The Economics of First Possession Rights to a Heterogeneous Resource: Prior Appropriation Rights to Water

Bryan Leonard
Economics Department and Bren School of Environmental Science and Management
UCSB

Gary D. Libecap
Bren School of Environmental Science and Management and Economics Department
UCSB and NBER
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Abstract

We analyze the economics of first-possession property rights to a large heterogeneous resource allocated under incomplete information and competitive claiming by agents. Our focus is on prior-appropriation surface water rights used in 18 western US states and generally in at least 3 western Canadian provinces, with specific attention to Colorado, 1852-2013. Prior appropriation was an institutional innovation, replacing common-law riparian rights, in a setting where water supplies were scarce, unevenly distributed, and remote from production sites where water was a key input. Prior appropriation emerged very rapidly within 20 years or less to be the dominant rights regime covering an immense area of over 1,197,000 square miles, suggesting large economic advantages relative to the incumbent institutional regime. Voluntary, large-scale property rights changes are unusual empirically. Prior appropriation encouraged valuable search and narrowed the information required to establish ownership to that described in immediate water diversion rather than an entire river basin. It thereby also lowered individual bounding and enforcement costs. Beneficial use revealed how much water remained for subsequent rights claimants. We examine the economic advantages of prior appropriation. The benefits of prior appropriation in general depended upon how rights were obtained, an issue that we examine in detail. At the time of claiming water there was little information about water source characteristics, and the process of claiming revealed such information. Hence, there was a tradeoff between claiming at a particular time and waiting. At any time, water rights claimants were equal in their lack of knowledge of the best water diversion locations. Each round of claiming revealed new information, but the quantities of remaining high-quality diversion sites were reduced. Individual claims were based on observable resource characteristics, such as current stream flow or quantity, distance to stream head, terrain topography, and proximate soil quality. Because claiming initially took place under open-access conditions, there was potential for rent dissipation. Nevertheless, so long as search revealed critical resource characteristics, they were stable, and individual claims were recognized, there was no basis for rent dissipation, even in a rush to claim given the number of claimants and resource size. In this regard we differ from the literature on first possession that generally points to full dissipation. 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. Prior appropriation rights endure, affecting the distribution of water ownership and exchange. Assessment of the prior appropriation's welfare effects requires accounting for its role in generating property rights to water, investment, production, and the transaction costs of water exchange.

Introduction

We analyze the economics of a first-possession property right to a large heterogeneous resource under incomplete information and competitive claiming. First possession assigns ownership based on time and ownership typically is maintained by beneficial use (Epstein 1979, 1986; Rose 1985, 1990; Ellickson 1993; Lueck 1996, 1998). It is the most common, but understudied property rights regime. Our focus is on prior-appropriation surface water rights used in 18 western US states and at least 3 Canadian provinces, with specific attention to Colorado, 1852-2013. Prior appropriation was an institutional innovation, abruptly replacing common-law riparian water rights, in a setting where water supplies were scarce, unevenly distributed, and often remote from production sites where water was a key input. Prior appropriation emerged very rapidly, within 20 years over an immense area of some 1,197,000 square miles, eventually including all 11 western states and western Canadian provinces. Such voluntary, large-scale property rights change is unusual empirically, suggesting very significant net economic gains relative to the incumbent property regime.[1] A setting like this has not been analyzed previously. Although Kanazawa (1998) explores the early development of prior appropriation in the mining camps, prior appropriation developed largely from demands for irrigation in the semi-arid region west of the 100th meridian of North America. Frontier lands, opened by the Homestead Act and other laws (Gates 1968, Allen 1991) required irrigation to be productive and land claimants jointly sought land and water that often had to be moved from streams to farm sites (Romero 2002, 536-7; Getches 1997, 20). As with western land, minerals, and timber, diversion sites to claim and divert water for irrigation occurred through first possession. Today 70-80% of western water consumption remains in agriculture (Brewer et al 2008).

Neither the voluntary large-scale property rights innovation found in prior appropriation rights to water nor first possession has been examined empirically in the literature. Given the magnitude of the change, this alone would merit thorough analysis. Existing work generally is far more narrowly focused with criticism of prior appropriation as inefficient and inequitable. In environmental law (Freyfogle 1996; Kenney 2005; Daniels 2007) prior appropriation is argued to be inflexible, based on historical use patterns, not reflecting contemporary demands for environmental and recreational water applications. Although this literature asserts that prior appropriation is unfair, allocating most water to agriculture based on past use, the authors have not explored why water was distributed in this way, what the net efficiency gains were from a prior appropriation system, and what the costs of alternative arrangements might have been. Hobbs (2002) is unusual in this regard in tracing irrigation investment and economic growth associated with secure property rights. The separate economics literature has focused on the high transaction costs of exchanging prior appropriation rights when there are downstream effects on low priority rights holders, whose water is disrupted by the trade of high-priority upstream rights (Smith 2008, Libecap 2011). An alternative rights structure proposed by Young (2014) and others is to redefine water rights as shares in a total annual allowable stream withdrawal that would avoid the problem of interrupted return flows. These authors, however, also do not examine the underlying economic origins or benefits of prior appropriation as a major

[1] Property regimes 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.

institutional innovation or the transaction costs of a centralized restructuring of contemporary water rights. Thoyer (2006) explores some of the complexities involved by illustrating how high-priority owners could be made worse off if their access to water was made more uncertain as would be the case under a share system.

The limited economics literature on first possession largely is theoretical. 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). Parties with lower search costs or other skills define prior-appropriation claims before others, reducing the race and congestion over particular spots or other dimensions of the resource. Moreover, if there is full information about differential search costs, entry is lowered and the race for control is reduced because only low-cost agents have positive expected payoffs in competing for property rights. 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 1996; 1998). The legal scholarship on first possession is more favorable, being less concerned with dissipation and more on how the practice encourages valuable discovery and provides a clear, simple way to define ownership that can be equitable (Epstein 1979, 1985; Rose 1985, 1990; Ellickson 1993). This literature, however, does not examine why prior appropriation emerged in the first place.

In this paper we analyze the economic characteristics of prior appropriation surface water rights as first possession rights and their long-term economic effects from 1852 to 2013. Our data cover all of eastern Colorado from 1852-2013, some 7,800 rights and include location on stream, diversion size, date, infrastructure investment, topography, stream flow, annual stream flow variation, amount of water in the stream for claiming, soil quality, distance to arable land, amount of available arable land near the stream, precipitation and drought. Additionally, we have census data on irrigated lands, crops, land values, and infrastructure. We use these data to examine why prior appropriation displaced riparian water rights in such a dramatic fashion. Our analysis extends literatures on institutional change, first possession, and prior appropriation. It also informs debate over the efficiency of prior appropriation and the costs of proposed water rights reforms.

When settlers moved across the North American continent in the mid-19th century, the available land and water resources open for claiming under federal land laws were large relative to the number of settlers in any year. Moreover resource quality generally was unknown. The high Great Plains were referred to collectively as the Great American Desert. Stream locations, flows and land qualities varied in unknown ways. Settlers initially moved through the region to California and the West Coast because expected rents were too low and native hostilities too high (Allen 1991). Gradually, however, information was generated by search, and homestead claims proceeded in waves as new rounds of water and land claimants were attracted by expected new rents from land and water ownership. Over the 19th and early 20th centuries, the region gradually filled with claimants and available unclaimed high-quality water and land declined. At the same time, economic development around irrigated agriculture took place. As in the mining camps, it became quickly apparent that the incumbent common law property rights institution, riparian water rights, was incompatible with rent maximization associated with resource use and first possession ownership that separated water from land and allowed for its transfer to locations remote from water sources independently was adopted throughout the region.

