and Johnson (1979); Reid (1980); Zerbe and Anderson (2001); McDowell (2002); Clay and Wright (2005); Libecap (2007) and Stewart (2009).

tion, and stream location in their claiming decisions. Soil quality and variable stream flow due to drought, however, were not known. Variable stream flow was particularly critical because water claims could be made at a time of unusually high water supplies, but provide insufficient water during drought. There was a general misunderstanding of the region's dry climate and of the potential for drought to dramatically shift production potentials (Libecap and Hansen, 2002; Hansen and Libecap, 2004a,b).

The costs of establishing property rights were potentially high; learning about stream variability, soil quality, and optimal farming techniques was time-consuming and successful use of water required investment in major diversion infrastructure to move water away from the rugged and unproductive riparian terrain. The report on the Colorado Territory by Cyrus Thomas to the U.S. Congress exemplifies the degree of heterogeneity and uncertainty facing potential claimants:

> I made an effort to ascertain what the average cost of ditching is to the acre, but found it next to an impossibility to do this. The difference in the nature of the ground at different points, the uncertainty in regard to the price of labor, the difference in the sizes of the ditches, would render an average, if it could be obtained, worthless. (Hayden, 1869, 150)

Each additional wave of settlers brought competition in the definition of property rights but also created the potential for coordination in the construction of critical diversion infrastructure. These challenges had not presented themselves in settings where the riparian doctrine previously dominated—where land had been more homogeneous with established ownership, the climate had been better understood, farming practices were well-established, and the terrain had not required water to be moved to distant irrigation sites. The riparian doctrine granted a right to a share of the water on a stream to any owner of land adjacent to the stream.[10] This property rights scheme was ill-suited to western water resources because it did not provide sufficient security in the face of uncertainty about resource conditions and competition from future water claimants to facilitate search, information generation, and coordination among early claimants.

Table 1 presents the results of a simple linear probability model for whether or not a state adopted prior appropriation. The dependent variable is equal to one for states (or sub-regions of states) that adopted prior appropriation and zero for areas that maintained

[10] Rose (1990)discusses the early evolution of riparian water rights in the eastern US.

the riparian doctrine.[11] While we lack the ability to precisely identify the determinants of state-level variation in property rights regimes, we do find suggestive evidence that states with lower stream density, less rainfall, and more rugged terrain are more likely to administer water rights via prior appropriation.

Table 1: Adoption of Prior Appropriation

	(1)	(2)	(3)
	$Y = \mathbb{1}$(Prior Appropriation)		
Stream Density	-0.285***	-0.0875	-0.576**
	(-3.21)	(-1.48)	(-2.56)
Roughness	0.000910***	0.000691***	0.000750***
	(8.19)	(5.86)	(7.16)
Precipitation		-0.000507***	-0.000329**
		(-4.30)	(-2.43)
(Stream Density)^2			0.218**
			(2.49)
Constant	0.152*	0.577***	0.539***
	(1.71)	(3.91)	(3.83)
N	57	57	57
R^2	0.610	0.706	0.729

Robust standard errors in parentheses

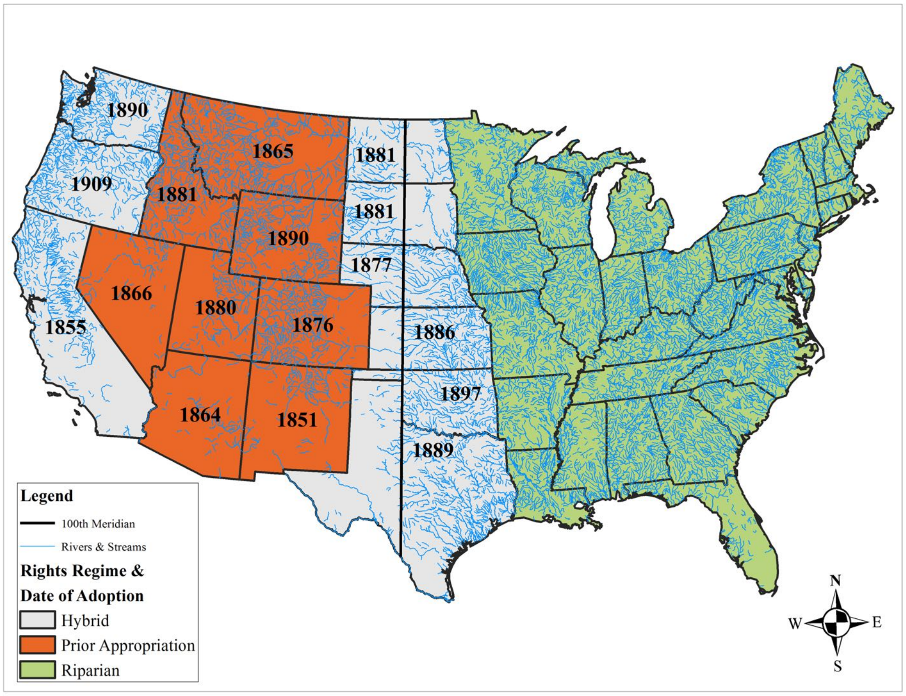
* $p < .1$, ** $p < .05$, *** $p < .01$

Figure 1—a visual representation of the results in Table 1—depicts the distribution of major streams and types of water rights in the United States to illustrate the dramatic nature of the shift in property rights regimes for water that occurred west of the 100th meridian. Consistent with Table 1, it is evident that states with abundant water resources held to the riparian doctrine, while those in more arid regions with lower stream density rapidly adopted new institutions that persist to this day. This pattern suggests that prior appropriation may have emerged as an institutional response to the need to put increasingly scare water to its highest-valued use in an environment with high information costs. Unfortunately, we cannot hope to answer this question by studying variation in water regimes at the state level, where many idiosyncratic and unobserved factors confound empirical analysis.

To better understand the economic factors that led to the rise of prior appropriation, we

[11] We divide the states with hybrid water rights regimes into sub-regions according to their climate. North and South Dakota, Nebraska, Kansas, Oklahoma, and Texas are divided along the 100th meridian, Washington and Oregon are divided along the Cascade Mountain Range, and California is divided into a Northern and Southern regions at the latitude of Lake Tahoe.

Figure 1: Institutional Innovation



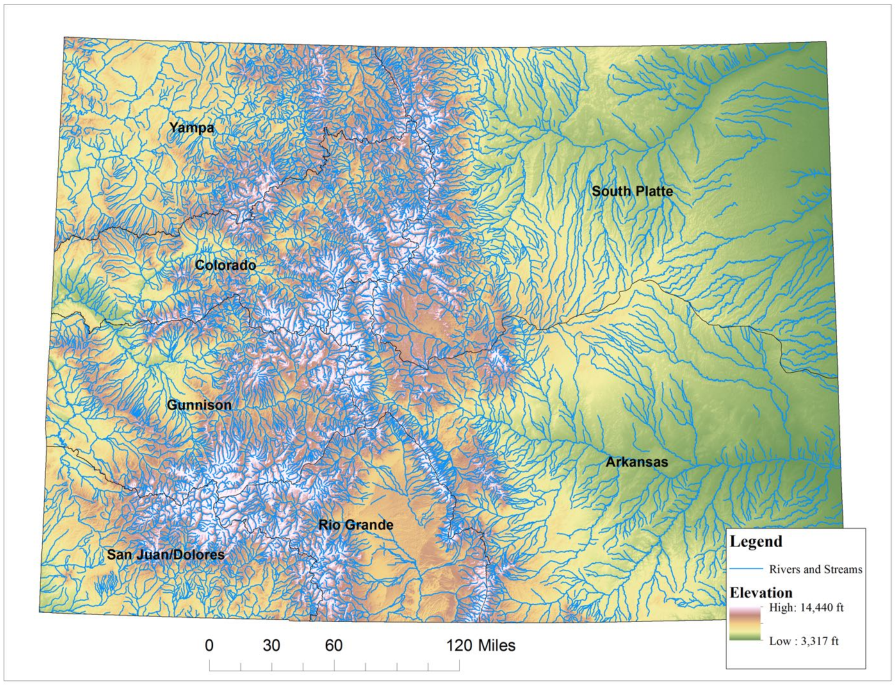
focus on Colorado—the place where settlers in the westward movement of the agricultural frontier first encountered semi-arid terrain in a territory not dominated by pre-existing riparian water rights holders.[12] In the rugged terrain of Colorado it was apparent that agriculture required irrigation and the movement of water from streams to agricultural lands. Colorado covers an area of some 66,620,160 acres containing over 107,000 miles of stream with elevations ranging from 6,800 to 14,440 feet.[13] Figure 2 depicts water and land resources as well as Water Divisions in Colorado and demonstrates the scale of the information and decision problem facing potential claimants. Stream resources were widely dispersed across the landscape in areas not directly adjacent to productive farmland. Settlers in the 19th century had to confront this vast resource and determine the best location in which to establish rights to land and water.

From first settlement in the 1860s to the 1876 Colorado Constitution and the 1882 Col-

[12]Prior appropriation first emerged in Colorado as a full tangible property right to water and became known as the Colorado Doctrine. It was a general template for other western territories and states and generally, western Canadian provinces(Schorr, 2005). Only in the wetter states of California, Oregon, and Washington did remnants of riparian water rights remain (Hess, 1916; Dunbar, 1950; Hobbs Jr, 1997).

[13]The 1900 population of Colorado was 539,500, implying a population density of one person per 123 acres.

Figure 2: Water Resources in Colorado

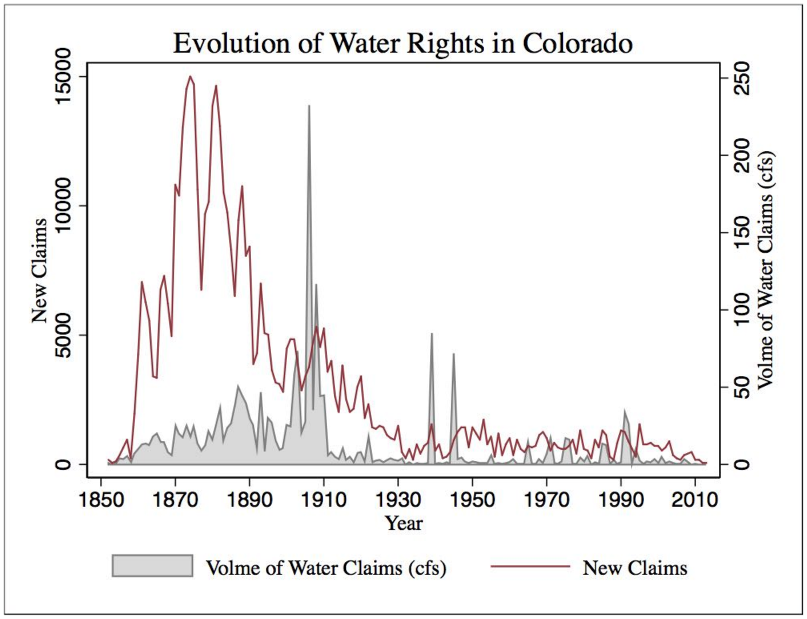


orado Supreme Court ruling in *Coffin v. Left Hand Ditch Co* (6 Colo 443), riparian rights were rejected and prior appropriation rights acknowledged. Mirroring the allocation of rights to other natural resources through first possession lowered the costs of adoption for potential claimants and allowed them to simultaneously establish rights to land and water.[14] Priority access to water tended to be defined by stream, so that being the first claimant on a given stream granted the highest priority to water in any given year. High information and infrastructure costs created the potential for early claimants to generate positive externalities by indirectly providing information about profitable claim locations and diversion practices. Subsequent claimants could build on senior users' knowledge and investment, establishing claims at lower cost. Figure 3 shows the evolution of water claims in Colorado over time and indicates that claimants arrived in waves, primarily in the latter half of the 19th century.

Once in place, prior appropriation water rights became the basis for water trade, investment in dams and canals, and expansion of irrigated agriculture and other activities critical for economic development. Because diversion dams, primary canals, and feeder ditches to

[14] Dunbar (1983, 1985) outlines the early history of prior appropriation in Colorado and Burness and Quirk (1979, 1980a,b) develop a formal economic model of prior appropriation rights to water.

Figure 3: The Timing and Volume of Water Claims in Colorado



remote fields required costly capital investment, settlers often joined together in staking prior appropriation claims with the same priority and in forming mutual ditch companies. Granting precedent to earlier rights facilitated coordination for investment by creating a property right that was secure against the arrival of new claimants. Commercial ditch companies were also established by purchasing existing water rights and then delivering water to irrigators under contract (Libecap 2011).[15] Next, we develop a theoretical model to better understand the conditions under which prior appropriation is preferable to share-based allocation rules and analyze the implications for claimants' behavior under prior appropriation.

3 Economic Model of Riparian vs. Appropriative Rights

We build upon the model of prior appropriation developed by Burness and Quirk (1979) to provide new insights about the conditions under which prior appropriation is more efficient than riparian water rights and derive testable implications about the behavior of individuals within a prior appropriation system under these conditions. We begin by characterizing the diverter's problem under prior appropriation and the aggregate rents generated by water

[15] One ditch, the Yeager Ditch, was completed as early as 1863, but most construction and expansion of irrigation water occurred after 1870. The Cache La Poudre River drainage in North-Central Colorado was the center of early rights claiming and irrigation.

claims under this system. Then, we present the diverter's problem under a share-based system and compare the aggregate rents generated by prior appropriation to those generated by share-based systems for a given number of users. Finally, we show that for a sufficiently large positive externality from investment in establishing claims, prior appropriation is the efficient rights allocation mechanism and derive predictions about how individuals will establish prior appropriation claims under these conditions.

The model takes the timing and arrival of claimants as given, focusing on sequential claims established by homogeneous users. Users establish a water right by constructing diversion infrastructure of size x based on their expected deliveries of water and earn revenues from diversion according to the function $R(x)$ satisfying $R'(x) > 0, \quad R''(x) < 0$. The costs of constructing diversion capacity of size x are given by the function $C(x)$ satisfying $C'(x) > 0, \quad C''(x) > 0$. Define $p_i = \sum_{j=1}^{i-1} x_j$ to be the total volume of water claimed prior to user i.

Let the random variable S be the total water available in the stream in a given year, with cumulative distribution function $F(s) = Pr(S \leq s)$ and probability density function $f(s)$. We assume that users cannot divert more water than their diversion infrastructure allows. Hence, in choosing diversion capacity (and claim size) users face a trade-off between the known costs of investment and variable flows that may or may not exceed constructed capacity. For simplicity we assume that capacity investment is a once-and-for-all decision.

3.1 Investment and Aggregate Rents in the Baseline Case

Under prior appropriation users maximize their expected profits by choosing what size claim to establish, subject to the availability of water. Each user i solves

$$\max_{x_i} \quad \mathbb{E}\left[\pi(x_i)\right] = \left[1 - F(p_i + x_i)\right] R(x_i) + \int_{p_i}^{p_i + x_i} R(t - p_i) f(t) dt - C(x_i) \tag{1}$$

Expected profits can be broken into three parts. First, there is the revenue from receiving a full allocation x times the probability that stream flows are sufficiently large for all senior claims to be satisfied and user i to receive her full allocation. Second, there is the expected revenue from diverting a less than full allocation for levels of stream flow that allow a partial diversion. This occurs when $p_i < s < p_i + x_i$; all claims senior to user i are satisfied but user i exhausts the remaining water before receiving her full diversion. Finally, the user bears the cost of constructing diversion facilities regardless of how much water she receives. The first-order condition is

$$\frac{\partial \mathbb{E}\left[\pi(x_i)\right]}{\partial x_i} = -f(p_i+x_i)R(x_i) + \left[1-F(p_i+x_i)\right]R'(x_i) + f(p_i+x_i)R(x_i) - C'(x_i) = 0$$
$$= \left[1-F(p_i+x_i)\right]R'(x_i) - C'(x_i) = 0 \tag{2}$$

Users maximize expected profit by setting the expected marginal revenue of a claim equal to the marginal cost of establishing that claim. If the second-order condition for a maximum is satisfied then equation 2 has a unique solution that defines an implicit function $x_i = x_i^{*PA}(p_i)$ and the profit function for user i is[16]

$$V_i^{PA} = \mathbb{E}\left[\pi(x^{*PA}(p_i))\right] = \left[1-F(p_i+x^{*PA}(p_i))\right]R(x^{*PA}(p_i)) + ...$$
$$... + \int_{p_i}^{p_i+x^{*PA}(p_i)} R(t-p_i)f(t)dt - C(x^{*PA}(p_i)) \tag{3}$$

Define $\mathbf{V^{PA}} = \sum_{i=1}^{N} V_i^{PA}$ as the aggregate rents on a given stream from claims established under the prior appropriation doctrine. Then we have

Proposition 1: *Under prior appropriation, aggregate profits V^{PA} are increasing and concave in the number of appropriators for $N < \bar{N}^{PA}$ and have a unique maximum at $\bar{N}^{PA}$.*

Proof: see appendix. The intuition is that claiming will continue as long as the marginal claimant's expected profits are positive and that the final entrant will earn zero expected profits. Hence, aggregate profits are increasing in N for $N < N^{PA}$ and decreasing in N for $N > N^{PA}$. Users continue to enter as long as expected profits are positive and in equilibrium the final claimant earns zero profits.