We begin by using this setting to explore the economic rationale and patterns for first possession claims to water. Water was a large and heterogeneous resource with ownership assigned via successive rounds of entry and claiming based on information generated from previous claims. Quality was dispersed randomly in patterns that initially were unknown to claimants. First possession did not require knowledge of or bounding of the total resource, but rather only that claimants locate, select, and occupy a particular segment; designate defendable dimensions; proclaim timing or temporal position of the claim relative to competitors; and enforce it through occupancy, diligent development, or other indications of beneficial use. Beneficial use was constrained by production technologies and how the resource was employed as an input. In this way the market determined the size of the individual segments (Epstein 1979, 1986), and lowered bounding and enforcement costs. Beneficial use also revealed how much of the resource remained for subsequent rights claimants. Once first possession rights were established prior appropriation allowed for the diversion and transfer of water to productive sites away from the water source in a region where water supplies were limited and unevenly distributed. There was a tradeoff between claiming or waiting for new information to be revealed. At any time, all parties were equal in their lack of knowledge of high quality locations. Subsequent rounds of claiming revealed new information, but the quantities of remaining valuable sites were reduced. Those that went early had higher search costs, but had the potential of finding unowned sites that generated large rents. Through successive claiming a hierarchy of rights emerged of different value, producing declining inframarginal rents among claimants. Even so with parties ignorant at any point in time regarding the location of high quality segments, no party was advantaged and the resulting ownership allocation process was fair. In these ways, first possession as it applied to prior appropriation water rights lowered transaction costs and was equitable.

Individual claims were based on observable resource characteristics, and in the case of water, current stream flow or quantity, distance to stream head, terrain topography, and proximate soil quality. So long as search disclosed these characteristics, they were stable, and individual claims were respected locally, there was no basis for rent dissipation, even in a rush to claim. In this regard we differ from the literature that generally points to full dissipation with first possession claiming. Indeed, as we show 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. These advantages explain the abrupt voluntary shift from common law riparian rights to prior appropriation. One key resource characteristic was neither stable, nor observable initially, however-- stream flow variability due to drought. Absent an understanding of drought potential, stream flows were overestimated and excessive diversion claims and infrastructure investments were made relative to a full information setting, leading to rent dissipation. To support long-term investment and economic activity based on water use, prior appropriation rights have endured, molding the contemporary distribution of water ownership and the transaction costs of exchange. Assessments of the economic consequences of prior appropriation require consideration not only of current water rights exchange costs, but also of the economic returns generated over time by prior appropriation relative to riparian water rights.

II. Prior Appropriation as First Possession: Colorado Surface Water Rights

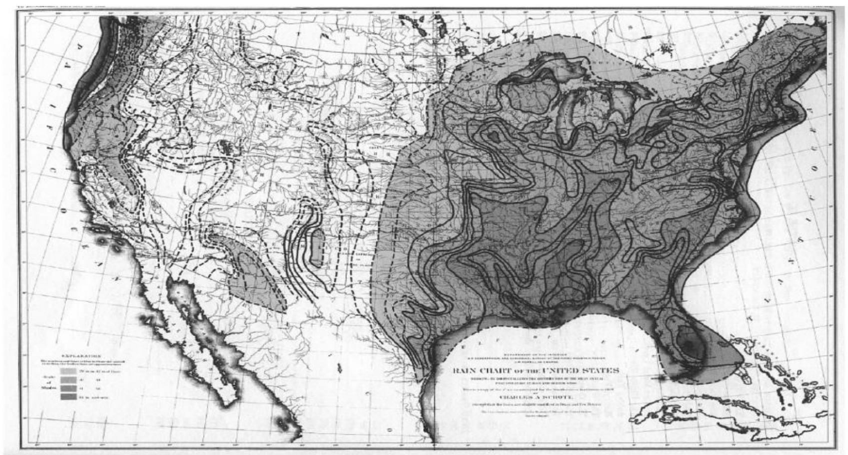
In the westward movement of the agricultural frontier Colorado was the place where settlers first encountered semi-arid terrain in a territory not dominated by pre-existing riparian water rights holders, as was the case in eastern-central Kansas. In Colorado it was very apparent that agriculture required irrigation and the movement of water from streams to agricultural lands. This in turn required a shift from riparian water rights that assigned water use to all adjacent land owners for reasonable applications to a new first-possession water right, prior appropriation. Prior appropriation allowed for individual, rather than communal claiming and use of water, and its separation from riparian lands. Settlers on the semi-arid frontier were making first-possession claims to land that only could be valuable with access to water. Water rights were allocated based on the time of the proclamation to divert, intent to place it to beneficial use without waste as determined by the territorial and later state governments, and subsequent diversion of water. Beneficial uses initially were ranked as domestic, agriculture, industrial, municipal and much later, recreation and stream flows. Failure to place diverted water into beneficial use resulted in abandonment and return of the use right to other potential claimants. Private usufruct rights were distributed as property that could be mortgaged and protected from takings, but water remained under territorial or state oversight. Water could be moved from place to place with the limitation that such changes not harm downstream vested rights holders.[2] Within a very short time, prior appropriation as an institutional innovation dominated property rights to water in the region.

Figure 1 shows an 1879 print of the western Great Plains, including Colorado, by John Wesley Powell illustrating how little was known of the area in terms of water resources and quality land. Early history of prior-appropriation water rights in Colorado is outlined by Dunbar (1983, 1985) and the economics of prior appropriation rights to water by Burness and Quirk (1979). Prior appropriation emerged quickly because of its enormous net economic benefits. Adoption costs were reduced because it mirrored the allocation of rights to other natural resources through first possession. Through most of the 19th century, all natural resources in the region—farm land, timber land, mineral land, range land--were open for first possession claiming. While the federal government attempted to sell lands early in the century at a floor price of between $1.25 to $2.50/acre, given the vastness of the area and small size of the US Army the government could not control or police entry. 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 Pre-emption Acts of 1830-41 (Gates 1968, 219-47), the federal government abandoned sales and with the enactment of the Homestead Act of 1862 and the Mining Law of 1868, first possession became the primary means

2 http://www.cwi.colostate.edu/ThePoudreRunsThroughIt/files/Historical_Context_Water_Law_Cache_La_Poudre.pdf 6-7.

of distributing property rights to valuable frontier resources (Gates 1968, 387-434; Libecap 2007).

Figure 1: The Semi-Arid West



Source: Powell, 1879, frontispiece, reprinted in Worster (2001, 349).

The western frontier was immense and varied in terrain, quality, and potential value. 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 miners, for example, earned only their opportunity wage (Clay and Jones 2008, 1010, 1022). Other studies of the relative homogeneity of parties include those by Umbeck (1977a; 1977b; 1981, 53); Libecap 1978; Libecap and Johnson (1979); Reid (1980, 18); Zerbe and Anderson (2001, 119); McDowell (2002, 2-19); Clay and Wright (2004, 176); Libecap (2007, 260); and Steward (2009). Although none of these studies examine prior appropriation claims to water, it is reasonable to assume that early water rights claimants had a similar lack of information about where to establish diversion rights. As with other western resources individuals competed with others for the best locations they faced a tradeoff between waiting to learn more from others at the risk of having the best sites taken. In the case of surface water and farm land, frontier migrants could observe relatively stable resource characteristics, such as topography, elevation, 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 diversion water claims could be made at a time of unusual water supplies, but provide insufficient water during drought. Indeed, as shown by Libecap and Hansen (2002) and Hansen and Libecap (2004a, 2004b), there was general misunderstanding of the region's dry climate and of the potential for drought to dramatically shift production potentials. We explore this issue in more detail below.