Under a riparian or other share-based system, users are able to divert equal shares of annual flow.[17] The arrival of a new claimant reduces the water available for all incumbent claimants by reducing the size of each user's share. In a true riparian setting, the geography of the river determines N, the total number of claimants, by constraining how many users can hold riverfront property. To simplify the analysis we treat N as a parameter.[18] In a

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[16] The second order condition is $\frac{\partial^2 \mathbb{E}[\pi(x_i)]}{\partial x_i^2} = -f(p_i+x_i)R'(x_i) + \left[1-F(p_i+x_i)\right]R''(x_i) - C''(x_i) \leq 0$. This holds without further assumption because $f(\cdot)$ is a proper pdf and hence must be non-negative.

[17] In practice riparian systems require that other parties on the stream are allowed "reasonable use."

[18] N, the number of claimants, may be endogenous in a more generalized water share system where riparian lands are not a prerequisite for holding a water right. Under such a system the diverter's problem is to maximize expected profits by choosing how much diversion infrastructure to build, given the expected flow

given year with water flow S, each user is able to divert S/N units of water. Hence, the diverter's problem under a share system is

$$\max_{x_i} \quad \mathbb{E}\left[\pi(x_i)\right] = [1 - F(Nx_i)]R(x_i) + \int_0^{Nx_i} \left[R\left(\frac{t}{N}\right) f(t)dt\right] - C(x_i) \tag{4}$$

The first two terms in equation 4 are expected revenues for a user with diversion capacity x_i in a share system with $N-1$ other users. The probability that user i receives enough water for a full diversion size x_i is the probability that their share of the flow is greater than the capacity they have constructed, or $Pr(S/N > x_i) = Pr(S > Nx_i) = [1 - F(Nx_i)]$. The second term is the expected revenue from diverting some amount less than x_i for levels of stream flow less than Nx_i. The costs of constructing diversion capacity are the same as under prior appropriation. The first order necessary condition for a maximum is

$$[1 - F(Nx_i)]R'(x_i) - C'(x_i) = 0 \tag{5}$$

Again, users set the expected marginal revenue of diversions equal to the marginal cost of establishing a given amount of diversion capacity. The difference between this condition and the analogous condition under prior appropriation is that expected diversions in the share system depend on the number of other users in the system. Assuming that the second order condition is satisfied, the first order condition defines an implicit function $x_i = x_i^{*S}(p_i, N)$ that can be used to generate the profit function for user i:[19]

$$V_i^S = [1 - F\left(Nx_i^{*S}(p_i, N)\right)]R\left(x_i^{*S}(p_i, N)\right) + \int_0^{Nx_i^{*S}(p_i,N)} \left[R\left(\frac{t}{N}\right) f(t)dt\right] - C\left(x_i^{*S}(p_i, N)\right) \tag{6}$$

Define $\mathbf{V^S} = \sum_{i=1}^{N} V_i^S = NV^S$ as the aggregate rents on a given stream from claims established under the riparian doctrine. Then we have

Proposition 2: $V^{PA} \lesseqgtr V^S$. *Either property rights regime can dominate for a given N.*

Proof: See appendix. The intuition for is that for any particular N, the distribution of diversion capacity will be different under each rights regime. A given N in the prior

of the river and expected number of other users on the stream. Of course, the Nash Equilibrium of this strategic game is for users to enter until expected profits for all users are zero, resulting in full rent dissipation.

[19]The second order condition is $\frac{\partial^2 \mathbb{E}[\pi_i(x_i)]}{\partial x_i^2} = -Nf(x_i)R'(x_i) + [1 - F(Nx_i)]R'' - C''(x_i) \leq 0$.

appropriation system implies a hierarchy of both diversion capacity and rents, with the highest priority user establishing the largest investments and earning the greatest rents (see Proposition 1). In the riparian system, users all establish equal diversion capacity and earn equal rents. Aggregate diversion capacity is lower under the riparian system, but that capacity is used more efficiently than under the appropriative system where some users earn higher marginal returns than others. The result is that aggregate rents may be higher for shares, even though less water is used.[20]

The relative efficiency of either system is closely related to the concavity of the profit function. For constant marginal revenue and marginal cost, the two systems result in equal aggregate investment and profit. As the revenue function becomes more concave or the cost function more convex, the relative efficiency of the share system for a given level of investment increases because there are larger gains from reallocating marginal units of water equally across users. On the other hand, assigning rights as shares reduces incentives to invest and lowers available diversion capacity. Prior appropriation is more likely to dominate when the number of potential entrants grows large because it secures the investments of senior users, making them indifferent to the arrival of new claimants (see Appendix A). The fact that new arrivals cannot dissipate rents captured by earlier claimants not only creates incentives for early investment, it prevents classic open-access dissipation of the resource due to over-entry. For this reason, prior appropriation becomes more profitable relative to shares when the number of potential users grows large relative to stream flow.

3.2 Positive Externalities from Prior Claims

General uncertainty about conditions and high information and transportation costs characterized the Western frontier and created the need for coordination. Investment in search and diversion infrastructure by early users may have been socially valuable in the sense that it lowered the cost of establishing a claim for subsequent users. Prior claims would lower costs for additional claimants by i) providing valuable information about where and how it is profitable to divert and use water ii) providing infrastructure that can be shared or added to at lower cost, or iii) creating general agglomeration effects (Crifasi, 2015). We allow for the existence of an additive positive externality from prior claims γp_i that lowers the fixed costs of establishing subsequent claims. The claimant's problem under prior appropriation

[20]Burness and Quirk (1979) show these two effects separately. They establish that aggregate rents are higher with a share-based system for a given level of investment, but that aggregate investment is higher under appropriation for a given N. They do not compare aggregate rents across the two systems for a given N.

in the presence of this positive externality is

$$\max_{x_i} \quad \mathbb{E}\left[\pi(x_i)\right] = \left[1 - F(p_i + x_i)\right] R(x_i) + \int_{p_i}^{p_i+x_i} R(t - p_i) f(t) dt - C(x_i) + \gamma p_i \qquad (7)$$

It is immediately apparent that the existence of an additive externality will not affect the magnitude of claims $x^{*PA}(p_i)$ under prior appropriation but will increase profits for junior users by reducing their fixed costs. Define $\mathbf{V^E} = \sum_{i=1}^{N} V_i^E$ as the aggregate rents on a given stream from claims established under the prior appropriation doctrine in the presence of a positive externality. This gives

Proposition 3: *In the presence of a positive externality from prior claims ($\gamma > 0$), V^{PA} has a convex region for small N and for sufficiently large γ, $V^E > V^S$.*

Proof: see appendix. The intuition is that aggregate rents under prior appropriation may increase at an increasing rate if the positive externality for junior claimants is large enough to offset their decrease in profit from facing lower expected available flows and constructing smaller capacity. Under these conditions, aggregate rents under the prior appropriation doctrine exceed those under the riparian system which lacks the positive externality.

We assume that the positive externality only exists under prior appropriation for several reasons.[21] First, prior appropriation protects senior users' investments from the arrival of junior users and thus makes them willing to engage in activities that generate positive externalities, such as information and infrastructure sharing. In contrast, each new arrival in a riparian system reduces the expected rents of incumbent users who thus an incentive to avoid generating positive externalities by concealing information and refusing to coordinate or share infrastructure capacity. Second, users who own a share of annual diversions rather than a fixed amount face greater uncertainty in their expected diversion, making them less willing to bear the fixed costs of collective organization and capital construction. As expected diversions become more variable, high fixed costs preclude profitable investment.

[21] We are developing a proof that prior appropriation is more efficient even if the externality exists in both systems—the intuition is that the positive externality magnifies the value of prior investment, which is always higher under prior appropriation for a given N.

3.3 Behavior of Claimants under Prior Appropriation

Next, we characterize individuals' choice of where to establish a first possession claim under the baseline case relative to when there are large positive externalities generated by prior claims to derive testable hypotheses about the behavior of claimants under the prior appropriation doctrine when γ is high. This will allow us to test the implications of our model despite the fact that we tend to observe either prior appropriation or riparian rights in a given area, with relatively little variation in which regime dominates—broadly, the eastern United States uses the riparian doctrine and the arid western states use the prior appropriation doctrine (see Figure 1).

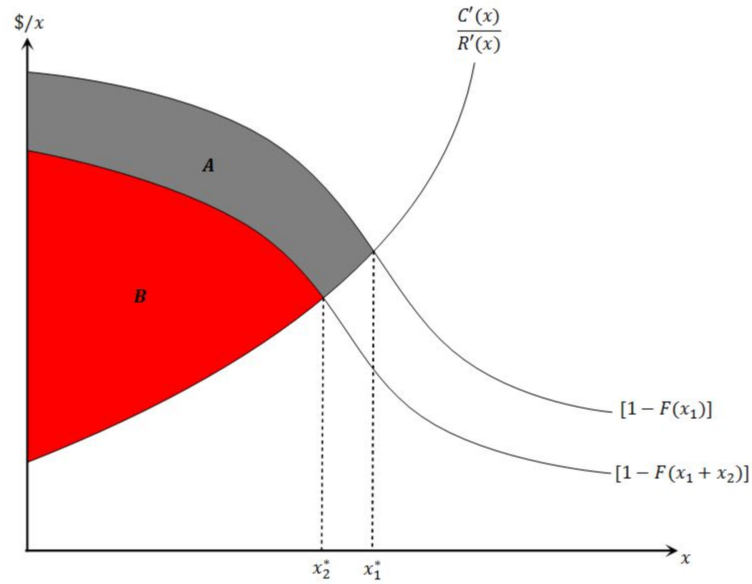
We assume that unknown streams are of equal expected productivity, so that the choice of where to establish a claim can be analyzed by comparing the value of being the ith claimant on a stream with the value of establishing the first claim on another stream of equal expected quality. In order for a new user to choose to follow prior claimants when other sites are available, it must be the case that the expected profits are higher for junior claimants for at least some number of total users N. This gives

Proposition 4: *In the convex region of V^E, profits are increasing for junior claimants relative to senior claimants: $V_i^E > V_{i-1}^E$ and users follow rather than search for a new stream.*

Proof: see appendix. Proposition 4 follows directly from Proposition 3 because for aggregate rents to be convex in N, it must be the case that junior claimants earn higher profits than the prior claimant so that aggregate profits are increasing at an increasing rate, due to the positive externality. This is only true for relative small N, however, because the resource scarcity effect eventually dominates the positive externality.

Proposition 4 has direct behavioral implications for where claimants choose to locate under prior appropriation depending on the magnitude of γ. Proposition 1 makes clear that profits decline with priority if there is no positive externality. Users would in general be better off searching for new streams rather than following prior claimants. This would imply that users would on average be less likely to locate on a particular stream in a particular year if there were more claims on that stream in the previous year. Absent a positive externality generated by prior claimants, users would always prefer to be higher priority if possible. This trade-off is depicted in Figure 4, which shows the optimal claim and profit from diversions for a senior user and a junior user. New claimants could earn area $A+B$ in expected profits by being the first claimant on a new stream, but only earn area B if they follow a previous

Figure 4: Follow or Search



user and establish a junior claim. If we observe users following one another, it must be that γp_i is larger than area A. This provides the basis for our primary empirical test of whether there existed positive externalities in the definition of prior appropriation claims.

3.4 Information Costs, Excess Claiming, and Testable Predictions

Claiming effort by senior claimants is more likely to generate positive externalities for junior claimants when there is uncertainty about the quality of water and land resources and when information and infrastructure investment are costly. In addition to directly testing for whether new claimants follow prior claimants, we derive predictions about the effect of different resource characteristics on the decision of where to establish a water right.

If it is true that information costs are an important determinant of behavior in allocating rights, we would expect claiming behavior to be more responsive to resource characteristics that are easier to observe. Factors that affect the value of diverted water and can be directly observed—topography, flow, and elevation—are predicted to have a larger effect on claims than resource characteristics that are more costly for users to deduce such as flow variability and soil quality. Flow variability is particularly important because users may establish excess claims on a given stream if they do not account for the inter-annual variability of flows. The prior appropriation system includes an inherent check against overuse of water on a stream within any given year because new claimants can only establish rights to residual water after senior diversions have been satisfied.

If users lack full knowledge about the probability of receiving similar flows in the future, there is a potential systemic bias in the structure of appropriative water rights that can lead to excess claiming. If users are especially prone to claim water in years of high flow, then legal claims will come to exceed expected annual flows and "paper" water rights will exceed "wet" water rights. We can analyze claiming behavior during drought to test for this systematic bias—if claims are less likely during drought then it must be the case that users respond to first-order resource availability but not to underlying variability in flows.

Finally, our model relies on the assumption that users are more willing to coordinate with other water claimants if their investments are more secure. The comparison in our model is between users who own a fixed diversion and users who own a share of annual diversions. We cannot directly test for differences in behavior between these two groups, but we can assess the effect of property rights security on investment and coordination within the prior appropriation system. The assumptions of our model imply that senior right-holders should be more willing to coordinate and invest in infrastructure than junior right-holders because their expected water deliveries are more certain. We can directly test this prediction with our data. Before moving on to our empirical analysis we summarize these predictions below.

Summary of Predictions

1. An increase in the number of claims on a stream will increase the number of subsequent claims on that stream.

2. Easily observed resource characteristics such as topography and average flow will be a stronger. determinant of claiming locations than less apparent characteristics such as flow variability and soil quality

3. Fewer claims will be established during drought.

4. Users with higher priority will invest in greater diversion infrastructure and are more likely to cooperate.

4 Empirical Determinants of Prior Appropriation Claims

4.1 Location Data

We assemble a unique data set of all known original appropriative surface water claims in Colorado. We combine geographic information on the point of diversion associated with each right with data on hydrology, soil quality, elevation, homestead claims, and irrigation to test our hypothesis about the determinants of first possession claims.[22] Colorado is divided into 7 Water Divisions that separately administer water rights, as depicted in Figure 2. We focus on Divisions 1 to 3 (the South Platte (1), Arkansas (2), and Rio Grande (3)), which comprise the eastern half of Colorado, are home to the majority of the state's agriculture, and have more complete diversion data available than other divisions. For each claim we know the date and geographic location of original appropriation, the name of the structure or ditch associated with the diversion, the name of the water source, and the size of the diversion.

Our goal is to characterize individuals' choices of where to establish first possession claims to water over time, so we divide Divisions 1 to 3 into a grid of 1 square-mile sections and create measures of location quality by grid cell.[23] Analyzing only the location where rights were actually claimed ignores a substantial amount of individuals' choice sets, so including information on other claimable locations is critical for avoiding selection bias. Figure 5 shows a map of Divisions 1 to 3 with the original location of all claims in our dataset, the major streams, and the grid squares used for the analysis.[24] Areas with productive soil are shaded in green.[25] The figure makes clear the massive spatial scale of the water resources in Colorado and the extent to which ignoring unclaimed locations discards valuable information about individuals' opportunity sets. We aggregate grid-level characteristics up to the level of stream and construct a panel of 1,922 streams from 1852 (the date of the first claim in our data) to 2013 (the date of the most recent claim).

Table 2 provides variable names, definitions, and summary statistics for the stream-level data and Appendix B provides detailed descriptions of how the geographic covariates were constructed. Variables relating to the stock and flow of rights along a river change over time,

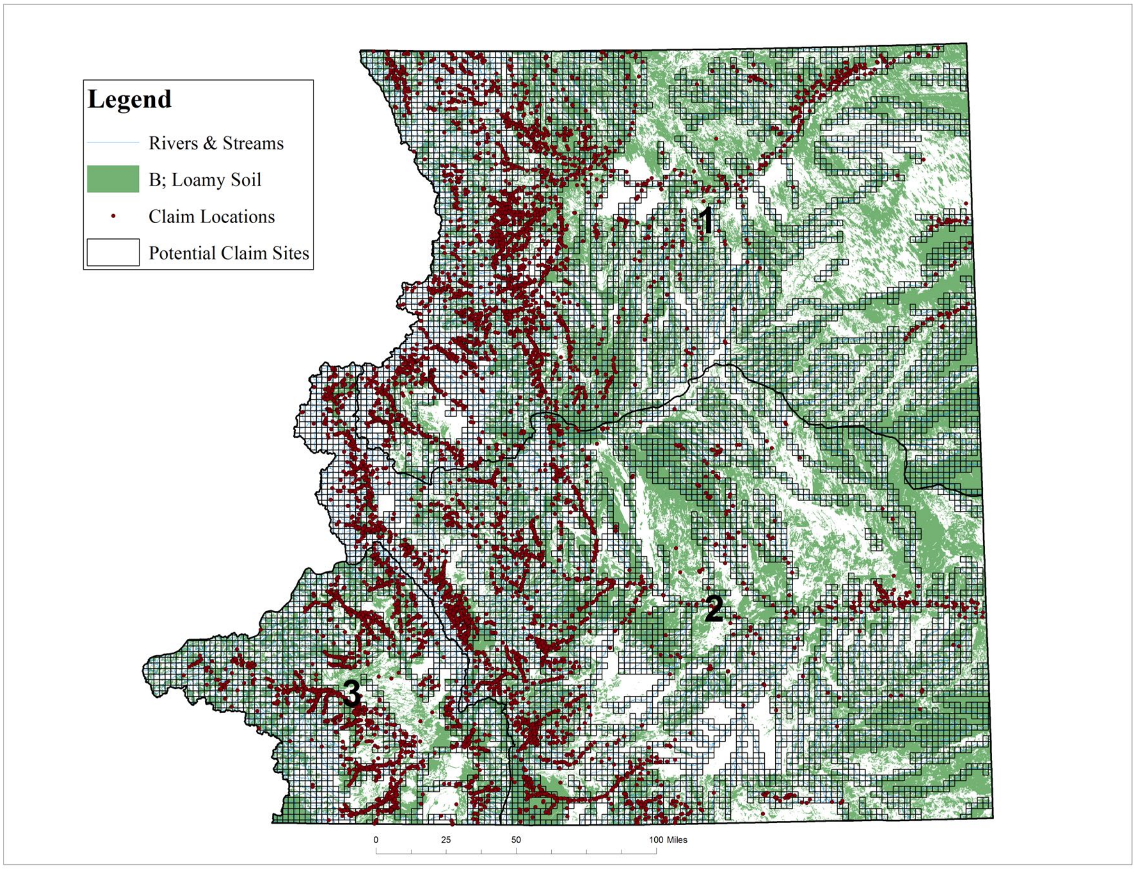
[22]GIS data on water rights were obtained directly from the Colorado Division of Water Resources.

[23]This grid approximates the Public Land Survey (PLSS) grid, but fills in gaps where GIS data on PLSS sections are not available. Actual homesteads and other land claims were defined as subsets of PLSS sections, so grid-level variation is similar to actual variation in land ownership and land use.

[24]We ignore sections that do not intersect any water features in our analysis because water claims can only established where there is water.

[25]We use soil group B, which is comprised primarily of loamy soil and is the most productive for agriculture.

Figure 5: Possible and Actual Claim Sites



whereas measures of resource quality are fixed. We aggregate from grid squares to streams for four reasons. First, priority varies by stream, so the fundamental trade-off between high-priority access and low information costs occurs at the stream level. Second, we observe variation in stream flow at the stream level, so subdividing beyond streams does not provide additional information about the water resource. Third, the count of claims in a given square mile in a given year is extremely small, by construction. Using such a fine spatial resolution reduces the variation in the dependent variable and results in an arbitrarily large number of zeros in the data. Fourth, the potential for measurement error in how we have delineated grid squares is reduced by aggregating up to a larger spatial unit that is defined based on underlying hydrologic variation rather than a more arbitrary partitioning of space.

Table 2: Stream-Level Summary Statistics

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	N	Mean	S.D.	Min	Max	Definition
New Claims	311,364	0.0253	0.529	0	62	Number of new claims on stream j in year t.
$\mathbb{1}$(New Claims)	311,364	0.0110	0.1045	0	1	Dummy variable equal to 1 if New Claims >0 in year t.
Initial Claims	311,364	0.00156	0.0510	0	2	Number of new claims on stream j in year 0.
$\mathbb{1}$(Initial Claims)	311,364	0.00104	0.0322	0	1	Dummy variable equal to 1 if Initial Claims >0.
Summer Flow	250,452	68.19	227.6	0	4,638	Flow (cfs) on stream j from May to August, averaged over 1890-2000.
Roughness	311,202	290.1	282.5	0.174	3,299	Std. dev. of slope multiplied by average slope along stream j.
Flow Variability	250,452	5.761	56.22	0.00687	1,353	Std. dev. of summer flow from 1890 to 2000.
$\mathbb{1}$(Drought)	311,364	0.160	0.367	0	1	Dummy variable = 1 during major drought years.
Homestead Acres$_{t-1}$	309,281	77.66	677.5	0	72,628	Number of acres homesteaded in township crossed by stream j in year $t-1$.
Homestead Claims$_{t-1}$	309,281	0.399	2.837	0	242	Number of homestead claims in township crossed by stream j in year $t-1$.
Total Homesteaded Acres	311,364	7,905	20,085	0	326,297	Cumulative acres homesteaded in township crossed by stream j as of year t
Percent Claimed	307,476	2.13	5.54	0	35.99	Cumulative prior water claimed/Summer Flow on stream j in year t
Acres Loamy Soil	311,364	367.29	3973.91	0	173086.5	Acres within 10 miles of stream j with loamy soil

Notes: 1) Data on homesteads were provided by Dippel et. al (Working Paper) and are based on Bureau of Land Management digitization of all land patents from the settlement of the Western United States. 2) Drought variables are based on major drought years described in Henz et al. (2004). 3) Annual historical flow estimates used to calculate Flow Variability could only be constructed for a subset of data due to the availability of other variables used in the hydrologic model. See online appendix for further detail.

4.2 Identification of Positive Spillovers in Establishing Water Rights

The presence of an additional senior user on a stream reduces the availability of water and makes any junior claimants unambiguously worse off and so should make the arrival of subsequent claimants less likely unless a positive externality exists. Hence, we look for evidence of positive spillovers by we estimating the effect of previous claims on a given stream on the probability and expected count of subsequent claims on that stream.[26] This gives our econometric model an inherently dynamic nature. We characterize number of claims on stream j in year t, which has the properties of a count variable, using a Poisson distribution.[27] The primary challenge to identification comes from the fact that there are unobserved location characteristics that we cannot measure, so that the presence of prior claims could act as a proxy for unobserved site quality and cause us to attribute the effect of these site attributes to positive spillovers instead. We can condition on soil quality, roughness, population pressure, stream flow, and stream variability, but any other variation in location quality observed by claimants but unobserved by us will bias our estimates if unaddressed.

Wooldridge (2005) provides a method for using initial values of y_{jt} to estimate Average Partial Effects (APE) of y_{jt-1} on y_{jt} that are averaged across the distribution of unobserved heterogeneity. We assume that y_{jt} has a Poisson distribution with conditional mean

$$\mathbb{E}(y_{jt}|y_{jt-1}, ..., y_{j0}, \mathbf{x_j}, u_j) = u_j \exp(x_{jt}\beta + y_{jt-1}\rho) \tag{8}$$

Where u_j is a site-specific unobserved effect. Wooldridge shows that ρ can be identified by specifying a distribution for $u_{jt}|y_{j0}, \mathbf{x_j}$. In particular, if we assume

$$u_j = \nu_j \exp(\delta y_{j0} + \gamma \mathbf{x_j}) \qquad \nu_j \sim \text{gamma}(\eta, \eta) \tag{9}$$

then forming the likelihood and integrating out the distribution of u_j conditional on y_{j0} and $\mathbf{x_j}$ results in an estimator that is equivalent to the random effects Poisson estimator in Hausman et al. (1984). We implement this solution and estimate a random effects model controlling for y_{j0} to recover the partial effects of the variables of interest, averaged over

[26] This is more appropriate than a multinomial approach because our hypotheses concern how changes in the characteristics of the possible choices themselves affect behavior, whereas multinomial choice models are designed to estimate how individual characteristics affect the choices that those individuals make. We lack data on individual characteristics but are able to construct rich panel data on locations, so we rely on dynamic panel methods for our estimations.

[27] In a given year most of the 1,922 streams receive zero new claims, there cannot be a negative number of claims, and the maximum number of claims on any stream in a given year is 62

the distribution of u_j. Placing parametric restrictions on the distribution of unobserved heterogeneity and the conditional distribution of $(y_{jt}|y_{jt-1}...y_{j0})$ is what allows us to use the initial values y_{j0} to trace the evolution of y_{jt} separately from the unobserved effect. We prefer this method to a fixed effects approach, which would necessarily discard all streams that never receive a claim, resulting in potential selection bias.

Identification requires several assumptions. First, we must assume that we have correctly specified the densities for the outcome of interest in equation 8 and the unobserved effect in equation 9. We maintain this assumption, emphasizing the count nature of our dependent variable and the standard use of a gamma distribution for modeling random effects in similar contexts.[28] Second, we must assume that ν_j is independent of $\mathbf{x_j}$ and y_{j0}. This requires that the random component of the unobserved heterogeneity in site quality is in fact random and not dependent on observed covariates.[29] Our covariates are either fixed geographic characteristics or lagged values of other variables, making this assumption plausible.

Third, we must assume that the dynamics of y_{jt} follow a first-order Markov process—that the dependence of y_{jt} on the complete history of claims in the same location can be summarized by the relationship between y_{jt} and y_{jt-1}.[30]. We argue that conditioning on the cumulative diversions along a stream—an element of $\mathbf{x_j}$—alleviates concern that the cumulative stock of claims prior to period $t-1$ could directly affect y_{jt}. In any given period, users direct their location choice based on what users in the previous period did and on the total amount of the resource that is still available for claiming, but the total number of claims is not directly relevant except through its affect on y_{jt-1}. Claims from the previous period provide a signal to potential followers about whether claiming on stream j is profitable, given the declining rents of claiming on a given stream as claims accumulate. Beyond this signal, the effect of prior claims will be captured in our measurement of cumulative prior diversions.

4.3 Empirical Estimates of Claiming Externalities

Table 3 reports the results of the random effects Poisson estimator. We calculate and report the estimated average marginal effects of each of the covariates on the probability of a stream receiving at least one new claim in a given year.[31] All specifications control for stream size and variability (Summer Flow and Flow Variability), drought, land quantity

[28]We perform a variety of simulations and confirm that the estimator is robust to alternative data generating processes for u_j.

[29]But note that the unobserved component of equation 8—u_j—is allowed to depend on $\mathbf{x_j}$ and y_{j0}.

[30]This is implicit in equation 8.

[31]Averaged across the distribution of unobserved heterogeneity u_j.

and quality (Roughness, Acres Loamy Soil, Watershed Acres), population pressure (Lagged Homestead Claims), and initial claims (required for identification). Column 2 controls for the total amount of water already claimed on a stream, and column 3 also controls for the total number of acres already homesteaded in the same township as the stream. We predict that claims will be more likely when water is abundant (higher Summer Flow, less water claimed, and Drought = 0) and when there is population pressure (more lagged Homestead Claims). Limited information with high search costs implies that difficult-to-assess variables like Flow Variability and Soil Quality should not affect claiming behavior. The key test for the existence of positive externalities is whether the coefficient on Lagged Claims is positive.

Nearly all of the variables in Table 3 have the expected signs. Across all three specifications, the probability of new water claims is greater when there are more Lagged Water Claims or Lagged Homestead Claims, Watershed Acres are greater, and the stream—measured by Summer Flow—is larger. New Claims are less likely during Drought and when more of the land around the stream has already been homesteaded. In Column 2, more Total Water Claimed reduces the probability of new claims, but the coefficient becomes positive in Column 3 once we control for Total Homesteaded Acres.

Consistent with our intuition, several of the variables have no effect of the probability of new water claims on a stream. Topographic Roughness, Flow Variability, and Acres of Loamy Soil are insignificant with precisely-estimated zero coefficients in all three specifications. This is consistent with our hypothesis that claimants in the 19th century faced significant information problems. Migrants were unable to assess the inter-annual variability of stream flow or the viability of soil because they lacked knowledge of the long-term climate and necessary farming techniques in the region, as was the case across the West.

Table 3 provides strong evidence for the existence of significant positive externalities in the definition of prior appropriation water rights. The estimated coefficient on Lagged Claims is statistically significant across specifications and indicates that the probability of at least one new claim on a stream in any particular year increases by about a half of a percentage point for each claim established on that stream the previous year. This is an effect size of roughly 20%, as the mean probability of new claims is just 2.5%—this means that the presence of just five new claims on a stream doubles the probability of new claims on the same stream in the following year. Combined with the finding that critical resource characteristics did not influence location choice, this result suggests that early claimants generated important information for subsequent claimants.

We are able to rule out the possibility that claimants' decisions to locate near prior

Table 3: **Empirical Determinants of Prior Appropriation Claims**

$\frac{\partial Pr(NewClaims>0)}{\partial x}$	(1)	(2)	(3)
	Poisson Estimates, Y = New Water Claims$_{jt}$		
Lagged Claims	0.00556***	0.00570***	0.00490***
	(0.000658)	(0.000621)	(0.000622)
Summer Flow	0.0000590*	0.0000594*	0.0000641*
	(0.0000330)	(0.0000333)	(0.0000345)
Flow Variability	-0.0000167	-0.0000172	-0.0000198
	(0.0000122)	(0.0000125)	(0.0000127)
$\mathbb{1}$(Drought)	-0.0105***	-0.0101***	-0.00832***
	(0.00158)	(0.00169)	(0.00132)
Roughness	-0.0000169	-0.0000170	-0.0000233
	(0.0000168)	(0.0000169)	(0.0000191)
Acres Loamy Soil	-0.00000191	-0.00000159	0.00000182
	(0.00000313)	(0.00000302)	(0.00000299)
Watershed Acres	0.00000500*	0.00000501*	0.00000520*
	(0.00000282)	(0.00000289)	(0.00000293)
Homestead Claims$_{t-1}$	0.000220***	0.000254***	0.000297**
	(0.0000451)	(0.0000550)	(0.000133)
Initial Claims	0.00941**	0.00934**	0.00329
	(0.00394)	(0.00386)	(0.00505)
Total Water Claimed (cfs)		-4.84e-08**	0.000000104**
		(2.33e-08)	(5.20e-08)
Total Homesteaded Acres			-0.000000546**
			(0.000000230)
N	248,745	248,745	248,745
χ^2 for $H_0: R.E. = 0$	7,979.36	7,571.86	8,322.72

Notes: Standard errors are clustered by stream and reported in parentheses. N= 248,745 is the number of stream-year cells for which we have overlapping data on all covariates. * $p < .1$, ** $p < .05$, *** $p < .01$

claimants are driven by other benefits not related to water claims by examining the role of population growth in the evolution of water rights. Although the existence of new homestead claims in the same township as a stream makes new claims on that stream more likely by about 0.02 percentage points in the following year, a single water claim has the same effect on the probability of new claims as roughly 22 homestead claims. This indicates that water claimants' decision to follow prior claimants was driven by benefits specific to the definition of water rights rather than a general positive benefit of locating near other settlers on the frontier. In Section 5 we analyze the mechanisms for this resource-specific externality.

The estimated effect of Lagged Claims is also large relative to other covariates. Claims are more likely to be established on larger streams, but the effect of a single lagged claim is equivalent to an 95 cfs increase in Summer Flow, about 1/3 greater than the average stream's Summer Flow of 68 cfs. Similarly, although claims are about 40% less likely during a major drought, the presence of just two prior claims on a stream could offset this major resource shock. These relative magnitudes demonstrate the economic significance of the externalities generated by early claimants—the information and potential coordination benefits of locating near prior claimants are on par with major shifts in the availability of water resources.

Information benefits provided by early claimants included demonstration of where and how irrigation ditches could be established. As we detail below, the best locations to divert water from the stream were not obvious and had to be discovered by experimenting. Techniques for irrigating flat, plateaued lands above stream channels were particularly valuable but not initially apparent. The development of these methods attracted waves of subsequent settlers to jointly claim water and land in areas previously considered unproductive.

Though information generated by early claimants generated a positive externality by lowering information costs for subsequent claimants, it also created the possibility for rent dissipation. The fact that claims were less prevalent during drought, combined with users' unresponsiveness to variability, points to the possibility of dissipation through over-claiming of the resource identified in our theory (although we note that a share-based allocation would have exacerbated rent dissipation due to over-entry). Claims are more likely when water is more abundant, indicating a first-order responsiveness to resource abundance that does not account for the underlying variability in the resource. It so happens that much of the settlement of the Great Plains and the Western United States occurred during a period of unusually high rainfall (Libecap and Hansen, 2002;, Hansen and Libecap, 2004). This bias in the timing of water claims, rather than some inherent institutional weakness in the initial allocation of property rights, can explain the mismatch between legal water rights and available supplies observed today.

Early claims generated real value for subsequent claimants equivalent to major changes in expected resource availability, but the accumulation of prior claims itself reduced resources available for future claimants. Column 2 of Table 3 indicates that an increase in the cumulative volume of claimed water on a stream reduces the probability of new claims on that stream by an statistically significant but economically small margin—an increase in the volume of claimed over over 100,000 cfs would be required to offset the positive effect of a lagged claim. In contrast, an increase in the cumulative total of homesteaded acres along a stream reduced the probability of new claims by about 1% for every 1,800 acres claimed (roughly ten homesteads).

Reductions in available resources had a real effect on claimants behavior, although the effect of water availability is quite small. This minuscule effect may be driven by claimants' lack of full knowledge of the legal volume of prior claims—the sum of "paper" water rights may not have been of primary concern to settlers as they observed real flows and chose claim sites. If claimants imperfectly understood or partially disregarded the actual measurement of water, then the average Summer Flow of a stream is likely to be a better measure what they perceived the resource constraint to be.