From first settlement in the 1860s to the 1876 Colorado Constitution to the 1882 Colorado Supreme Court ruling in *Coffin v Left Hand Ditch* Co (6 Colo 443), riparian rights were rejected and prior appropriation rights acknowledged to facilitate the construction of diversion dams and canals to support irrigated agriculture: "In a dry and thirsty land it is necessary to divert the waters of streams from their natural channels, in order to obtain the fruits of the soil, and this necessity is so universal and imperious that it claims recognition of the law. The value and usefulness of agricultural lands, in this territory, depend upon the supply of water for irrigation, and this can only be obtained by constructing artificial channels through which it may flow over adjacent lands. These artificial channels are often of great length, and rarely within the lands of a single proprietor…..Where the lands of this territory were derived from the general government, they were subject to the law of nature, which holds them barren until awakened to fertility by nourishing streams of water, and purchasers could have no benefit from the grant without the right to irrigate them." (*Yunker v. Nichols* 1872, 1 Colorado 551-55, quoted in Hess 1916, 654 and discussed in Hobbs 1997, 1). Prior appropriation was first formally recognized in Colorado as a full tangible property right to water as was also possible with land and this institution became known as the Colorado Doctrine. It became a general template for other western territories and states (Schorr 2005) and generally, western Canadian provinces. Only in the relatively wetter states of California, Oregon, and Washington did remnants of riparian water rights remain (Hess, 1916, 655-6; Dunbar 1950, 241; Hobbs 1997, 2, 5).

Under prior appropriation, the first claimant to a diversion site had the highest priority in securing sufficient water for beneficial use. Subsequent claimants would be ranked lower and have lower-priority access to water. Early actions of the Colorado courts and legislature illustrate the process of institutional change associated with the shift from riparianism to prior appropriation. Courts and legislatures sought to more precisely measure priority rights when there were competing diversions and in creating an institutional infrastructure to arbitrate disputes. So long as early irrigators had ditches that were small relative to stream sizes, conflicts were limited. As the number of diversions increased, however, upstream interception could damage a downstream rights holder with higher priority. For example an 1861 Territorial law (Dunbar 1950, 68, 245-9) created an arbitration mechanism when more there were claimants than stream flow would support. A series of adjudication laws were enacted in 1879 and 1881 to identify irrigation rights by priority and quantity via judicial decree and administration of court judgments. Priorities were set according to the year in which the application for an adjudication decree was filed with territorial or state courts and ranked in order of the date of appropriation (Hobbs, 1997, 9-10). After the 1870s Colorado was divided into water divisions and divisions into districts with ditch riders to measure and enforce claims based on priority. District courts mediated disputes and adjudicated rights until specialized water courts were established in 1969. The 1879 Irrigation Act empowered district courts to determine the priority right of each water user on each stream according to when a ditch or canal was constructed and water was first diverted and put to beneficial use. The right to store water in reservoirs was also affirmed by the legislature in 1879. The Map and Statement Act of 1903 defined recording requirements with the State Engineer as well as the information required in any rights dispute or proposed change in water delivery or use. The data included a map, names of water claimants, diversion location including section, township, and range, diversion ditch headgate location, canal size (width and depth of water, carrying capacity in cubic feet per second, and acres irrigated. These data also were filed with county clerks and local district courts. Within the relatively short period in the latter part of the 19th century a water rights regime was put in place along with a legal institutional structure to refine and enforce it.

As part of its economic benefits relative to riparianism, prior-appropriation coordinated joint development of irrigation infrastructure and irrigated agriculture by groups of settlers and exclusion of those who did not participate. Because diversion dams, primary canals, and feeder ditches to remote fields required costly capital investment, settlers often joined in staking prior appropriation right claims with the same priority and in forming mutual ditch companies, with shares based on irrigated acreage. Alternatively, commercial ditch companies were established by purchasing existing water rights and then delivering water to irrigators under contract (Libecap 2011). 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 northcentral Colorado was the center of early rights claiming and irrigation. Dunbar (1950, 242-5) describes the conflict between the Union colony of settlers that jointly claimed a water right and dug a large Colony Canal No. 2 (280 cfs) in 1870-1 from the Cache la Poudre River to irrigate 60,000 acres and the 1873-4 Larimer County Land Improvement Company that had a lower priority water right and upstream canal. Upstream diversions intercepted higher priority water. Resolution of this and other water rights disputes though local courts and the territorial and state legislature ultimately led to the more precise definition and enforcement of prior appropriation water rights.[3] Later we describe water trading and ditch consolidation that took place within the framework of the new property rights system and the expansion of irrigated agriculture and land values.

Figure 2: River Basins in Colorado

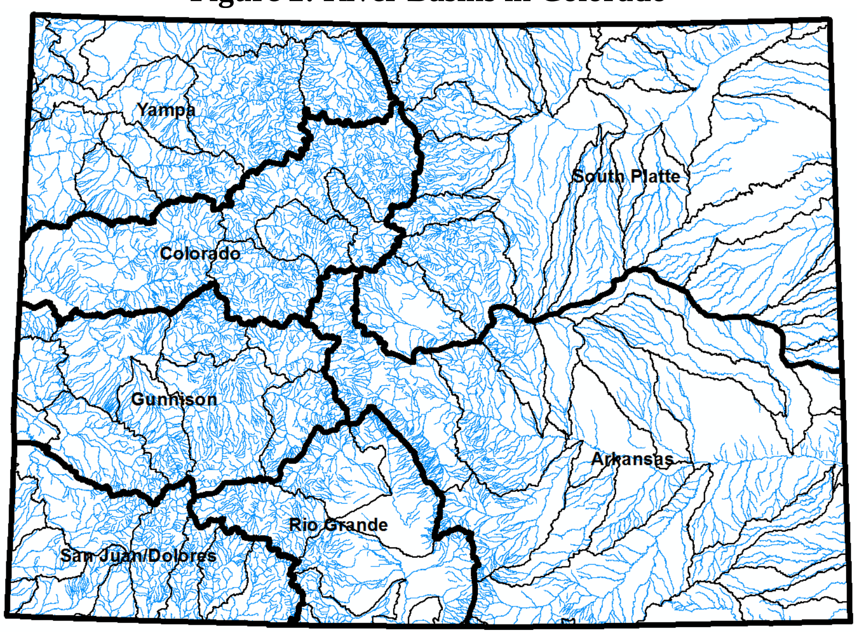


Figure 2 shows the river basins in Colorado and Figure 3 below the pattern of prior appropriation water rights claims. The western parts of Colorado have limited agricultural potential and a far smaller population. It is evident from Figure 3 that most high priority water rights and the largest volumes of water claimed occurred prior to 1920. Figure 4 describes the

[3] http://www.cwi.colostate.edu/ThePoudreRunsThroughIt/files/Historical_Context_Water_Law_Cache_La_Poudre.pdf, 1.

priority of water right over time across streams by showing the number of claimants with a particular priority in a given year. Each bar represents the number of users who were the ith claimant on their respective stream in a given year. Because each stream had its own priority ladder, the figure reveals movement of claimants spatially across time with surges in the number of high-priority claims as areas with existing claims become congested and users must search out new streams. This figure also highlights the tradeoff faced by users who follow senior claimants. Areas with more prior claims are better understood and have more existing diversion infrastructure, but also may have less water available for claiming. Next, we develop a simple model to explore this tradeoff.