To assess the the trade-off between resource availability and information externalities, we estimate the effect of Lagged Claims on the probability of New Claims for different size streams and plot the results in Figure 6. The vertical axis is the estimated marginal effect of Lagged Claims on the probability of at least one new claim on a stream, and the horizontal axis is average stream size. The figure shows how the effect of Lagged Claims on Pr(New Claims) varies with stream size and depicts a clear trade-off between the benefits of following earlier users and the reduced expected benefits from decreased water availability; the positive effect of lagged claims is monotonically increasing in stream size.[32] Claimants were more likely to follow prior users on larger streams than on smaller ones, indicating a direct positive effect of following that depends on their being enough water for information and coordination to be taken advantage of by subsequent claimants.[33]

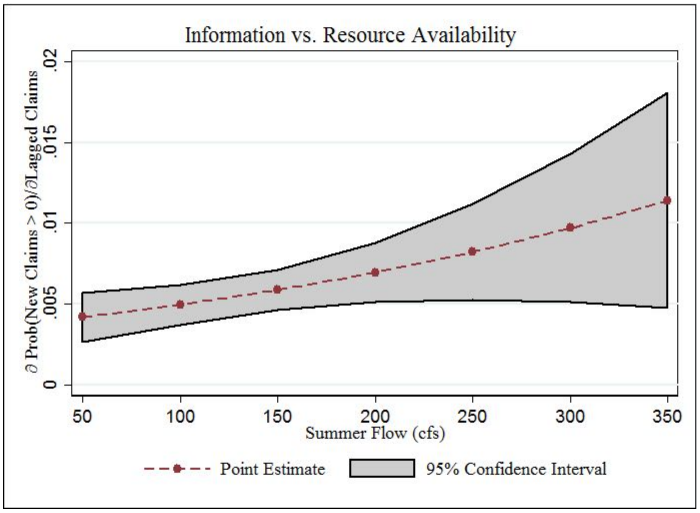
The development of water rights on South Boulder Creek near Boulder, Colorado illustrates the economic behavior we identify in Table 3. The earliest claims on South Boulder Creek are associated with the Jones and Donnelly Ditch, which was established in 1859 to irrigate fertile land near the creek (Crifasi, 2015, p 105). Seven other water rights were established on South Boulder Creek in that same year. This prompted an additional eight claimants to follow suit and establish water rights on South Boulder Creek the following year in 1860. Finding the fertile lowlands already homesteaded, these new claimants developed methods for irrigating more remote lands that were often on bluffs above the creek.[34] This

[32]Figure 6 is a visual depiction of the cross-partial derivative $\frac{\partial^2 Pr(NewClaims)}{\partial LaggedClaims \partial SummerFlow}$.

[33]It may also be that the range of learning opportunities was narrowed on smaller streams, where the number of possible diversion sites and techniques was smaller than on large streams.

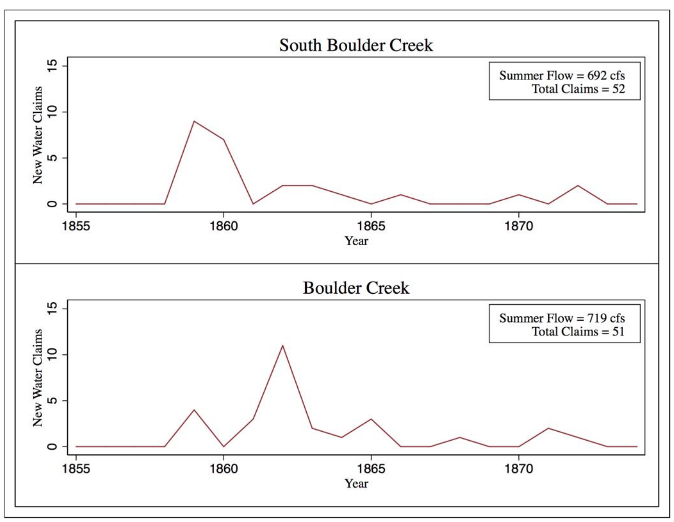
[34]Lemuel McIntonish, who filed his claim in 1862, built one of the first "high line" ditches in Colorado,

Figure 6: The Information-Resource Trade-Off



discovery prompted a subsequent wave of similar "high line" ditches on Boulder and South Boulder Creeks, including the Farmer's Ditch which would eventually supply much of the water for the city of Boulder (Crifasi, 2015, p 187).

Figure 7: Evolution of Claims Near Boulder, Colorado



Eventually, claiming on both streams ceased as all available farmland and water was fully appropriated. Figure 7 depicts the early development of claims on Boulder and South

demonstrating for the first time that highlands could be irrigated by diverting water further upstream and guiding it to one's land at a shallow grade (Crifasi, 2015, p 187).

Boulder Creeks.[35] Claiming fell in 1861 on South Boulder Creek after two years of heavy claiming—between 1859 and 1861 the volume of claimed water went from zero to over twice our estimate of the mean summer stream flow. Similarly, when the multi-year wave of new claims on Boulder Creek ceased in 1866, prior claims exceeded average summer flow by a factor of ten.[36] The trade-off between resource availability and positive externalities from prior claims is borne out in analysis of claiming behavior on particular streams—new claimants are initially quick to follow prior claimants, but they are equally quick to find new streams once the resource constraint binds.

We find strong evidence of high information costs, resource constraints, and positive spillovers in the search and investment required to establish prior appropriation water rights. Conditional on resource availability, homestead pressure, and unobserved site quality, an increase in the number of new water claims along a particular stream increases the probability of new claims along that same stream in the next year by 20%.[37] When deciding where to establish a claim, new users are more responsive to choices of earlier claimants than they are to many important, but difficult-to-observe resource characteristics like soil quality and stream variability. The fact that claims are more likely when water is abundant indicates a systematic bias in the timing of claims that explains the overcapacity of irrigation infrastructure described by Coman (1911), Teele (1904), Hutchins (1929), and Libecap (2011).

4.4 Robustness

We re-estimate our model using a set of alternative estimators to evaluate the robustness of our identification strategy given the unique character of our data set. There are three primary concerns that could threaten identification. First, our dataset contains a large number of zeros because in any year most streams receive zero claims.[38] Second, the distribution of

[35] Most water rights established after 1875 in the Boulder Valley were for "tailings" or return flows of pre-existing claims (Crifasi, 2015).

[36] The excess of claimed water above estimated flow can be explained by the ability of parties to re-appropriate return flows from prior users and our inability to measure actual flows prior to 1890. Early measurements of water rights were notoriously rough, making exact comparisons between water rights and flow difficult (Crifasi, 2015).

[37] In a series of robustness checks, discussed in appendix B, we find evidence of attenuation bias due to excess zeros and find that alternative estimators produce larger estimated marginal effects than our main results reported in Table 3, which should be interpreted as a lower bound on the magnitude of positive spillover effects from investment.

[38] In any given year, most of the 1,922 streams in our same do not receive new claims. Moreover, the identifying assumption for the random effects probit is slightly less restrictive for our setting in that it only requires that the probability of a new claim in year t depends only on whether there was a claim in the previous year and not whether there were claims in other, earlier years.

unobserved heterogeneity may be incorrectly specified in Equation 9 if ν_j is not independent of $\mathbf{x_j}$. Third, estimates of ρ are biased if the errors in our model are serially correlated.

We address the first problem by reproducing the estimated marginal effects from Table 3 using a random effects Probit—also discussed in Wooldridge (2005)—where the dependent variable is a dummy that is equal to 1 if there was a new claim along on stream j in year t. The Probit is more robust to the presence of excess zeros because it is designed to take only 0 and 1 outcomes, whereas the Poisson distribution is more sensitive. The results are reported in Appendix Table C1. To alleviate concern over our identifying assumptions about the relationship between ν_j and $\mathbf{x_j}$, we estimate fixed effects Poisson and fixed effects Logit models and find results similar to the random effects Poisson and Probit. These results are reported in Appendix Tables C2 and C3.[39]

We address the problem of potential serial correlation in the error in two ways. First, we restrict the data set to claims prior to 1950 and estimate the model using a linear GLS technique from Hsiang (2010) that allows for an AR(1) structure in addition to spatial autocorrelation in the error term. Second, we perform a series of Monte Carlo simulations to understand the behavior of the random effects Poisson estimator in the presence of serially correlated errors and/or excess zeros in the dependent variable. Our results (forthcoming in an online appendix) suggest a consistent attenuation bias in the presence of either complication, suggesting that our estimates are lower bounds on actual effect sizes.

5 Economic Implications of Prior Appropriation

5.1 Claim-Level Data

Next, we analyze the economic outcomes associated with prior appropriation claims to understand the specific mechanisms for the externality identified in Section 4, focusing on coordination and investment. We use a single water right as the unit of analysis in this section and develop separate, rights-level measures of the geographic covariates from the previous section by matching rights to the characteristics of the grid sections within 10 miles of each right, providing measures of the quality of nearby lands that would have been available for development. We also construct the variable CoOp, which is equal to one for claims established on the same stream on the same day as other rights. We argue that these rights are associated with ditch companies and other forms of formal cooperation (Hutchins,

[39]We not not estimate marginal effects in these models. Instead, we report the raw coefficient estimates.

1929).[40] We obtained GIS data on irrigation canals and ditches for Divisions 1 (South Platte) and 3 (Rio Grande) in addition to parcel-level GIS data on crop choice and irrigated acreage by crop for certain historical years from the Colorado Division of Water Resources.[41] Each right has a unique identifier number that we use to match it to ditches and to parcels of irrigated land, resulting in 550 rights for which we have complete data.[42] Table 4 provides summary statistics for the claim-level data.

Stream flow, flow variability, and homesteads are defined by stream as in Section 4. We measure the quality of the land endowment or potential land endowment associated with each right slightly differently in this section than in Section 4. For each right we calculate the number of acres of loamy soil within ten miles of the point of diversion in addition to the roughness of the terrain within a ten-mile radius of the point of diversion. We also calculate the total acreage of all one-mile grid squares that are adjacent to the stream. These variables capture the quality of the land endowment available for claiming in proximity to each right. For the subset of our data that we are able to match to actual irrigated parcels, we calculate the characteristics of parcels associated with each right. We control for these important geographic covariates because the quality of the land and water resources near each right may have a direct affect on agricultural output that would bias our estimates of the effect of property rights on returns to irrigation if unaddressed.

To measure farm size, we calculate the total number of acres irrigated on all parcels associated with each right for which we have matching data, captured in the variable Irrigated Acres. Our irrigation data also tell us what crops and how many acres were planted on each parcel. We use estimates of average yield per-acre and prices for Colorado for each crop in our dataset from the Census of Agriculture from 1936 and 1956 to estimate the total value of irrigated agricultural output for each parcel and matching water right in our dataset. The variable Total Income reports the sum of income from each crop associated with a right in a given year, in 2015 dollars. These data form our primary basis for estimating the returns to irrigated agriculture in eastern Colorado.[43] Next, we use these data to assess possible channels for the externalities we identified in Section 4.

[40] We are currently verifying this interpretation by researching the ditch names associated with each of these rights and confirming that they were associated with some form of joint construction or claiming effort.

[41] We use data for 1956 for Division 1 and 1936 for Division 3. No data are available for division 2.

[42] We perform a variety of tests to check for selection bias on the claims for which ditch data are variable.

[43] Because there are potentially other irrigated parcels for which the Department of Water Resources does not have data, our estimates of on the value of agricultural production due to the expansion of irrigated acreage made possible by the prior appropriation doctrine by be biased downwards.

Table 4: Claim-Level Summary Statistics

Variable	(1) N	(2) Mean	(3) S.D.	(4) Min	(5) Max	(6) Definition
Claim Size	7,999	15.63	123.4	0	8,631	Volume of water (cfs)
Claim Date	7,999	-23,211	11,900	-39,346	19,395	Days since 1/1/1960.
Total Income	778	605,953	2,833,755	0	4.56e+07	Income from acres irrigated using right i in year t.
Irrigated Acres	778	1,592.6	5,811.7	1.516	91,987	Total acres irrigated using right i in year t.
Income Per Acre	778	544.44	390.91	68.23	1,933	Income per acre from acres irrigated using right i in year t.
Ditch Meters	778	10,658	28,420	45.06	352,729	Meters of ditch associated with right i.
Percent Loamy Soil	778	1.022	4.803	0	1	Share of Irrigated Acres possessing loamy soil.
Acres Loamy Soil (Parcel)	778	37.43	102.3	0	640	Acres of loamy soil on acres irrigated by right i.
Acres Loamy Soil (Proximity)	6,482	3,804	4,078	0	16,291	Acres of loamy soil within 10 miles of right i.
Stream Length	7,889	5.258	4.291	0.0550	36.23	Length of stream (km) that right i lies on.
CoOp	7,999	0.259	0.438	0	1	Dummy var. = 1 for rights associated with cooperation or mutual ditches.
Summer Flow	7,889	501.8	1,266	0	8,470	Flow (cfs) on stream j from May to August, averaged over 1890-2000.
Flow Variability	6,337	23.82	145.6	0	1,224	Std. dev. of summer flow from 1890 to 2000.
Roughness	6,479	142.7	107.7	0.0720	934.2	Avg. Slope*Std. Dev. Slope (w/in 10 mi. of right).
Acres	6,482	11,022	11,902	0	53,696	Total acres near stream j associated with right i.
Claim Year	7,999	1896	32.54	1852	2013	Year in which right i was established.
Homestead Acres	7,999	346.3	1,297	0	35,463	Acres homesteaded during in which right i was established.
Homesteads	7,999	2.179	7.024	0	131	Number of new homesteads during year in which right i was established.
1st Priority Decile	7,999	0.248	0.432	0	1	Dummy var. =1 claims with priority in top 10% on a stream.
2nd Priority Decile	7,999	0.0815	0.274	0	1	Dummy var. =1 claims with priority in 11%-20% on a stream.
3rd Priority Decile	7,999	0.0911	0.288	0	1	Dummy var. =1 claims with priority in 21%-30% on a stream.
4th Priority Decile	7,999	0.0913	0.288	0	1	Dummy var. =1 claims with priority in 31%-40% on a stream.
5th Priority Decile	7,999	0.0729	0.260	0	1	Dummy var. =1 claims with priority in 41%-50% on a stream.
6th Priority Decile	7,999	0.111	0.314	0	1	Dummy var. =1 claims with priority in 51%-60% on a stream.
7th Priority Decile	7,999	0.0973	0.296	0	1	Dummy var. =1 claims with priority in 61%-70% on a stream.
8th Priority Decile	7,999	0.0783	0.269	0	1	Dummy var. =1 claims with priority in 71%-80% on a stream.
9th Priority Decile	7,999	0.0780	0.268	0	1	Dummy var. =1 claims with priority in 81%-90% on a stream.
99th Priority Percentile	7,999	0.0499	0.218	0	1	Dummy var. =1 claims with priority in 91%-99% on a stream.

Note: We have data on 7,999 claims in eastern Colorado, but only 778 claims have matching ditch data. Of these, only 550 also have complete elevation and flow data available.

5.2 Coordination and Investment

In this section we examine infrastructure-related benefits of first possession claims. To do this, we estimate the effect of priority-differentiated water rights on coordination and investment in irrigation infrastructure in eastern Colorado. First we use our entire data set to ask whether coordination was more likely for users with more senior water rights. Then, we use a subset of our data to estimate the effect of coordination on investment and how this effect varies across different institutional settings. We have data on ditch investment for Divisions 1 (South Platte) and 3 (Rio Grande), which comprised markedly different institutional settings for the development of prior appropriation. Division 3, mainly comprised of the San Luis River Valley, had a predominantly hispanic population with a long history of communal norms that governed irrigation.[44] In contrast, Division 1 was settled by relatively heterogeneous immigrants from across the United States and Europe (Crifasi, 2015). Whereas long-evolved shared cultural norms guided behavior in Division 3, the legal doctrine of prior appropriation was the common denominator among the heterogeneous settlers of Division 1. (Hicks and Peña, 2003). This key difference between the two jurisdictions allows to us to assess the role of formal property rights as a coordination mechanism with and without the presence of common social norms and informal institutions See Appendix Table C7 for a comparison of the two groups.

First, we examine the determinants of cooperation across all of eastern Colorado, focusing on the hypothesis that users with more secure (higher priority) water rights are more likely to coordinate. Priority is an ordinal ranking of rights along a stream. Including this simple priority measure in a regression would force the effect of priority to be linear, implying that the difference between being the first and second claimant is the same as the difference between being, say, the fourteenth and fifteenth claimant. To allow for a non-linear, semi-parametric effect of priority on cooperation in ditch construction, we rank rights by priority and create bins for each decile of the distribution of priority by stream, yielding ten dummy variables that indicate which decile each claim is in. For example, if the 1st Decile Dummy is equal to 1, the associated water right was among the first 10% of claims along the stream it lies on and had high-priority access to water during drought. This allows changes in priority to affect the probability of coordination differently at different points in the distribution of priority.

We use a fixed effect logit regression to obtain semi-parametric estimates of the marginal

[44] In fact, it was observation of these and other *acequias* in New Mexico that prompted the first settlers to attempt irrigation in eastern Colorado (Crifasi, 2015).

Table 5: Marginal Effects of Priority on Cooperation

	(1)	(2)	(3)	(4)
	Divisions 1-3		Division 1	Division 3
1st Priority Decile	0.123***	0.119***	0.0207	0.194**
	(0.0359)	(0.0390)	(0.0779)	(0.0861)
2nd Priority Decile	0.0541	0.0725	0.0154	0.123
	(0.0456)	(0.0472)	(0.0929)	(0.102)
3rd Priority Decile	0.0882*	0.119**	-0.00675	0.202*
	(0.0468)	(0.0488)	(0.0861)	(0.119)
4th Priority Decile	0.0318	0.0419	0.0624	0.00619
	(0.0432)	(0.0431)	(0.0855)	(0.0905)
6th Priority Decile	-0.0154	-0.00285	-0.0558	0.0391
	(0.0518)	(0.0495)	(0.0698)	(0.0997)
7th Priority Decile	0.0366	0.0359	-0.0761	0.146
	(0.0401)	(0.0421)	(0.0674)	(0.107)
8th Priority Decile	-0.0591	-0.0910*	-0.181**	-0.0301
	(0.0447)	(0.0485)	(0.0753)	(0.0902)
9th Priority Decile	-0.160***	-0.211***	-0.238**	-0.292*
	(0.0465)	(0.0522)	(0.0939)	(0.175)
99th Priority Percentile	-0.236***	-0.330***	-0.488***	-5.193***
	(0.0643)	(0.0774)	(0.189)	(1.314)
Homesteads	Yes**	Yes*	Yes	Yes
Summer Flow	Yes***	Yes***	Yes*	Yes**
Flow Variability	Yes	Yes	Yes	Yes*
Roughness	Yes	Yes	Yes	Yes
Acres of Loamy Soil	Yes	Yes	Yes	Yes
Acres	Yes	Yes	Yes*	Yes
Watershed Fixed Effects	No	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes
N	4,756	4,354	1,206	937

Standard errors are clustered by watershed and reported in parentheses

* $p < .1$, ** $p < .05$, *** $p < .01$

effect of priority on coordination among right-holders in infrastructure investment, relying primarily on within-watershed variation for identification. The dependent variable is a dummy that is equal to 1 for rights that are established on the same stream on the same day. We control for stream characteristics, land quality within ten miles, population pressure, and watershed and year fixed effects. Table 5 presents the estimated marginal effects of each priority decile on the probability of cooperation, relative to the 5th decile.[45] Columns 1 and 2 are estimated jointly for all three divisions, where columns 3 and 4 report the results for Divisions 1 and 3 separately.

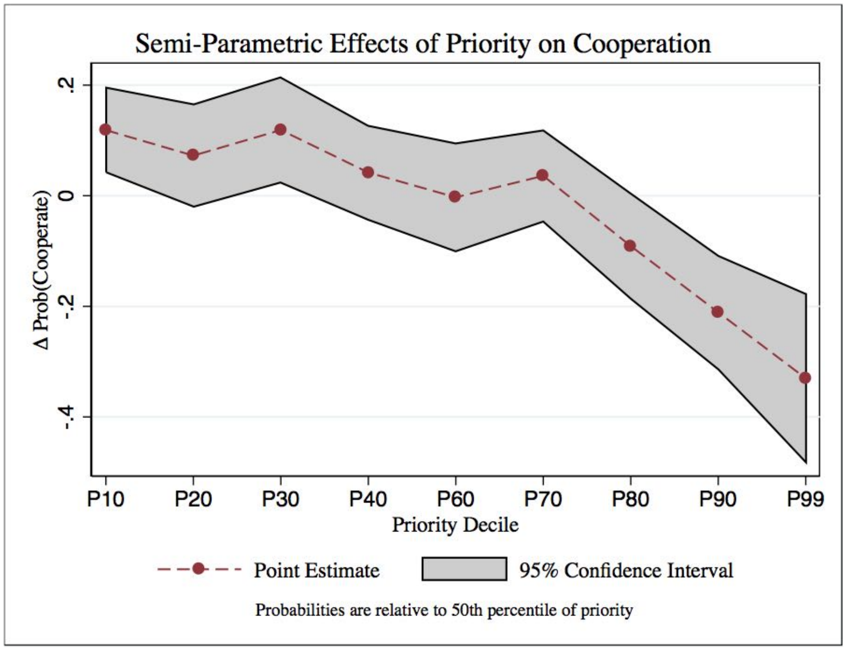
We find a higher probability of coordinating for investment in infrastructure for rights above the 5th decile and lower probability of coordinating for rights below the 5th decile. Figure 8 depicts the marginal effects of each priority decile on cooperation associated with the model in column 2 of Table 5. Prior appropriation water rights in the top 10% of priority on a given stream are about 12 percentage points more likely to jointly establish claims and ditches than users in the middle decile, while very junior right-holders in the 10th decile are 20-30 percentage points less likely to coordinate. Taken together, these estimates imply that water right-holders with the highest priority on a stream were 40 percentage points more likely to coordinate with one another than the most junior right-holders. This general pattern holds within Division 1 and Division 3 separately, particularly with respect to the lowest priority right-holders. As Figure 8 indicates, much of this effect is concentrated in the bottom half of the distribution of priority—the effect of priority on investment is larger for users with low priority.

Those right-holders with the most variable water supply were the least likely to jointly invest in irrigation capital. By contrast, right-holders in the top half of the priority distribution face relatively small differences in their exposure to stream variability and have a high likelihood of securing water and not stranding ditch capital and hence have a similar probability of coordinating. However, each drop in priority in the lower half of the distribution represents a larger shift in real access to water, generating larger effects on the probability of coordination. The more heterogeneous users become in their exposure to risk, the less likely they are to cooperate. This is consistent with Wiggins and Libecap (1985), who find that cooperation among oil field operators in oil field coordination and investment becomes less likely as they become more heterogeneous.

Next, we assess the extent to which ditch investment differed according to whether or not claimants coordinated with other water right-holders. Our measure of investment is the length of the ditch (in meters) associated with a given water right. Longer ditches were costlier to construct but allowed users access to more valuable farmland, particularly in Colorado where land adjacent to streams was often rugged and unsuitable to farming (Hayden, 1869). The costs of ditch investment had to be borne up front, before there was

[45] Marginal effects are estimated at the median values of the controls and standard errors are calculated using the delta method.

Figure 8: Marginal Effects of Priority on Cooperation



reliable information about the availability of water over time.

Coordination between water right-holders could increase ditch investment because i) it allowed users to share these upfront costs, ii) allowed for the possibility of pooling water claims during times of limited flow to maximize the value of irrigated agriculture, iii) it created a framework for governance and assignment of maintenance responsibilities, and iv) it helped prevent post-contractual opportunism from informal promises of water deliveries. (Crifasi, 2015). Users who cooperated still developed individual ditches known as laterals to bring water to their own particular fields (see Figure 9 below). This gives us unique ditch lengths for each water right in this portion of our sample, even if those users were part of a cooperative effort.

Prior appropriation facilitated the cooperation necessary for development by making users in any given period secure against the arrivals of future claimants. A share system must confront the problem of how to incorporate demands of future claimants, whereas prior appropriation right-holders are ensured that their rights are paramount relative to future arrivals. In fact, claimants eventually began constructing large ditches for the sole purpose of selling access to future settlers in need of water (Crifasi, 2015). This required security of ownership so that ditch builders could reap the rewards of their costly investment. Prior appropriation also provided a way to clearly delineate group membership by creating a secure property right that could serve as a legal basis for incorporation—new arrivals would have to buy their way into existing arrangements. This reduced uncertainty about group size and heterogeneity, which lowered the costs of collective action (Ostrom, 1990).

Table 6 reports our estimates of the effect of cooperation and priority on Ditch Meters using a GMM approach developed by Hsiang (2010) that adjusts for possible spatial and time-series autocorrelation in the error term. We include watershed and year fixed effects and variety of controls for access to water and land resources, with complete results on the controls reported in Appendix Table C5.[46] Columns 1, 2, and 3 are estimated jointly across Divisions 1 and 3, while columns 4 and 5 are estimated separately for each Division.[47] In our preferred specifications we find that cooperative claimants' ditches are 10,198 meters longer than non-cooperative claimants' in Division 1, but that coordination does not affect ditch investment in Division 3.[48]

Two possible explanations for the null effect of coordination on investment in Division 3 are that the predominantly Hispanic population either i) lacked full access to the legal system for enforcing prior appropriation claims or ii) had less wealth and access to credit than settlers in Division 1, thereby reducing investment. The fact that high-priority claimants are more likely to cooperate in Division 3, just as in Division 1 (Table 5), makes it unlikely that legal status varied sharply between groups, pointing towards another explanation for differences in investment incentives. On the other hand, differences in wealth would result in less ditch building overall but should not reduce the role of formal coordination for projects that were undertaken. We suspect that the differential role of formal coordination between Divisions 1 and 3 can be explained by the dominant communal norms in Division 3. These strong norms for sharing available water during drought may have undermined the formal legal status of prior appropriation rights by obligating water users to informally share their legally secure

[46]The pattern of spatial dependence follows Conley (2008).

[47]Ditch data are not available for Division 2.

[48]One potential concern with our results on ditch investment is that investment and cooperation are jointly determined and that CoOp is endogenous in Table 6. If this is true, then the finding that CoOp ditches are longer may be due to simultaneity bias. We argue that the empirical time-line associated with establishing and then developing a water claim resolves this issue. While intended ditch length may be simultaneously determined with whether or not a right is claimed cooperatively, actual ditch construction is a costly and time-consuming process—the average ditch in our sample is 10.5 kilometers long. The upshot is that the cooperative status of a water claim is exogenous to ditch length because the former necessarily predates the latter. A similar concern could be stated and similarly dismissed with respect to the endogeneity of priority. To check the robustness of our results we reproduce them first by omitting priority and then by using then number of claims in the same month and same watershed as a given right as in instrument for CoOp and obtain similar estimates of key parameters. In general we find that after controlling for coordination, priority has no direct effect on ditch investment. For the sake of brevity we do not report the coefficients for each decile, but they are available in appendix Table C3.

Table 6: Effects of Coordination and Priority on Investment

	(1)	(2)	(3)	(4)	(5)
	Divisions 1 & 3			Division 1	Division 3
CoOp	5,963.9**	4,461.5**	4,472.0**	10,197.9**	-2,202.6
	(2,736.0)	(2,199.0)	(2,195.7)	(4,004.1)	(2,139.6)
Claim Size	244.7***	255.7***	256.3***	352.2***	130.0***
	(61.56)	(69.15)	(69.33)	(102.0)	(29.70)
Priority Controls	Yes	Yes	Yes	Yes	Yes
Summer Flow	Yes	Yes	Yes	Yes	Yes
Flow Variability	Yes	Yes*	Yes*	Yes	Yes**
Roughness	Yes	Yes	Yes	Yes	Yes
Acres of Loamy Soil	Yes***	Yes	Yes	Yes**	Yes
Claim Year	Yes	Yes	Yes	Yes	Yes
Homesteads		Yes			
Homestead Acres			Yes	Yes	Yes
Watershed Fixed Effects	No	Yes	Yes	Yes	Yes
N	550	550	550	292	258
R^2	0.293	0.354	0.353	0.464	0.169

Spatial HAC standard errors reported in parentheses

* $p < .1$, ** $p < .05$, *** $p < .01$

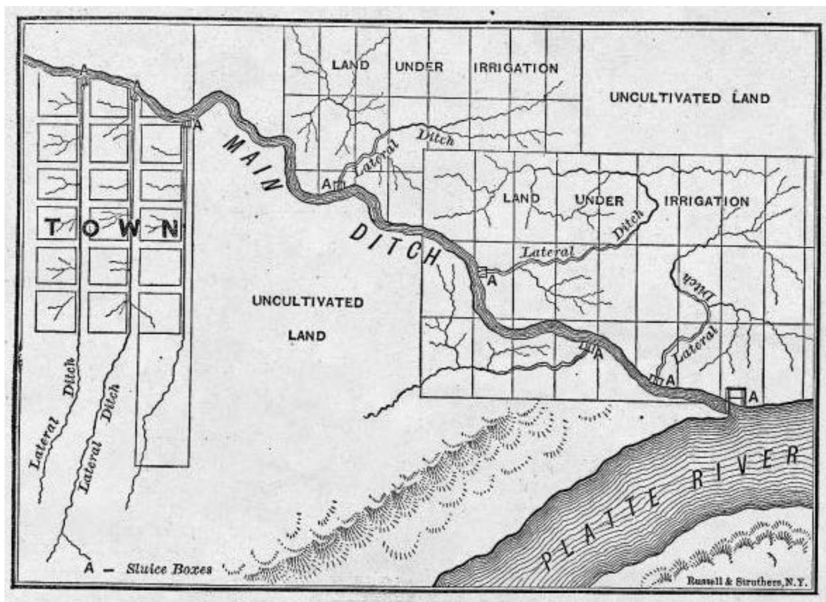
water rights, reducing the coordinating role for formal property rights.

We find evidence that priority-differentiated rights served as a basis for coordination and subsequent investment in eastern Colorado. Across all three Divisions, higher priority claimants are much more likely to establish claims in formal coordination with one another than low-priority claimants. Users in the first 50% of claims on a stream were relatively similar, with the very earliest claimants having a slightly higher probability of coordinating. In contrast, the lower-priority right-holders on a stream were much less likely to coordinate, and the effect of a decline in priority is the most pronounced for the most junior claimants. Subsequently, claimants who coordinated made much larger infrastructure investments.

For example, the McGinn Ditch on South Boulder Creek and Farmer's Ditch on Boulder Creek were both large, cooperative ditch investments that ultimately provided water and lowered future construction costs for subsequent claimants. The McGinn ditch was constructed in 1860 and had the number 2 priority on South Boulder Creek. Farmer's Ditch was the longest ditch in Boulder Valley when it was constructed in 1862, costing $6,500

($165,000 in 2015 dollars) and ultimately irrigating over 3,000 acres of land (Crifasi, 2015, 187). Ditch's like Farmer's became the focal point for future development by lowering costs for subsequent claimants in two ways. First, Farmer's sold shares in water available on the ditch, providing a means for new settlers to get water without undertaking investment themselves. Second, new claimants could establish small "laterals" off the main ditch to irrigate even more distant lands.

Figure 9: Coordinated Investment



THE COLORADO SYSTEM OF IRRIGATION.

Source: *Harper's Weekly*, 6/20/1874, p 514.

Figure 9, taken from the June 20th, 1874 issue of *Harper's Weekly*, depicts an arrangement typical for eastern Colorado and highlights the increase in usable farmland associated with coordinated development of irrigation. Secure prior appropriation property rights gave early claimants an incentive to coordinate and develop major diversion projects—the Main Ditch in the figure—which could be added onto by subsequent claimants, to the profit of the original investors. Early claimants would have no incentive to provide this initial investment if they were legally obligated to share water with new arrivals, as would be the case under the riparian doctrine. Farmer's was the first ditch of its kind, but many similar arrangements emerged across eastern Colorado(Crifasi, 2015). This pattern of development demonstrates the specific mechanism for the positive externalities we identify in Section 4. Figure 9 also shows the expansion of potentially productive farmland facilitated by investment in diversion infrastructure. Next, we assess the contribution of prior appropriation to the expansion of irrigated agriculture in Colorado and across the West.

5.3 Irrigation and Income Per Acre

Ultimately the purpose of establishing a water right in Eastern Colorado was to provide water as an input into irrigated agriculture. Prior appropriation added value to agricultural endeavors in at least three ways. First, granting priority to early claimants provided an incentive for socially valuable search and infrastructure investment by giving property rights to water greater certainty of water deliveries than they afforded by riparian rights. Second, this greater certainty facilitated joint development of ditches by lowering the probability of stranded capital and fallowed fields. And third, the separation of water from land claims led to a much greater and more productive area being irrigated than would have been possible under the riparian system. Having analyzed the first two channels, we now turn to the third.

We begin by depicting the extent of land resources that could have been irrigated under the riparian doctrine, given that settlers on the Western frontier were generally constrained to homestead sites totaling 160 to 320 acres.[49] We conservatively assume that land within a half mile of a stream or river could have been claimed and considered adjacent to the water for the purposes of assigning riparian water rights. Figure 10 depicts riparian lands in eastern Colorado—indicated by cross hatch shading—and the location of loamy soils best suited to farming, indicated with green shading.