Figure 3: The Time Pattern and Volume of First Possession Rights Claiming

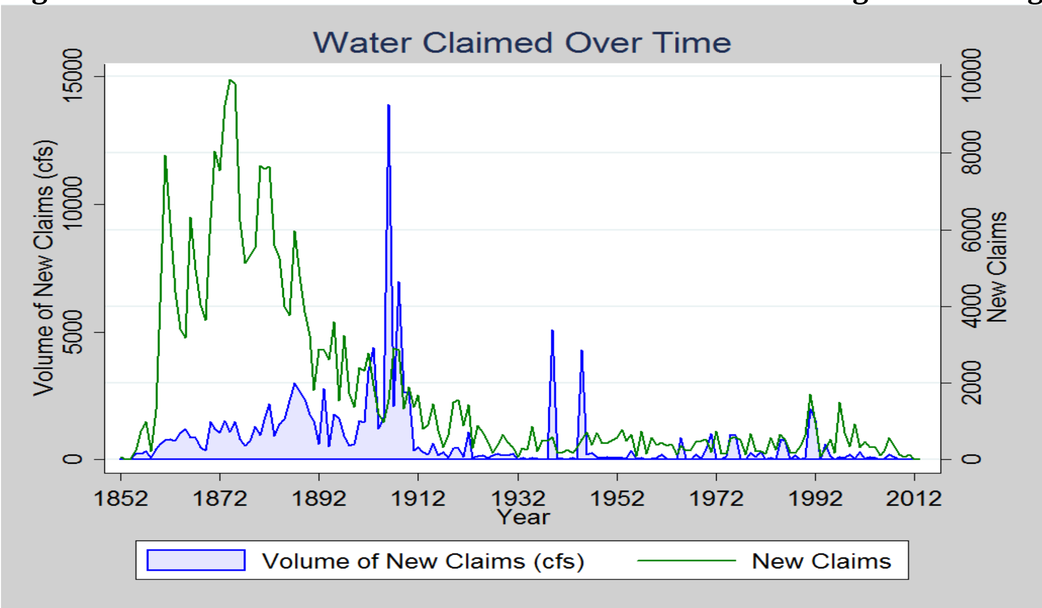
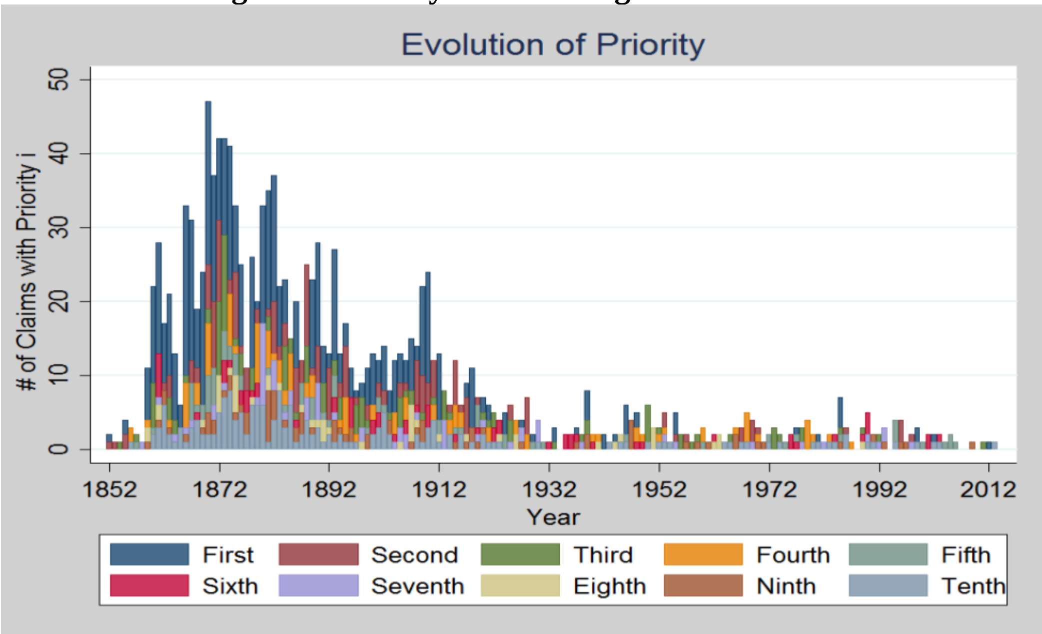


Figure 4: Priority of Water Rights across Time



III. Model of First Possession, Application to Prior Appropriation, and Hypotheses

Model

To examine the economics of first possession claiming we develop a simple model to emphasize one of the fundamental tradeoffs faced by users who establish claims to heterogeneous resources via first possession. Our model takes the timing and arrival of claimants as given, focusing on simultaneous claims established by homogeneous users within a given period. Users hold limited information about the resource such that all locations with no previous claims have the same expected productivity. We allow the marginal costs of establishing a claim to vary based on the quantity of the resource already claimed in a given location, inducing a tradeoff between resource availability and the possibility of capitalizing on earlier claimants' investments in a given area. We also highlight directions for further development of the model.

Lueck (1995) and others show that in a competition to claim a single asset, the lowest-cost user establishes a claim before any other user and no actual "race" ensues. Indeed, it is common in the literature on first possession to assume that users have exogenously given differences in claiming costs. We extend this convenience to the multiple-asset case and assume that claimants arrive in waves based on exogenous differences in fixed claiming costs. These exogenous cost differences induce a ordering of when different groups of users establish a claim without affecting the decision of which units of the resource to claim within a period. We assume that users within a given wave are homogeneous and focus on the choice of where to establish a claim within a period.

In what follows we characterize the choice facing junior claimants of whether to follow senior users or establish a claim in a new, unknown location. Since unknown locations are of equal expected productivity, this choice can be analyzed by comparing the value of following vs. the value of establishing a generic new claim. Users face a downward-sloping benefit function that declines with the total amount of the resource claimed in a given area.[4] Users also face a marginal cost of establishing a claim that depends directly on the previous amount of the resource claimed. We summarize expected profit for users who follow (superscript F) or search (superscript S) below.

$$\pi_i^F = q_i\big(a - b(\bar{q} + q_i + q_{-i})\big) - g(\bar{q})cq_i$$

$$\pi_i^S = q_i(a - bq_i) - cq_i$$

Where $\bar{q}$ denotes the amount of the resource already claimed in a particular location, q_{-i} denotes the amount of the resource claimed by other users in the same location within the same period, and $g(\bar{q})$ is a general function of the quantity of prior claims that shifts the costs for current users who establish claims in the same location.

[4] This allows the possibility of a downward-sloping demand curve if the resource is sold directly or of declining marginal product if the resource is an input into some productive process. In the later case, we allow the marginal benefit to depend on total appropriations as a way to express the limited availability of the resource.

User i decides whether to follow the senior user based on their diversion size, $\bar{q}$ or establish a claim in "uncharted" territory, taking the actions of other users as given. To simplify exposition we assume that there is one location in which to follow other users, but that there are other locations from which to choose. Individuals must decide between being one of n users who follow previous claims and establishing a new claim in some area on their own. We solve for a Cournot-Nash equilibrium among the users who choose to follow, initially taking n as given. The optimal claim size and resulting profit for users who follow are

$$q_i^F = \frac{n(a - b\bar{q} - g(\bar{q})c)}{b(n+1)}$$

$$V_i^F = \frac{(a - b\bar{q} - g(\bar{q})c)^2}{b(n+1)^2}$$

Alternatively, users can seek out an entirely new location. Given our focus on large, heterogeneous resources of unknown quality, we assume that there are enough distinct locations in which to claim that each user can be the first claimant in some area if they so choose. We also assume that each location has the same expected productivity and claiming costs. Given these assumptions, the optimal claim size and resulting profit for users who search are

$$q_i^S = \frac{a - c}{2b}$$

$$V_i^S = \frac{(a - c)^2}{4b}$$

Users within a given wave will follow previous claimants as long as the expected profit of doing so exceeds the expected profit of claiming in a new location, given the number of other claimants simultaneously choosing to follow. We can use this fact to solve for the number of users within a give wave of claiming who choose to follow prior claimants. In an equilibrium where both following and searching occur, it must be that

$$V_i^F(n) = V_i^S$$

$$\Leftrightarrow$$

$$\frac{(a - b\bar{q} - g(\bar{q})c)^2}{b(n+1)^2} = \frac{(a - c)^2}{4b}$$

We use this condition to solve for the number of users who follow previous claims within a given wave and derive predictions for how the parameters of the model affect the number of followers.[5] The number of followers in equilibrium is

$$N^F = \frac{a - 2b\bar{q} - c[g(\bar{q}) - 1]}{a - c}$$

Of primary interest is the effect of prior claims on the number of users within a given wave who choose to follow:

$$\frac{\partial N^F}{\partial \bar{q}} = \frac{-1}{a - c}(2b + g'(\bar{q})c) = \begin{cases} < 0 & g'(\bar{q}) \geq 0 \\ > 0 & -g'(\bar{q}) > {}^{2b}/_{c} \end{cases}$$