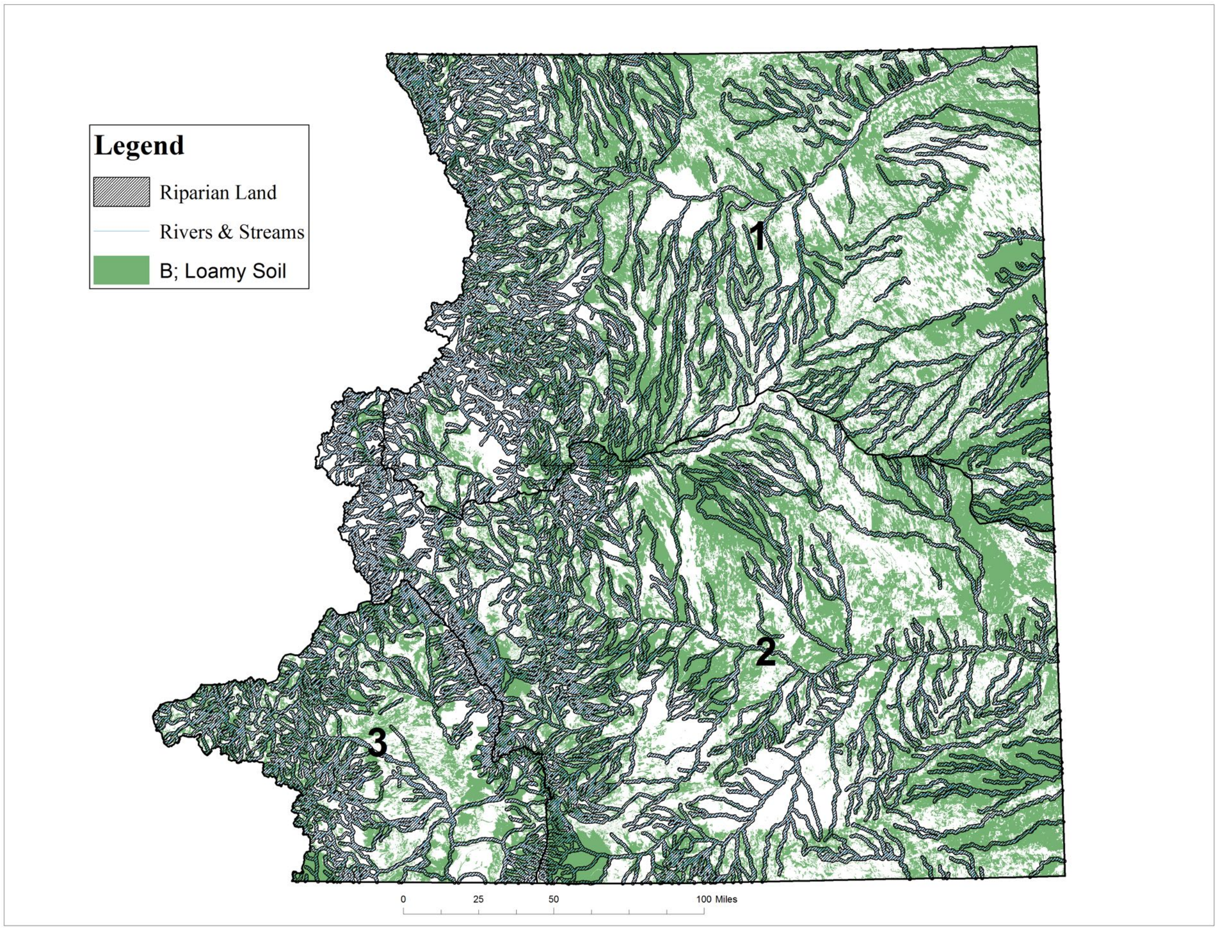
The map in Figure 10 reveals that the riparian doctrine would have constrained not just the total area of land available for farming, but would have precluded the ability to irrigate some of the most productive soils in the region that were remote from streams. Our data allow us to estimate the contribution of prior appropriation to irrigated agriculture in eastern Colorado. We match our data on water rights with GIS data on actual irrigated acreage prior to the advent of groundwater pumping in Divisions 1 and 3 to calculate the actual contribution of the prior appropriation doctrine to agriculture in the region.

Figures 11 and 12 depict riparian land and actual irrigated acreage in 1956 for Division 1 and 1936 for Division 3, the earliest years for which GIS data are available in each Division. We focus on these early years so that we can isolate the effect of access to surface water as opposed to groundwater.[50] Roughly 45% of the irrigated land in Division 1 and 34%

[49]Dippel et al. (working paper) demonstrate that many homestead claims were supplemented with cash sale of land, so that a given claim site might actually exceed 160 acres.

[50]Estimates from later in the 20th century are contaminated by the ability of farmers to supplement their surface water rights by pumping groundwater. The technology for groundwater pumping became widely

Figure 10: Riparian and Arable Land in Eastern Colorado

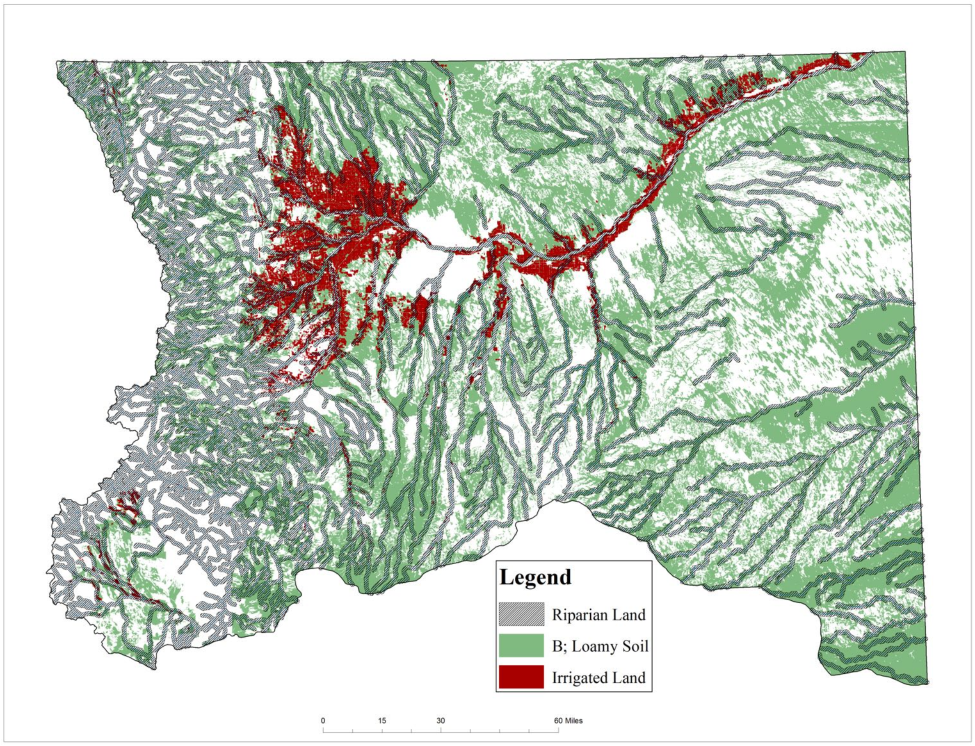


in Division 3 was riparian. The ability to claim water from streams and put it to use on nonadjacent land allowed for a substantial increase in irrigated acreage in both Divisions, resulting in a additional 546,552 acres of usable farmland across the two divisions.

These land-based estimates form an upper bound on the expansion of irrigated agriculture made possible by prior appropriation. The counter-factual scenario involving adherence to the riparian doctrine may have resulted in more riparian land being irrigated, given that non-riparian lands would have been unavailable. However, the fact that users incurred substantial infrastructure costs to reach non-riparian lands and left much of the riparian corridor untouched suggests superior land quality and productivity on non-riparian lands. The ri-

available after World War II.

Figure 11: Riparian and Irrigated Land in Division 1



parian system would have constrained rights holders to the more rugged terrain adjacent to streams and limited total farm size, assuming only riparian homesteads could have access to water. This, in turn, may have precluded important twentieth-century innovations in farming technology centered around the development of large, flat farms in the West (Gardner, 2009; Olmstead and Rhode, 2001).

While our estimates may overstate the degree of expansion due to prior appropriation in terms of land area, focusing on per-acre returns allows us to better understand to contribution of prior appropriation to farm productivity. We combine our parcel-level data on irrigated acres and crop choice with historical state-level data from the Agricultural Census on prices and yields for each crop to estimate the value of production on riparian and non-riparian lands for the rights for which we have data. These results are summarized in Table 7. The value of non-riparian irrigated agricultural production was $228,480,781 in Division 1 and $58,583,937 in Division 3. The ability to move water away from streams increased combined agricultural output in Colorado in our sample years by 134%.

Figure 12: Riparian and Irrigated Land in Division 3

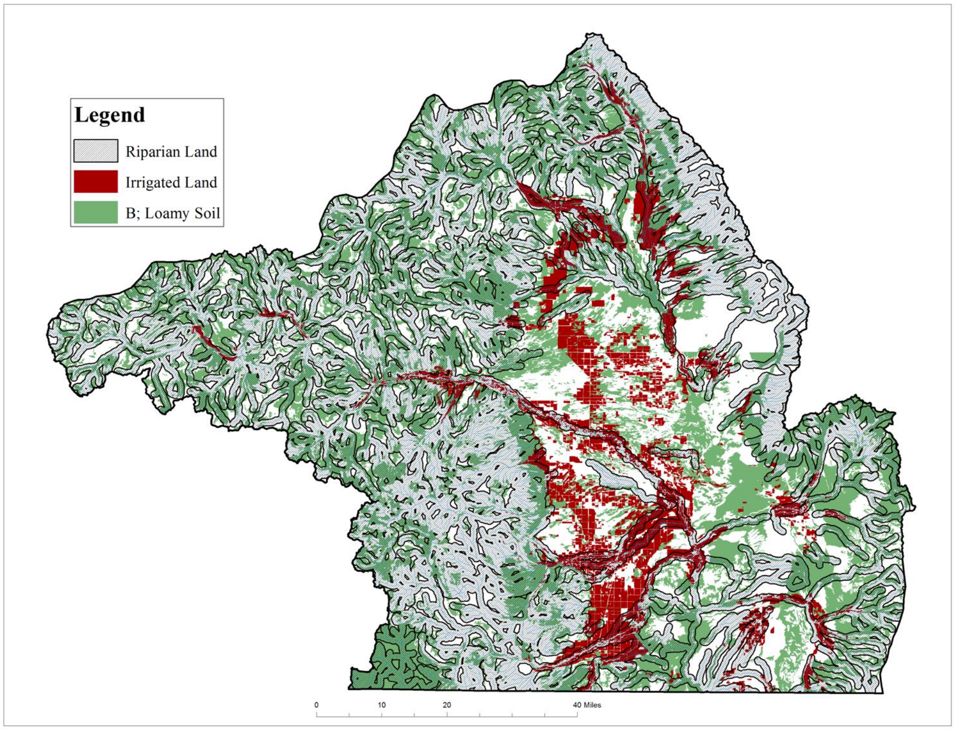


Table 7: Irrigated vs. Riparian Land

	Division 1		Division 3	
	Riparian	Non-Riparian	Riparian	Non-Riparian
Irrigated Acres	337,917	408,275	72,350	138,277
Total Farm Income	$183,310,710	$228,480,781	$30,948,204	$58,583,937
Average Income Per Acre	$527.50	$548.32	$601.67	$600.10
	(3.28)	(3.05)	(14.64)	(12.36)

The variation in income per acre across land type and Division is striking. In Division 1, the average non-riparian farm earned roughly $20 more per acre than the average riparian farm, while farms in Division 3 exhibit no difference.[51] This provides suggestive evidence that non-riparian lands were more productive than riparian lands. Moreover, it seems that the ability to coordinate and construct especially large diversion infrastructure was critical to reaching these productive lands, given that formal coordination facilitated investment in

[51]This difference is statistically significant at the 99% level.

Division 1 but not in Division 3.

Taken together, these results suggest that formal coordination under the prior appropriation doctrine was an important determinant of per-acre income for farmers. Coordination affects income per acre through several possible channels. First, coordination increases ditch investment, which may directly impact income per acre if greater investment facilitates access to more productive land. Second, coordination may affect income per acre via farm size if larger farms are more efficient. Coordination likely affects farm size indirectly through ditch investment, but may have a direct effect as well. Third, there may be a direct effect of coordination on income per acre if users who operate coordinated water claims also coordinated on other margins. Equation 10 summarizes the possible channels.

$$\frac{\mathrm{d}IPA}{\mathrm{d}CoOp} = \frac{\partial IPA}{\partial Acres}\left[\frac{\partial Acres}{\partial Ditches}\cdot\frac{\partial Ditches}{\partial CoOp} + \frac{\partial Acres}{\partial CoOp}\right] + \frac{\partial IPA}{\partial Ditches}\cdot\frac{\partial Ditches}{\partial CoOp} + \frac{\partial IPA}{\partial CoOp} \tag{10}$$

We further exploit our parcel-level data on irrigated acreage and crop choice to estimate how coordination and water supply security furnished by prior appropriation water rights affected outcomes for farmers in eastern Colorado. We estimate a series of linear regressions using the GMM technique mentioned above to obtain each of the partial derivatives in equation 10 and construct the total effect of coordination on income per acre. Table 8 presents our estimates of the effect of cooperation on income per acre by Division. The results used to construct these estimates are available in Appendix Table C6. As a starting point we report the reduced form estimate of cooperation on income per acre, not controlling for ditch length or farm size. The second row contains our estimate corresponding to the various channels in equation 10, estimated using GMM with spatial HAC standard errors that are uncorrelated across equations, and the third row presents a robustness check using seemingly unrelated regression (SUR) to account for possible correlation in the errors across equations.

We estimate that income per acre was \$105 to \$132 higher (relative to a mean of \$544 per acre) for users in Division 1 who coordinated their water rights claims and investment, but find no effect of coordination on farm size or on income per acre in Division 3. This difference is largely driven by the fact that coordination promoted ditch investment in Division 1 but not in Division 3. Farm Size increases by an acre for each additional ten meters of ditch investment in Division 1 and by over 2 acres in Division 3. Table 7 suggests that the ability to move water away from riparian lands to more productive locations increased income per acre

Table 8: The Effect of Coordination on Income Per Acre

	Division 1	Division 3
Reduced Form[a]	105.7***	-7.934
	(28.60)	(51.50)
Back of the Envelope[b]	132.20***	-10.53
	(15.06)	(29.04)
S.U.R.[c]	109.12***	-12.32
	(38.16)	(49.74)

[a] Spatial HAC GMM standard errors reported in parentheses
[b] Spatial HAC GMM standard errors estimated equation-by-equation.
Standard error of the prediction obtained using the delta method and
assuming errors are uncorrelated across equations
[c] Correlated standard errors reported in parentheses
* $p < .1$, ** $p < .05$, *** $p < .01$

by $20 in Division 1, but Table 8 indicates that productivity gains for users who coordinated with one another were even larger. Coordination led to much longer ditches in Division 1, so the difference in the average non-riparian gain of $20 and the cooperation-specific gain of over $100 may be due to the fact that users who cooperated were able to build larger ditches and bring water to the most productive yet most remote lands.

Our results provide the most complete empirical picture to date of the importance of property rights in facilitating coordination between users in the presence of uncertainty of water supplies. Priority-based rights served as a basis for coordination that facilitated large increases in ditch investment, allowing farmers to move water out of the riparian corridor, develop larger farms, and earn greater returns on each acre under production. Our results confirm the notion that allowing water to be separated from streams facilitated a more flexible evolution of farming practices than would have been possible with the riparian doctrine. Before concluding we estimate the contribution of this innovation to state income in the Western United States.

5.4 Irrigated Agriculture and the Development of the West

We perform a back-of-the-envelope calculation of the contribution of irrigated agriculture and prior appropriation to economic development in the Western United States in the early 20th century. Table 9 presents our estimates of the value of irrigated crop production for western states in 1910 and 1930. Using data from Easterlin (1960) and the Bureau of Economic Analysis, we also report the value of irrigated crops as a percentage of state or territory income. Finally, using an average of the share of non-riparian income in total agricultural income from Divisions 1 and 3 in Colorado, we estimate the value of non-riparian irrigated agriculture as a percentage of state income.[52] This represents the estimated share of state income due to agricultural production that could not have taken place under the riparian doctrine because water could not have been brought to non-riparian lands.

Table 9: Contribution of Agriculture to State/Territory Income

	1910			1930		
	Irrigated Crop Value	% of State Income	Non-Rip. %	Irrigated Crop Value	% of State Income	Non-Rip. %
Arizona	$109,088,226	7.8%	4.4 %	$218,429,933	6.8%	3.9%
California	$1,198,335,054	5.4%	3.1%	$4,730,240,019	6.6%	3.8%
Colorado	$955,887,896	15.4%	8.8%	$1,216,338,604	14.4%	8.2%
Idaho	$411,487,005	26.0%	14.8%	$1,176,322,174	38.2%	21.8%
Montana	$357,644,113	12.9%	7.3%	$543,002,901	14.2%	8.1%
Nevada	$129,481,278	19.7%	11.3%	$199,548,712	18.5%	10.6%
New Mexico	$132,129,974	9.2%	5.2%	$282,107,719	14.2%	8.1%
Oregon	$182,079,466	3.9%	2.2%	$425,281,996	5.2%	3.0%
Utah	$355,860,090	15.1%	8.6%	$526,011,917	14.8%	8.4%
Washington	$182,766,338	2.9%	1.7%	$896,351,083	6.2%	3.5%
Wyoming	$182,849,867	13.7%	7.8%	$355,530,834	19.1%	10.9%

Notes: 1) All dollar amounts are reported in 2015 dollars. 2) Territory income is used for states prior to statehood. 3) Crop values are from the 1910 Agricultural Census, Volumes 6 & 7 and United States Agricultural Data, 1930, distributed from the Inter-university Consortium for Political and Social Research (ICPSR). 4) Income is estimated using population data from 1910 and 1930 ICPSR and per capita income from Easterlin (1960) and data from the Department of Commerce, Bureau of Economic Analysis provided by Robert Margo, Boston University. 5) Non-riparian contribution based on weighted average share of riparian in total irrigated land from table 6.