If $g'(\bar{q}) \geq 0$, then the effect of prior claims on the surplus of following is unambiguously negative. In order for increases in prior claims to increase the value of following, it must be that $-g'(\bar{q}) > \frac{b}{c}$. This means that additional prior claims only make following more attractive if they cause costs to fall (that is, if $g'(\bar{q})$ is sufficiently negative).

This argument sets up a key test of our model—claimants will tend to cluster spatially around prior claims only if there are positive externalities associated with the investment in claiming and discovery made by initial users. The intuition is clear: following prior claimants involves establishing a claim in an area where less of the resource is available and the value of marginal units of the resource is lower. There must be some offsetting reduction in claiming costs associated with following prior users to induce empirically observed following behavior. The next section of the paper discusses challenges in identifying the "following effect" we are interested in.

A related question of interest is whether users who choose follow will claim more of the resource than those who search. Continuing to focus on the equilibrium where there are both followers and searchers, we substitute our expression for N^F into the optimal claim size for followers to compare the choice of how much to claim. Followers divert more than searchers if

$$\frac{N^F(a - b\bar{q} - g(\bar{q})c)}{b(N^F + 1)} > \frac{a - c}{2b}$$

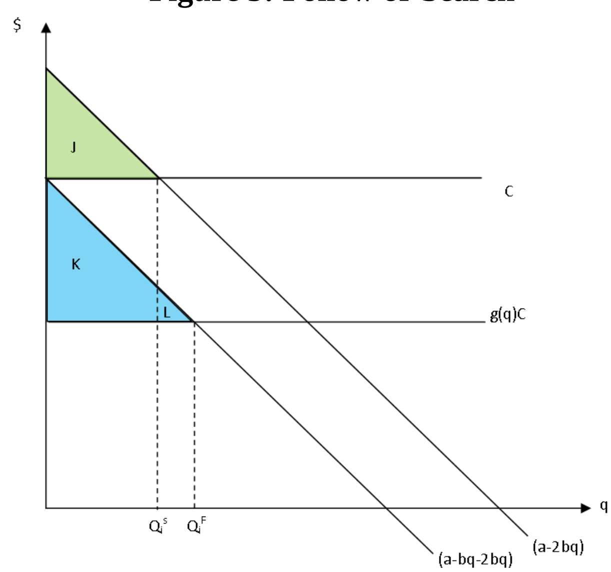
[5] We focus on the equilibrium where some users search and some follow. There is also an equilibrium where all users search if the expected value of following is too low as well as a possible equilibrium where all users follow if the costs reductions associated with being a follower are large relative to the reduction in the value marginal product of the resource *and* the number of claimants in a wave. Analyzing the interior case provides intuition about all three equilibrium because the all-search equilibrium corresponds to $N^F = 0$ and the all-follow equilibrium corresponds to $N^F = N^{Max}$.

Substituting for N^F and solving, this condition is equivalent to

$$g(\bar{q})c > 2b\bar{q}$$

The term on the left is the marginal cost of claiming for followers, and the term on the right is equal to the reduction in the value of marginal product of a claim due to the size of prior claims. Intuitively, this condition says that followers' claims are larger than searcher's claims if the marginal costs of claiming are large relative to the slope of the marginal revenue curve. This is illustrated in figure 5. As can be seen from the figure, the condition for followers' claims to exceed searchers' claims is more likely to hold in settings where the cost advantage from following is larger—area J represents profit from searching and area K + L represents profit from following. In order for K+L to exceed J, it must be that Q^F is to the right of Q^S. The structure of the Cournot-Nash equilibrium will confound this effect by reducing claim size as the number of followers increases, but we would expect a general positive relationship between the number of followers and the expected size of claims once we generalize the model beyond two locations. That is, the factors that make following more attractive than claiming also increase the optimal size of a claim for followers.

Figure 5: Follow or Search



Applications and Corollaries in the case of Water

The structure and intuition of our simple model rely on our broader conceptualization of the information costs associated with defining rights to a large, heterogeneous resource. The assumption that important features of the resource's productivity are unobservable ex ante is what creates the tradeoff between following prior claimants and claiming in a new location altogether. This notion also has implications for the cost-minimizing strategy for defining the rights themselves. Given that rights have multiple attributes, transactions costs—the costs of defining and enforcing property rights—are minimized when rights are defined along dimensions that are easy to observe and to police. This principle leads to some specific hypotheses in the case of surface water appropriation. 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.

As we have already noted, a primary impetus for the development of prior appropriation in the arid western United States was the need to move water away from streams for both agriculture and mining. Given the size and ruggedness of the western frontier and the non-point nature of the application of water for irrigation, defining rights relative to the point of diversion rather than the point of use reduced the cost of defending those rights. Similarly, using time as a primary dimension along which to define water rights reduced the need to tie rights to some other observable dimension such as land ownership (as was the case for riparian rights in the east). In settings where many users did not have ex ante land claims, time was a sensible dimension along which to fix claims.

Disputes among claimants of heterogeneous and variable resources can arise even in settings where the transactions costs of establishing the rights themselves are relatively low. The possibility of such disputes is especially pronounced in cases where the level of the resource varies from period to period in ways that are not necessarily well-understood by claimants. This suggests that users will seek to establish claims that are more easily defended from encroachment by subsequent users, especially when formal enforcement mechanisms are weak or absent, as was the case in the early settlement of the western frontier. Although the timing of a claim establishes legal priority, locating a claim further upstream creates a de facto priority to the water by reducing the probability that subsequent users will locate even further upstream. Locating closer to the head of a stream reduces expected losses and enforcement costs, especially early in the history of water claiming when formal legal institutions were weak. Hence, we predict that users will tend to locate further upstream, ceteris paribus.

The predictions of our formal model and of our broader framework that we seek to test in the next section are summarized below.

Summary of Predictions

1. An increase in the number of claims in a given location will increase the number of subsequent claims in that location
2. Diversions will be higher for users who follow prior claimants than for users who locate in unclaimed locations[6]
3. Users will prefer to locate towards the mouth of the stream, ceteris paribus

[6] This prediction is closely related to the assumption of constant marginal costs. We mark this as a potential limitation of the theory and suggest refinements in our discussion of our empirical results below. Increasing marginal costs and/or a formal incorporation of uncertainty could reverse this prediction or make it ambiguous because the optimal claim size in a given location depends on the steepness of the marginal cost curve and the actual resource endowment in that area, both of which could in principle differ across areas. Our simple model for this draft abstracts away from these possible differences between locations.