Table 9 indicates that irrigation of non-riparian lands contributed 2-14% of state income in 1910 and 3-21% in 1930. Overall, irrigated agriculture has played a critical role in the development of the West, accounting for more than 10% of total income in many states by 1930. Moreover, we estimate that more than half of the value generated by irrigated agriculture is associated the irrigation of non-riparian lands.[53] The riparian doctrine would not have allowed irrigation to take place in these areas because it did not allow the separation

[52] We calculate a weighted average of the share of non-riparian income in total irrigated income from Divisions 1 and 3, weighted by total irrigated acreage in each Division. We estimate that roughly 57% of irrigated land is non-riparian and could not have been irrigated under a strict riparian system.

[53] This estimate is an upper bound on the value-added by prior appropriation because strict adherence to the riparian doctrine would likely have led to the irrigation of more riparian lands, relative to what we observe today.

of water from land. We find that these more remote lands were more productive by between \$20 and \$100 per-acre. This enhanced productivity is consistent with the observed behavior of claimants, who undertook costly investment to irrigate these areas. In contrast, the riparian doctrine would have undermined the incentives for water rights holders to invest in and maintain critical diversion infrastructure which allowed these non-riparian lands to be irrigated because rights holders could have not fully or securely appropriated the returns on their investments.

6 Conclusion

We analyze the economic determinants and long-run economic implications of prior appropriation surface water rights assigned from 1852 to 2013. In one of the first detailed empirical studies of the evolution of property rights, we find strong evidence of a trade-off between resource availability and positive externalities associated with information and coordination generated by prior claimants when property rights evolve under uncertainty. Search effort and capital investment by early claimants generated positive externalities by providing information about effective locations and techniques for constructing diversion infrastructure. These actions increased the probability of subsequent claims on the same stream by 20%, an effect equivalent to a near doubling of available water.

Our theoretical model emphasizes the advantages of prior appropriation over the riparian doctrine for facilitating costly investment under uncertainty, and we find evidence that investment was critical for the development of agriculture in the West. We demonstrate that secure, first-possession property rights served as a basis for legal coordination via incorporation and other cooperative agreements that led to substantially higher levels of infrastructure investment—the top 10% of claimants on stream are 40 percentage points more likely to form ditch companies than claimants below the median priority. Subsequently, cooperation led a doubling of average ditch length (about 10 km) that greatly expanded the quantity of irrigable land and access to higher quality lands, especially in Division 1. In contrast, we find no effect of the ability to legally cooperate around priority-based rights in Division 3 and attribute the difference to long-evolved communal sharing norms in Division 3 that may have undermined the *de jure* benefits of prior appropriation.

Prior appropriation added value to agricultural endeavors in at least three ways. First, granting priority to early claimants provided an incentive for socially valuable search and infrastructure investment by giving property rights to water greater certainty of water deliveries than under the previous riparian rights regime. Second, this greater certainty facilitated joint development of ditches by lowering the probability of stranded capital and fallowed fields. And third, the separation of water from land claims led to a much greater and more productive area being irrigated than would have been possible under the riparian system.

Our study of eastern Colorado indicates that prior appropriation allowed a more than doubling of irrigated farmland by i) allowing water to be separated from streams and ii) providing incentives to invest in the ditch infrastructure necessary to reach productive but non-riparian land. We find that non-riparian lands in Division 1 yielded $20 more per acre than riparian lands and that lands irrigated by the most expansive, cooperative ditch investments earned over $100 per acre more than other lands. We provide the first empirical estimate of the contribution of irrigated agriculture to twentieth-century economic development in the Western United States and find that between 5 and 40% of state income in 1930 came from irrigated crop production. Extrapolating from our results in Colorado, we estimate that 3.5-20% of state income in 1930 is directly attributable to the expansion of irrigation under the prior appropriation doctrine.

The value of prior appropriation is not just a question of history, however. As we show in our model and confirm empirically, reducing the security of property rights to resources reduces the incentives to invest those resources. In a setting where investments generate positive externalities, providing incentives to develop (historically) and maintain (today) infrastructure is an important policy issue. Popular proposals to reassign water rights as shares to annual flow not only ignore the important institutional history of prior appropriation, but they risk undermining incentives for continued maintenance and investment in important infrastructure. Ultimately, the value of any particular form of property right to a natural resource is its ability to align individual incentives to reconcile competing demands for the resource without dissipating economic rents. Prior appropriation was an institutional innovation in the arid west that facilitated socially valuable search by individuals, served as a basis for coordination, and provided a basis for trade and investment that led to an more than doubling of irrigated agriculture in the Western United States that had a lasting impact on states' economic development.

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Appendix A: Theory

Proposition 1: *Under prior appropriation, aggregate profits V^{PA} are increasing and concave in the number of appropriators for $N < \bar{N}^{PA}$ and have a unique maximum at $\bar{N}^{PA}$.*

Proof: First, note that $\frac{\partial V^{PA}}{\partial N} = \frac{\partial \sum_{i=1}^{N} V_i^{PA}}{\partial N} = V_N^{PA}$; the arrival of new claimants under prior appropriation does not alter senior claimant's behavior, so the change in aggregate profit is just the profit of the new arrival. Burness and Quirk (1979) show that under the appropriative system profits are strictly lower for junior claimants: $V_i^{PA} > V_j^{PA} \quad \forall \quad i < j$. This implies that aggregate profits are increasing but at a decreasing rate: $\frac{\partial^2 V^{PA}}{\partial N^2} = V_N^{PA} - V_{N-1}^{PA} < 0$. Denote the marginal entrant who earns zero profit to be $\bar{N}^{PA}$. For $N < \bar{N}^{PA}$, each user earns strictly positive profit so $V_i^{PA} > 0 \quad \forall \quad i < \bar{N}^{PA}$. Similarly, any additional claimants would earn zero profit after $\bar{N}^{PA}$: $V_j^{PA} < 0 \quad \forall \quad j > \bar{N}^{PA}$. By definition, $V_{\bar{N}^{PA}}^{PA}$=0. Hence, V^{PA} is increasing an concave in N with a unique maximum at $\bar{N}^{PA}$. QED.

Proposition 2: $V^{PA} \lesseqgtr V^S$. *Either property rights regime can dominate.*

Proof: We prove Proposition 2 by providing an example of either regime dominating.

Case 1: $V^{PA} > V^S$. We begin by noting that $\bar{N}^{PA}$ is the maximum number of users that establish rights under prior appropriation, even if the number of potential users N exceeds $\bar{N}^{PA}$ (not entering strictly dominates entering and earning negative expected profit. See Proposition 1). Next, consider the first-order necessary condition for the shareholder's problem:

$$[1 - F(Nx_i)]R'(x_i) = C'(x_i)$$

Since $F(\cdot)$ is a proper cumulative density function, $\lim_{n \to \infty} [1 - F(Nx_i)] = 0$ and the first order condition reduces to

$$0 = C'(x_i)$$

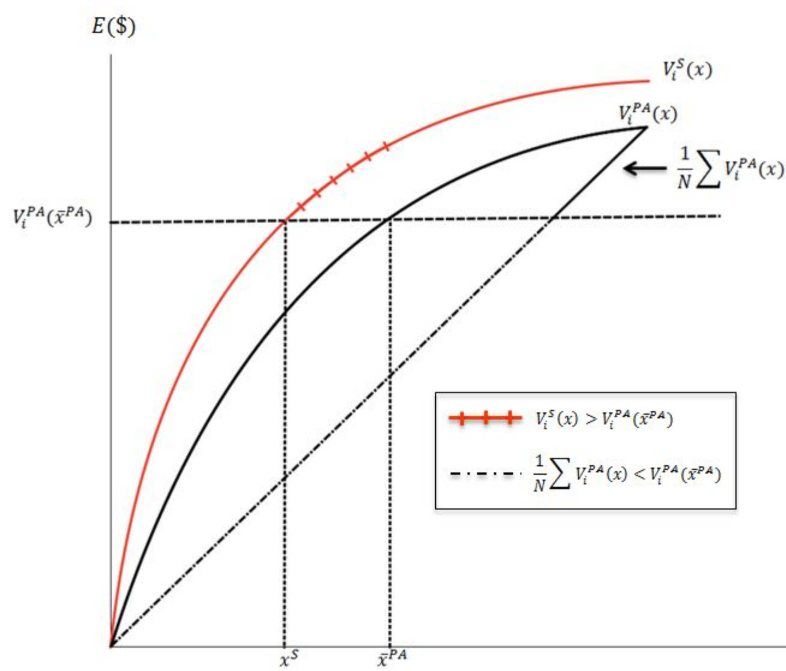
It follows that $x_i^* = 0$, $V^S(0) = 0 < V^{PA}$. For sufficiently large N, the expected share size approaches zero and expected revenues do not exceed expected costs, resulting in zero investment. The prior appropriation system allows the first $\bar{N}^{PA}$ users to enter and make secure investments, resulting in positive (and thus higher) aggregate expected profit.

Case 2: $V^S > V^{PA}$. Burness and Quirk (1979) establish that expected profits under the share system are higher than under prior appropriation *for a given* x, but that investment is higher under prior appropriation *for a given* N. We want to show that it is possible for $NV_i^S(x_i^s(N)) > \sum_{i=1}^N V_i^{PA}$ given $Nx_i^S < \sum_{i=1}^N x_i^{PA}$for some N. Which is equivalent to $V_i^S(x_i^s(N)) > \frac{1}{N}\sum_{i=1}^N V_i^{PA}$ given $x_i^S(N) < \frac{1}{N}\sum_{i=1}^N x_i^{PA}$. That is, we need to show that it is possible for a the profits of a share smaller than the average prior appropriation claim to exceed the average profits from prior appropriation.

Define $\bar{x}^{PA} = \frac{1}{N}\sum_{i=1}^N x_i^{PA}$ to be the size of the average prior appropriation claim for a given N. From Jensen's Inequality we have that $V^{PA}(\bar{x}^{PA}) \geq \frac{1}{N}\sum_{i=1}^N V_i^{PA} \quad \forall \quad N$ since V^{PA} is concave. Since $V_i^S(x) > V_i^{PA}(x)$ for any given x, it must be that $V_i^S(\bar{x}^{PA}) > V_i^{PA}(\bar{x}^{PA})$. Finally, we note that $\frac{\partial V_i^S}{\partial x} > 0$ (greater investment results in greater expected profit, for a given N). Taken together, these inequalities imply that $\exists \quad x_i^S(N) < \bar{x}^{PA}$ satisfying $V_i^S(x_i^S(N) > \frac{1}{N}\sum_{i=1}^N V_i^{PA}$ (see graph) as long as $V_i^S(x)$ is continuous in x.

Hence, we can have either $V^{PA} > V^S$ or $V^{PA} < V^S$. QED.

Figure 13: Proposition 2



Proposition 3: *In the presence of a positive externality from prior claims ($\gamma > 0$), V^E has a convex region for small N and for sufficiently large γ, $V^E > V^S$.*

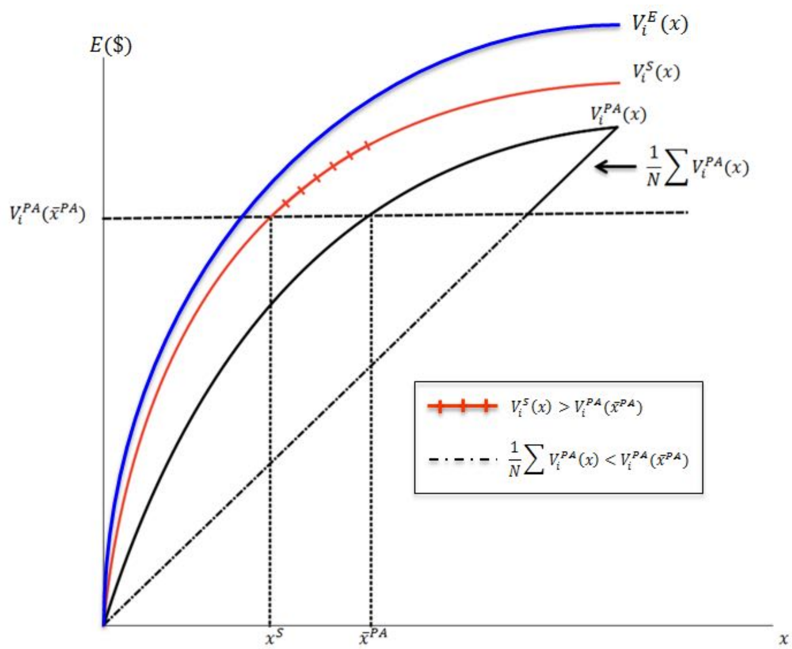
Proof: First, we establish that V^E has a convex region (in N) for sufficiently large γ.

$$\begin{aligned}
\frac{\partial^2 V^E}{\partial N^2} &= V_N^E - V_{N-1}^E \\
&= V_N^{PA} + \gamma p_N - V_{N-1}^{PA} - \gamma p_{N-1} \\
&= V_N^{PA} - V_{N-1}^{PA} + \gamma(p_N - p_{N-1}) > 0 \iff \gamma > \frac{V_{N-1}^{PA} - V_N^{PA}}{p_N - p_{N-1}} = \frac{-\frac{\partial^2 V^E}{\partial N^2}}{x_N^{PA}}
\end{aligned}$$

If the positive externality is the larger than the ratio of the change in profits for the marginal user to the investment of marginal user, then V^E is convex.

Next, we establish that $V^E > V^S$ for sufficiently large γ. Note that $V_i^E = V_i^{PA} + \gamma p_i$. This implies. $V^E = \sum_{i=1}^N V_i^{PA} + \gamma x_1^{PA} + \gamma(x_1^{PA} + x_2^{PA}) + ... + \gamma(x_1^{PA} + ... + x_{N-1}^{PA}) = V^{PA}(N) + \gamma \sum_{i=1}^N (N-i)x_i^{PA}$. Recall that the case where shares dominate prior appropriation relied on the fact that Jensen's Inequality implies $V_i^S(x) > V_i^{PA}(x)$, but since $V_i^E(x) > V_i^{PA}(x)$, the conclusion that $\exists \quad x_i^S(N) < \bar{x}^{PA}$ satisfying $V_i^S(x_i^S(N) > \frac{1}{N}\sum_{i=1}^N V_i^{PA}$ no longer follows (see graph). QED.

Figure 14: Proposition 3



Proposition 4: *In the convex region of V^E, profits are increasing for junior claimants relative to senior claimants: $V_i^E > V_{i-1}^E$ and users follow rather than search for a new stream.*

Proof:

Assume V^E is convex in N

$\Rightarrow \frac{\partial^2 V^E}{\partial N^2} = V_i^E - V_{i-1}^E > 0$

$\Rightarrow V_i^E > V_{i-1}^E$

For the second part of the proof note that in the convex region of V^E, $V_i^E > V_1^E$ for $i > 1$. Hence, junior claimants on streams earn higher expected profits than the earliest claimants in the positive of a sufficiently large positive externality. If expected flows are equal across streams, being a junior claimant strictly dominates claiming a new stream, and users follow. QED.

Appendix B: G.I.S. Data Construction

GIS Hydrologic data on basins, stream names, and network characteristics come from the National Hydrography Dataset (NHD). The NHD dataset has been programmed as a linear network geodatabase that allows for tracing elements' relative positions along the network, a feature which we exploit. Estimates of stream flow across this network were obtained from NHDPLUS V2.[54] Elevation data are measured at 30-meter intervals and come from the National Elevation Dataset. These data are used to compute the slope and standard deviation of slope in the neighborhood of each right. Our soil data are from the USDA Soil Survey Geographic Database (SSURGO).

We calculate measures of resource quality relating to both land and streams for each grid square. We calculate the average and standard deviation of slope in each grid square and construct the variable roughness, which is the average slope multiplied by the standard deviation of slope.[55] We use the SSURGO data to calculate the number of acres of soil in each hydrologic soil group defined by the USDA. This measure of soil quality is based on the structure of the soil itself rather than its current water content. This allows use to current GIS measure of soil quality to estimate historical soil quality over the period of our

[54]NHDPLUS, provided by the Horizon Systems Corporation, is an augmented version of the National Hydrography dataset that has been combined with the National Elevation Dataset and the PRISM climate dataset to produce a variety of flow-related statistics across the entire stream network.

[55]This construction captures the fact that both steeper terrain and more variable terrain contribute to rugged topography and make various forms of development more difficult.

study. We focus on Soil group B, which is comprised primarily of loamy soil and is the most productive for agriculture. We also calculate the total area (in acres) of the watershed that a square resides in using the HUC8 classification of watersheds from the National Hydrography Dataset (NHD).

We perform a network trace to locate each square along the stream network defined by the NHD and use this location to create a variety of variables relating to the water resource itself. We calculate the distance from each grid square to the head of the stream it lies on (as delineated by the NHD).[56] The NHDPlus V2 dataset created by Horizon Systems Corporation provides monthly and annual stream flow estimates for each reach on the NHD network. We use this information to create a measure of the total flow across May through August.[57] We combine these contemporary estimates of stream flow with contemporary and historical estimate of precipitation from the PRISM dataset and elevation data from the NED to estimate a model for predicting historical flows along the entire stream network. We use these estimates to calculate the average summer flow and standard deviation of flow from 1890 to 2000.[58] The variable Summer Flow is the century-long average of total summer flow, based on flows in May through August of each year. The variable Flow Variability is the standard deviation of stream flow for a given reach over this period. Details on the hydrologic and econometric models underlying these calculations are available (or will be shortly) in an on-line appendix.

[56] For most streams the entire length of the stream is used. Major rivers are divided into reaches within the NHD, and we maintain this division because we believe it reflects the fact that relative positive along major rivers is less critical than relative position along smaller streams.

[57] These are the months during which irrigation is critical to support crop growth.

[58] PRISM data on historical precipitation are only available back to 1890. Rather than clip our dataset and having yearly estimates of flow, we use century long averages to capture average stream characteristics.

Appendix C: Robustness Checks and Additional Results

Table C1: Estimated Average Partial Effects on Prob(New Claims)

$\frac{\partial Pr(NewClaims > 0)}{\partial x}$	(1)	(2)	(3)
	Probit Estimates, Y = $\mathbb{1}$(New Claims$_{jt}$ >0)		
$\mathbb{1}$(Lagged Claims>0)	0.0456***	0.0459***	0.0365***
	(0.00490)	(0.00492)	(0.00420)
Summer Flow	0.00000590***	0.00000720***	0.00000656***
	(0.00000186)	(0.00000209)	(0.00000201)
Flow Variability	-0.00000228	-0.00000271	-0.00000364
	(0.00000459)	(0.00000482)	(0.00000479)
$\mathbb{1}$(Drought)	-0.00247***	-0.00246***	-0.00186***
	(0.000341)	(0.000353)	(0.000325)
Roughness	-0.00000254***	-0.00000284***	-0.00000386***
	(0.000000911)	(0.000000928)	(0.000000986)
Acres Loamy Soil	0.000000115	0.000000126	0.00000133**
	(0.000000468)	(0.000000475)	(0.000000535)
Watershed Acres	0.000000968***	0.00000107***	0.00000100***
	(0.000000202)	(0.000000204)	(0.000000211)
Homestead Claims$_{jt-1}$	0.000120***	0.000124***	0.000121***
	(0.0000202)	(0.0000209)	(0.0000289)
$\mathbb{1}$(Initial Claims>0)	0.0112***	0.0113***	0.00894***
	(0.00139)	(0.00132)	(0.00104)
Total Water Claimed (cfs)		-2.04e-08***	2.13e-08***
		(6.23e-09)	(6.17e-09)
Total Homesteaded Acres			-0.000000122***
			(2.19e-08)
N	248,745	248,745	248,745
χ^2	2,081.90	2,148.38	2,326.26

Notes: Standard errors are clustered by stream and reported in parentheses. N= 248,745 is the number of stream-year cells for which we have overlapping data on all covariates. * $p < .1$, ** $p < .05$, *** $p < .01$

Table C2: Coefficient Estimates - FE Poisson

	(1)	(2)	(3)	(4)
	Y = New Water Claims$_{jt}$			
Lagged Claims	0.352***	0.364***	0.362***	0.310***
	(0.0271)	(0.0254)	(0.0255)	(0.0230)
Lagged Claims*Flow	-0.0000412**	-0.0000653**	-0.0000646**	-0.0000668***
	(0.0000196)	(0.0000269)	(0.0000269)	(0.0000208)
$\mathbb{1}$(Drought)	-0.646***	-0.621***	-0.638***	-0.502***
	(0.0715)	(0.0732)	(0.0802)	(0.0730)
Homestead Claims$_{t-1}$	0.0137***	0.0159***	0.0158***	0.0181**
	(0.00240)	(0.00272)	(0.00274)	(0.00787)
Total Water Claimed		-0.00000303**	-0.00000302**	0.00000675***
(cfs)		(0.00000145)	(0.00000144)	(0.00000149)
Lagged Claims*		0.000000247	0.000000225	-0.000000351
Total Water Claimed		(0.000000311)	(0.000000306)	(0.000000258)
Lagged Claims*$\mathbb{1}$(Drought)			0.0584	
			(0.0783)	
Total Homesteaded				-0.0000350***
Acres				(0.00000789)
N	112,217	112,217	112,217	112,217
χ^2	292.8	427.0	423.4	422.2

Notes: Robust standard errors are reported in parentheses. N= 112,217 is the number of stream-year cells for which we have overlapping data on all covariates. Streams that never receive a claim are dropped from the fixed effects specification. * $p < .1$, ** $p < .05$, *** $p < .01$

Table C3: Coefficient Estimates - Fixed Effects Logit

	(1)	(2)	(3)	(4)
		Y = $\mathbb{1}$(New Claims$_{jt}$ >0)		
$\mathbb{1}$(Lagged Claims>0)	1.935***	1.930***	1.963***	1.720***
	(0.0820)	(0.0711)	(0.0851)	(0.0855)
$\mathbb{1}$(Lagged Claims>0)*Flow	-0.0000602	-0.0000184	-0.0000157	-0.0000939
	(0.0000605)	(0.0000105)	(0.000131)	(0.000128)
$\mathbb{1}$(Drought)	-0.544***	-0.524***	-0.458***	-0.414***
	(0.0622)	(0.0605)	(0.0632)	(0.0560)
Homestead Claims$_{t-1}$	0.0176***	0.0177***	0.0179***	0.0225***
	(0.00282)	(0.00341)	(0.00310)	(0.00760)
Total Water Claimed		-0.00000246	-0.00000235	0.00000797**
(cfs)		(0.00000417)	(0.00000368)	(0.00000337)
$\mathbb{1}$(Lagged Claims>0)*		-0.00000184	-0.00000175	-0.00000238
Total Water Claimed		(0.00000526)	(0.00000566)	(0.00000793)
$\mathbb{1}$(Lagged Claims>0)*$\mathbb{1}$(Drought)			-0.437*	
			(0.225)	
Total Homesteaded				-0.0000317***
Acres				(0.00000710)
N	112,217	112,217	112,217	112,217

Notes: Robust standard errors are reported in parentheses. N= 112,217 is the number of stream-year cells for which we have overlapping data on all covariates. Streams that never receive a claim are dropped from the fixed effects specification. * $p < .1$, ** $p < .05$, *** $p < .01$

Table C4: Marginal Effects of Priority on Cooperation

	(1)	(2)	(3)	(4)
	Divisions 1-3		Division 1	Division 3
1st Priority Decile	0.123***	0.119***	0.0207	0.194**
	(0.0359)	(0.0390)	(0.0779)	(0.0861)
2nd Priority Decile	0.0541	0.0725	0.0154	0.123
	(0.0456)	(0.0472)	(0.0929)	(0.102)
3rd Priority Decile	0.0882*	0.119**	-0.00675	0.202*
	(0.0468)	(0.0488)	(0.0861)	(0.119)
4th Priority Decile	0.0318	0.0419	0.0624	0.00619
	(0.0432)	(0.0431)	(0.0855)	(0.0905)
6th Priority Decile	-0.0154	-0.00285	-0.0558	0.0391
	(0.0518)	(0.0495)	(0.0698)	(0.0997)
7th Priority Decile	0.0366	0.0359	-0.0761	0.146
	(0.0401)	(0.0421)	(0.0674)	(0.107)
8th Priority Decile	-0.0591	-0.0910*	-0.181**	-0.0301
	(0.0447)	(0.0485)	(0.0753)	(0.0902)
9th Priority Decile	-0.160***	-0.211***	-0.238**	-0.292*
	(0.0465)	(0.0522)	(0.0939)	(0.175)
99th Priority Percentile	-0.236***	-0.330***	-0.488***	-5.193***
	(0.0643)	(0.0774)	(0.189)	(1.314)
Homesteads	-0.00399**	-0.00320*	-0.00345	-0.00159
	(0.00166)	(0.00190)	(0.00295)	(0.00350)
Summer Flow	0.0000155***	0.0000211***	0.0000354*	0.0000383**
	(0.00000591)	(0.00000636)	(0.0000186)	(0.0000159)
Flow Variability	-0.000282	-0.000609	0.00189	-0.00300*
	(0.000252)	(0.00144)	(0.00293)	(0.00169)
Roughness	-0.000134	-0.000111	0.000368	-0.000840
	(0.000120)	(0.000141)	(0.000373)	(0.000746)
Acres of Loamy	0.00000849	0.0000125	0.0000630	-0.0000436
Soil	(0.0000132)	(0.0000205)	(0.0000433)	(0.0000285)
Acreage Along	-0.00000346	-0.00000743	-0.0000245*	0.0000101
Stream	(0.00000461)	(0.00000823)	(0.0000146)	(0.0000107)
Watershed Effects	No	Yes	Yes	Yes
Year Effects	Yes	Yes	Yes	Yes
N	4,756	4,354	1,206	937

Standard errors are clustered by watershed and resorted in parentheses

* $p < .1$, ** $p < .05$, *** $p < .01$

Table C5: Effects of Cooperation and Priority on Investment

	(1)	(2)	(3)	(4)	(5)
	Divisions 1 & 3			Division 1	Division 3
1st Priority Decile	3,891.1	3,179.9	3,230.5	15,898.6***	-13,274.3
	(7,957.6)	(6,944.3)	(6,908.2)	(5,321.7)	(11049.2)
2nd Priority Decile	-4,638.4	-3,609.0	-3,463.8	9,612.0	-16908.4
	(9,036.7)	(8,451.1)	(8,399.5)	(6,847.9)	(12398.0)
3rd Priority Decile	-5,055.8	-348.8	-267.3	18,908.4***	-14,920.8
	(8,657.2)	(7,454.8)	(7,410.0)	(5,773.6)	(11363.1)
4th Priority Decile	-3,142.4	-6,221.5	-6,157.4	1,630.6	-12,027.0
	(7,991.9)	(7,506.7)	(7,466.0)	(6,647.8)	(10,047.3)
6th Priority Decile	-4,690.8	-1,487.7	-1,568.5	10,418.2	-14,269.1
	(8,450.9)	(7,975.6)	(7,975.1)	(7,351.9)	(12,226.6)
7th Priority Decile	-5,845.4	-4,365.9	-4,384.2	-972.1	-8,698.5
	(8,353.6)	(6,887.6)	(6,837.7)	(5,670.3)	(12,088.3)
8th Priority Decile	-8,103.3	-5,729.3	-5,778.6	-2,603.8	-7,205.5
	(8,450.3)	(7,065.3)	(7,026.3)	(5,652.6)	(12,387.4)
9th Priority Decile	-8,720.3	-6,641.4	-6,747.5	5,386.8	-12,553.9
	(8,491.4)	(7,512.1)	(7,480.5)	(7,462.0)	(10,847.0)
99th Priority Percentile	-550.4	-751.9	-986.2	9,380.4	-14,208.5
	(12,560.4)	(9,532.2)	(9,616.6)	(9,735.9)	(13,410.6)
CoOp	5,963.9**	4,461.5**	4,472.0**	10,197.9**	-2,202.6
	(2,736.0)	(2,199.0)	(2,195.7)	(4,004.1)	(2,139.6)
Claim Size	244.7***	255.7***	256.3***	352.2***	130.0***
	(60.72)	(68.96)	(69.14)	(100.5)	(34.75)
Summer Flow	1.706	0.723	0.669	0.445	-0.604
	(1.144)	(0.968)	(0.967)	(1.963)	(1.023)
Flow Variability	56.94	349.2*	350.0*	173.2	287.1*
	(139.2)	(190.7)	(190.8)	(278.3)	(168.6)
Roughness	-19.79	-61.18	-61.21	22.55	-60.57
	(23.60)	(59.05)	(59.04)	(71.02)	(67.32)
Acres of Loamy Soil	0.904***	0.773	0.760	-2.842**	4.660
	(0.293)	(2.195)	(2.197)	(1.353)	(4.045)
Claim Year	1.268	2.425	2.426	-5.042	85.42
	(4.376)	(4.755)	(4.736)	(6.011)	(131.9)
Homestead Claims		-284.3			
		(227.0)			
Homesteaded Acres			-1.664	0.709	-1.954
			(1.481)	(1.782)	(1.702)
Watershed Fixed Effects	No	Yes	Yes	Yes	Yes
N	550	550	550	292	258
R^2	0.317	0.454	0.454	0.569	0.317

Spatial HAC standard errors are reported in parentheses

* $p < .1$, ** $p < .05$, *** $p < .01$

Table C6: Income Per Acre Pre-1960

	(1)	(2)	(3)	(4)	(5)	(6)
	Division 1			Division 3		
	Reduced Form	Irrigated Acres	Income Per Acre	Reduced Form	Irrigated Acres	Income Per Acre
CoOp	105.7***	-251.7	81.04***	-7.934	-162.5	-10.51
	(28.60)	(165.4)	(28.94)	(51.50)	(230.5)	(51.30)
Claim Size	1.139**	-3.963	1.162**	0.664*	-5.044	0.525
	(0.468)	(3.819)	(0.444)	(0.354)	(4.783)	(0.547)
Summer Flow	0.0249*	0.0448	0.0133	0.0348	-0.0726	0.0349
	(0.0128)	(0.0995)	(0.0128)	(0.0230)	(0.117)	(0.0237)
Flow Variability	-16.74***	-41.80	-15.87***	-2.871	-22.34	-3.046
	(4.991)	(29.78)	(5.036)	(4.676)	(21.96)	(4.738)
Roughness	-0.157	4.510	-0.212	-0.587	-0.893	-0.546
	(1.679)	(10.43)	(1.659)	(0.645)	(4.196)	(0.649)
Percent Loamy Soil	-0.638	-3.239	-0.244	155.0	-234.3	155.0
	(2.953)	(7.928)	(2.981)	(147.5)	(502.5)	(154.4)
Ditch Meters		0.0723***	0.00208*		0.206***	0.00239
		(0.0101)	(0.00117)		(0.0449)	(0.00424)
Irrigated Acres			0.0109			-0.00433
			(0.0107)			(0.00911)
Homesteaded Acres	-0.0883**	-0.433**	-0.0873**	-0.0108	0.0797	-0.0119
	(0.0356)	(0.172)	(0.0337)	(0.0173)	(0.0599)	(0.0178)
1st Priority Decile	43.19	-60.89	19.98	158.0**	356.4	156.0**
	(37.52)	(190.1)	(38.39)	(63.24)	(452.8)	(64.16)
2nd Priority Decile	11.28	-450.8	19.50	136.5*	213.5	137.7*
	(60.62)	(589.5)	(55.27)	(75.81)	(304.0)	(75.19)
3rd Priority Decile	142.3***	626.8	116.1**	82.67	106.5	84.03
	(45.50)	(434.9)	(50.68)	(64.20)	(316.5)	(62.52)
4th Priority Decile	35.01	-27.43	27.69	132.0	-103.8	130.1
	(49.52)	(218.3)	(46.03)	(96.47)	(355.8)	(96.95)
6th Priority Decile	75.06	65.17	86.39*	126.2*	22.23	126.2*
	(50.32)	(265.8)	(47.11)	(69.30)	(340.2)	(67.82)
7th Priority Decile	153.8	-107.9	143.5	121.1	758.3	133.3*
	(97.15)	(312.2)	(101.3)	(74.07)	(527.0)	(75.88)
8th Priority Decile	146.6*	119.6	149.9*	113.7	-245.0	97.70
	(77.84)	(255.1)	(75.92)	(87.59)	(687.2)	(97.28)
9th Priority Decile	218.7***	-29.53	201.8***	190.0*	-358.2	189.7*
	(50.71)	(256.7)	(51.83)	(97.70)	(350.1)	(97.79)
99th Priority Percentile	106.5	15.38	96.04	76.97	-541.8	69.67
	(99.42)	(334.4)	(94.73)	(83.40)	(601.3)	(81.17)
Watershed Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
N	169	169	169	178	178	178
R^2	0.873	0.830	0.879	0.692	0.735	0.698

Spatial HAC standard errors are reported in parentheses. Soil quality in Division 3 is collinear with watershed fixed effects.

* $p < .1$, ** $p < .05$, *** $p < .01$

Table C7: Division 1 vs. 3

	Division 1	Division 3
Total Income	785,035.7	323,869.8
	(139,492.2)	(111,086.7)
Irrigated Acres	1397.6	671.0
	(240.1)	(175.3)
IPA	561.9	523.4
	(17.8)	(26.9)
Claim Size	22.2	19.4
	(2.6)	(1.9)
Claim Date	-29936.76	-29163.77
	(316.8)	(354.3)
Acres Loamy Soil	60.2	11.1
	(8.1)	(1.7)
Ditch Meters	13522.2	7724.0
	(1532.2)	(965.1)