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

Extensions

The simple model presented here is a first attempt to formally derive several predictions from a much broader theoretical framework. As such, there are many possible extensions to the model that could generate additional insight and testable predictions. Our current model captures the resource tradeoff of following early claimants only implicitly—the marginal value of a claim is reduced when more of the resource has already been claimed, but there is no explicit resource constraint within a location. Including the constraint explicitly may shed light on the conditions under which the resource is completely exhausted in particular locations and elucidate the conditions for subsequent shortages during drought. Along the same lines, uncertainty about the amount of the resource or about the parameters of the revenue and cost functions could be formally included in the model. Our current efforts emphasize that a positive externality in claiming costs generated by initial claimants is a necessary condition for following behavior to occur, but formally adding uncertainty to the model would clarify how and if learning occurs in first possession settings. Finally, formally including the dynamics of the resource over time would provide a more intuitive mapping from out conceptualization to traditional models of first possession races. We plan to expand the model on at least some of these dimensions for subsequent drafts.

IV. Empirical Strategy and Analysis.

Data

We assemble a unique data set of all known original appropriative surface water right claims in Colorado. We combine geographic information on the point of diversion associated with each right with data on hydrology, soil quality, elevation, and irrigation to assess various margins of quality in initial claims to water. Colorado is divided into 7 Water Divisions that separately administer water rights. We focus initially on Divisions 1 to 3, which comprise the eastern half of Colorado, are home to much of the state's agriculture, and have more complete diversion data available than other divisions. Our data on water rights were obtained directly from the Colorado Division of Water Resource. For each right 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. Hydrologic data on basins, stream names, and network characteristics come from the National Hydrography Dataset (NHD). Estimates of stream flow across this network were obtained from NHDPLUS V2. 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 across Colorado. Our soil data are from the USDA Soil Survey Geographic Database (SSURGO).

Our goal is to characterize individuals' choices of where to establish first possession claims to water over time. Analyzing only the location where rights were actually claimed ignores a substantial amount of individuals' choice sets. In reality, all of the locations along rivers in Divisions 1 through 3 that could have been claimed but never were are an important factor in our analysis. In order to fully characterize and understand individuals' choices of where to establish claims to water, we must analyze *all* potential locations, not just those that were ultimately chosen. Accordingly, we divide Divisions 1 to 3 into a grid of 1 square mile sections and create measures of location quality by grid cell.[7] This grid approximates the Public Land Survey (PLSS) grid, but fills in gaps where GIS data on PLSS sections are not available. We believe this is an appropriate unit of analysis because actual land claims were typically defined as subsets of PLSS sections, so grid-level variation is similar to actual variation in land ownership and land use. Figure 6 shows a map of Divisions 1 to 3 with the locations of the rights, the major streams, and the grid squares used for the analysis. The size of each point is proportional to the claim size, and rights are color-coded from earliest (green) to most recent (red). Green areas indicate prime agricultural land.

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. This construction captures the fact that both steeper terrain and more variable terrain contribute to rugged topography. We use the SSURGO data to calculate the number of acres in each square categorized as "Prime Farmland if Irrigated," a classification of the USDA primarily based on soil structure that is unlikely to change over time. We interact this measure with the year to assess whether land quality is more easily determined later in the sample period (as technology advances and users learn). We also calculate the total area (in acres) of the watershed that a square lies in using the HUC8 classification of watersheds from the National Hydrography Dataset (NHD).

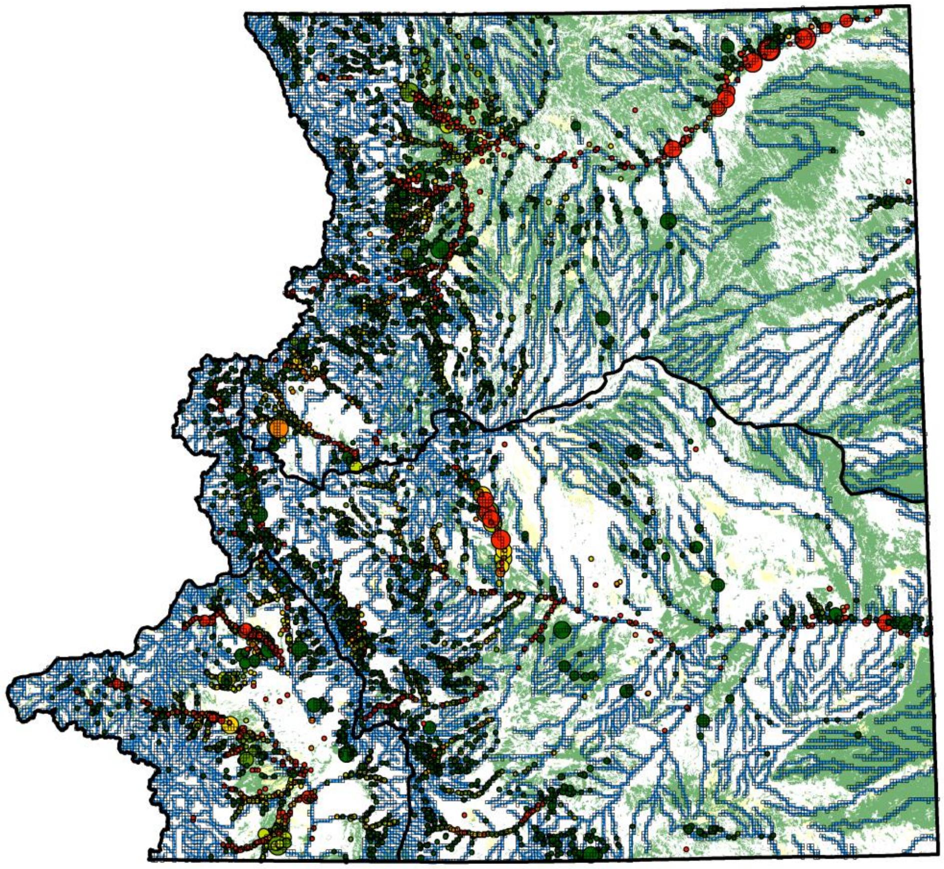
We locate each square along the stream network defined by the NHD and use this location to create a variety of variables relating to the water resource itself. We calculate the distance from each grid square to the head of the stream or reach it lies on (as defined by the NHD).[8] The NHDPlus V2 dataset 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 summerFlow—the total flow across May through August—and flowVariability, the standard deviation of flows across the same months. We construct a panel of grid squares from 1852 (the date of the first claim in our data) to 2013 (the date of the most recent claim). We also calculate the number of claims and amount of water claimed within each square in each year. Combining this with the distance to head variable, we calculate the number of prior, upstream claims from each square and the amount of water that has been previously claimed on the same stream in each year. Finally, we calculate the number of previous claims along the same stream, within the same watershed, and in other watersheds for each grid square in each year. To assess how "followers" differ from "searchers" we create a dummy variable that is equal to one for squares that had at least one claim in the previous period. Variables relating to

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

[8] 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.

the stock and flow of rights along a river change over time, whereas measures of resource quality are fixed. Table 1 provides variable names, definitions and summary statistics.

Figure 6: Possible and Actual Claim Sites



Identification

Most of our hypotheses concern the decision of where to establish a claim, so our econometric approach focuses on modeling the number of claims in a given location in a given year as a function of the variables described above. Our outcome of interest has the properties of a count variable—in a given year most squares receive zero new claims, there cannot be a negative number of claims, and the maximum number of claims in a given square in a year is 11. It is widely recognized that the linear regression model is inappropriate in setting where the dependent variable takes on only nonnegative integer values, so we use a Poisson regression model as is common in the literature. We are primarily interested in estimating the effect of previous claims on the number of new claims in a given location in a given period, giving our model an inherent dynamic structure. More specifically, we wish to estimate

$$y_{it} = \alpha + \theta \sum_{j=1}^{t} y_{it-j} + \vec{\beta}\vec{x}_i + \varepsilon_{it}$$

where y_{it} is the number of new claims in location *i* in year *t* and $\vec{\beta}\vec{x}_{it}$ is a vector of controls and other variables of interest. Our challenge is to identify θ, the effect of previous claims on current claims in the same location.

The primary challenge to identification comes from the fact that there are unobserved grid characteristics that may bias the estimate of θ if not properly dealt with. That is, if ε_{it} contains some unobserved component that is possibly correlated with $\sum_{j=1}^{t} y_{it-j}$, denoted u_i. The intuition for this concern in our particular setting is quite clear. Our model and resulting predictions rely on the fundamental assumption that the parameters of the model—a, b, and c—do not vary across locations and that all unknown locations have the same expected productivity. We can condition on soil quality, roughness, and stream flow, but any other variation in location quality that affects the expected productivity of a location is unobserved and will bias our estimates of the effect of lag in claiming if unaddressed. Put another way, the presence of additional prior claims could act as a proxy for unobserved site quality, causing us to attribute the effect of these site attributes to the "following" effect instead.

Addressing unobserved heterogeneity in dynamic panel contexts can be challenging even with a linear model for $\mathrm{E}(y_{it} | \sum_{j=1}^{t} y_{it-j} , \vec{\beta}\vec{x}_i)$ and the case of a nonlinear distribution is even more difficult. Fortunately, Wooldridge (2005) provides a technique for using initial values y_{i0} to estimate Average Partial Effects (APE) θ and $\vec{\beta}$ that are averaged across the distribution of unobserved heterogeneity. The key is to parametrically specify a conditional distribution for $(u_i | y_{i0}, \vec{x}_i)$. If this distribution is correctly specified (an untestable assumption), then standard maximum likelihood methods can be used. In particular, Wooldridge (2005) shows that a dynamic Poisson regression with unobserved heterogeneity is identified and can be estimated using the random effects Poisson estimator so long as one controls for the initial conditions y_{i0} and the random effect is assumed to have a gamma distribution. We assume

$$\mathrm{E}(y_{it} | y_{it-1}, \dots, y_{i0,} \vec{x}_i, u_i) = u_i \exp(\theta y_{it-1} + \vec{\beta}\vec{x}_i)$$

where

$$u_i = \nu_i \exp(\delta y_{i0} + \vec{\gamma}\vec{x}_i) \qquad \nu_i \sim gamma(\eta, \eta)$$

and employ a random effects Poisson estimator using standard software packages.

Table 2: Grid Panel Summary Statistics

Variable	Mean	SD	Min	Max	Definition
Claimed	0.00106	0.0325	0	1	Dummy variable equal to one if newGridClaims > 0
Flow Variability	-0.0585	0.175	0	0.979	Standard deviation of flow across May through August along the reach where a square is located
Follower	7.05e-05	0.00839	0	1	Dummy variable equal to one if laggedClaims > 0
Grid Distance To Head	14.37	33.50	0	360.3	Distance (in miles) from each square to the head of the stream that right lies on.
Watershed Acres	1.281e+06	570,847	365,026	2.469e+06	Area of the watershed that a square lies in.
Initial Claimed	7.64e-05	0.00874	0	1	Dummy variable equal to one if initClaims > 0
Initial Claims	7.64e-05	0.00874	0	1	Number of claims established in a square in 1852, the first year in our sample.
Lagged Claims	0.00125	0.0425	0	11	The total number of new claims established in a given square in the previous year.
Lagged Water	0.0193	4.447	0	8,631	The volume of new claims established in a given square in the previous year.
New Grid Claims	0.00124	0.0423	0	11	The number of new rights established in a square in year.
New Grid Water	0.0192	4.433	0	8,631	The volume of new water rights established in a square in year.
Prime Acres	38.54	73.16	0	1,280	Acres categorized as “prime farmland if irrigated” within a square.
Prior Stream Water	184.8	925.2	0	9,246	The total volume of water claimed on a stream prior to the current period.
Prior Upstream Claims	4.936	35.58	0	713	The number of rights established upstream of a square prior to the current period.
Prior Claims Elsewhere	157.5	269.0	0	1,318	Total number of pre-existing water rights in other watersheds in a given year.
Roughness	284.0	375.2	0.000926	4,362	The average slope (in percent) multiplied by the standard deviation of the slope of a grid square.
Summer Flow	225.4	805.0	0	8,470	Total flow across May through August along the reach where a square is located.

Notes: N = 4,009,222.

In addition to the parametric restriction on the densities of $(u_i|y_{i0}, \vec{x}_i)$ and $E(y_{it}|y_{it-1}, \dots, y_{i0,}\vec{x}_i, u_i)$, identification of θ and $\vec{\beta}$ relies on two key assumptions. First, we must assume that the dynamics of y_{it} are only first order—that the dependence of y_{it} on the complete history of claims in the same location can be summarized by the relationship between y_{it} and y_{it-1}. This assumption amounts to saying that the number of claims at a site in a year depends only on the number of claims in the previous year, or that last year's claims are a sufficient statistic for the history of claims. While our model focuses on the cumulative sum of claims in a given location, we believe this assumption holds with respect to the empirical count of claims.

Accordingly, we argue that with the *number* of claims as a dependent variable, conditioning on the cumulative diversions along a stream—and element of $\vec{x}_i$—alleviates concern that the cumulative stock of claims could matter. 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 has been claimed, but the total number of claims is not directly relevant except through its affect on y_{it-1}. Our intuition is that claims from the previous period provide as signal to potential followers as to whether claiming in a given location is still profitable, given the declining rents of claiming in a particular area as claims accumulate.

Second, we must assume that $\vec{x}_i = \{\vec{x}_{i0}, \dots, \vec{x}_T\}$ is strictly exogenous, conditional on u_i. This assumption is easily satisfied because the elements of $\vec{x}$ in our case are either fixed geographic characteristics or lagged values of other variables. Conditional on other unobserved factors u_i, these variables are strictly exogenous to the number of claims in a location in a given year. Wooldridge (2005) shows that the same general assumptions can be used to identify a dynamic probit model by including an initial condition in a random effects probit, which we estimate as a robustness check given the large number of zeros in our count data.

Empirical Results

Table 2 reports the estimated average partial effects from changes in each of the variables of interest. The dependent variable in columns 1 and 2 is the number of new claims in a given cell in a given year. The dependent variable in columns 3 and 4 is a dummy variable that is equal to 1 if there was a new claim in a given cell in a given year. Columns 2 and 4 also include the total number of prior claims in other squares within the same watershed in a given year. We focus on columns 1 and 2 where the dependent variable is the number of claims, but all of the results can be interpreted analogously for the probability of a claim in columns 2 and 4. All of the results are consistent across models and specifications. The coefficients on year and year-squared jointly indicate that the number of new claims in any particular location increased over time, but at a decreasing rate. This is consistent with our notion successive waves of users arriving until the resource is fully claimed.

Table 2: Random Effects Poisson and Probit Regressions on The Location of Claims

	(1) Poisson	(2) Poisson	(3) Probit	(4) Probit
	Y = New Claims in Location *i* in year *t*		Y = 1(New Claim in location *I* in year *t*)	
Lagged Claims	0.565***	0.575***		
	(0.0210)	(0.0212)		
Lagged claim			0.833***	0.853***
			(0.0286)	(0.0286)
Prior Stream Water	0.0000301	0.0000475**	0.0000173**	0.0000215***
	(0.0000238)	(0.0000236)	(0.00000814)	(0.00000802)
Prior Upstream Claims	0.00396***	0.00363***	0.00199***	0.00179***
	(0.000592)	(0.000587)	(0.000193)	(0.000190)
Summer Flow	0.000367***	0.000340***	0.000117***	0.000103***
	(0.0000291)	(0.0000274)	(0.00000644)	(0.00000621)
Flow Variability	-1.355***	-1.418***	-0.621***	-0.603***
	(0.111)	(0.109)	(0.0376)	(0.0360)
Roughness	-0.000675***	-0.000746***	-0.000208***	-0.000275***
	(0.0000756)	(0.0000743)	(0.0000248)	(0.0000248)
Prime Acres	0.0107	-0.00577	-0.000734	-0.00848**
	(0.0124)	(0.0121)	(0.00432)	(0.00411)
Prime Acres*Year	-0.00000689	0.00000194	-6.80e-08	0.00000411*
	(0.00000652)	(0.00000639)	(0.00000228)	(0.00000217)
Distance To Head	-0.00590***	-0.00494***	-0.00178***	-0.00136***
	(0.000681)	(0.000667)	(0.000212)	(0.000205)
Prior Claims Elsewhere		0.000747***		0.000368***
		(0.0000653)		(0.0000237)
Year	0.596***	0.443***	0.154***	0.0959***
	(0.0377)	(0.0394)	(0.0130)	(0.0133)
$Year^2$	-0.000162***	-0.000123***	-0.0000420***	-0.0000273***
	(0.00000988)	(0.0000103)	(0.00000339)	(0.00000347)
Watershed Acres	0.000000330***	0.000000180***	9.52e-08***	3.06e-08**
	(3.77e-08)	(3.89e-08)	(1.22e-08)	(1.28e-08)
Initial Claims	2.154	2.044		
	(1.423)	(1.354)		
Initial Claimed			0.888**	0.821**
			(0.361)	(0.363)
N	4009222	4009222	4009222	4009222

Standard errors (clustered by stream) in parentheses. * $p < .1$, ** $p < .05$, *** $p < .01$

The primary result of our model was that users will chose to follow senior claimants only if the investments of seniors generate positive externalities. The coefficient on Lagged Claims is positive and significant in both specifications, indicating that an increase in the prior year's claims in a given location increases the expected number of claims in a given year. The total amount of water previously claimed on the same stream as a square also increases the probability of a claim in three of four specifications. Finally, additional claims upstream from a given square increase the expected count of new claims in that square. These three coefficients indicate a strong positive relationship between the number and size of claims in a particular location and the likelihood of new users choosing to stake a claim in that location; that is, we have robust evidence that claimants choose to follow senior users. We take this as evidence that early claimants' investments in knowledge and infrastructure for diverting water generated substantial value for subsequent literature. This finding is consistent with the legal literature on first possession, which has tended to emphasize its value as a means to facilitate investment.

Table 2 also provides evidence in support of hypotheses 3 and 4. All else equal, fewer new claims are established in squares that are further from the head of the stream. This is consistent with hypothesis 3. Controlling for Distance to Head, users are actually more apt to locate downstream of senior users. We believe this reflects the fact the location was in part a strategy for preventing harm due to the actions of *future* claimants. In a given year, new claimants already have lower priority rights than senior users, so locating upstream from these users is likely of little value. Moreover, if earlier claimants had followed a similar strategy and established claims closer to the head of the stream, subsequent claimants would be forced to locate downstream from them. Accounting for this, users still prefer to be closer to the head of the stream. We take this as suggestive evidence of early movement towards the head of the stream, with claims slowly moving further downstream over time.

Hypothesis 4—users will be more responsive to easily observed covariates—is supported by several of the coefficients in table 2. The coefficient on Summer Flow is positive and significant, indicating that users seek areas along the stream with greater flow. Flow Variability, which measures the variability of flow over the summer months, is negative, significant, and large in magnitude (it is measured in the same units as Summer Flow, for comparison). Evidently, users make strong efforts to avoid claiming water in areas subject to variability within a year. While we believe that annual variability is more difficult for users to assess and so will not significantly affect the choice of location, we are still constructing a measure of annual variability and cannot assess that hypotheses at this time. As we suggested earlier, unobserved annual variability could lead to overclaiming of water sites and rent dissipation. Squares that are more rugged also have significantly fewer claims, providing further support for hypothesis 4, as ruggedness is easily observed. In contrast, Prime Acres is not significantly different from zero in three of four models. This could be consistent with our prediction that difficult-to-assess aspects of resource quality will not influence claim location. Another possibility that we cannot rule out in the current analysis is that the point of diversion is not the appropriate location to measure soil quality. Distance to prime acre location might address this issue more directly.

The results so far are consistent with hypotheses 1, 3, and 4. Next, we assess hypothesis 2, which concerns the size of followers' claims relative to searchers' claims. Table 3 reports the results of OLS regressions on the volume of water claimed in a given location in a given year. Column 1 includes watershed fixed effects and column 2 includes both watershed fixed effects and year fixed effects. Column 1 identifies the effect of each covariate in a given location using variation in amount of water claimed in that location compared to the average claim size within the same watershed over time. Column 2 identifies the effect of each covariate using variation water claimed in a given location, relative to other claims in the same watershed in the same year. The coefficient estimates are remarkably similar across columns, indicating that the primary source of identifying variation is differences in the cross-sectional dimension, and that the results are not being driven by shocks to claiming in any particular year.

Table 3: OLS Regressions on the Volume of Claims

	(1)	(2)
	Y = Volume of water (cfs) claimed in square *i* in year *t*	
Follower	-9.671***	-9.664***
	(2.891)	(2.889)
New Grid Claims	13.07***	13.08***
	(2.123)	(2.124)
Roughness	0.0000197***	0.0000197***
	(0.00000743)	(0.00000742)
Prime Acres	0.00169	0.00169
	(0.00108)	(0.00108)
Prime Acres*Year	-0.000000872	-0.000000873
	(0.000000544)	(0.000000544)
Summer Flow	0.0000212**	0.0000213**
	(0.00000851)	(0.00000852)
Flow Variability	0.0356*	0.0356*
	(0.0189)	(0.0189)
Lagged Claims	-0.162**	-0.155**
	(0.0772)	(0.0771)
Prior Stream Water	-0.00000305	-0.00000312
	(0.00000436)	(0.00000425)
Prior Upstream Claims	0.000297	0.000286
	(0.000195)	(0.000192)
Year	0.0218***	-0.000654
	(0.00674)	(0.00159)
$Year^2$	-0.00000561***	0.000000182
	(0.00000174)	(0.000000412)
Watershed Acres	-3.00e-08***	-3.00e-08***
	(1.14e-08)	(1.14e-08)
Watershed Fixed Effects	Yes	Yes
Year Fixed Effects	No	Yes
N	3265885	3265885
R^2	0.011	0.011

Standard errors (clustered by stream) in parentheses. * $p < .1$, ** $p < .05$, *** $p < .01$

The coefficient on New Grid Claims indicates that users divert about 13 cfs on average, as adding an additional claimant increases expected diversions by 13.1 cfs. Users in locations where there is higher summer flow tend to divert more water. Surprisingly, the coefficient on Summer Variability is positive, significant, and substantially larger than the effect of average flow. This may reflect the fact that water placing a binding constraint on agricultural production in areas where the flow changes dramatically over the course of the summer.[9] The year and year-squared coefficients are both significant and together indicate that claim sizes increased over time, but at a decreasing rate. The coefficient on Follower is negative and highly significant and

[9] Ideally, we would like to estimate whether annual variability in flows affects the claiming decision, but we are still in the process of estimating historical flows across the stream network.

indicates that users who follow prior claimants divert about 10 cfs less than users who claim new streams within the same watershed. Lagged Claims is also negative and significant; conditional on being a followers, users divert less water if there were more claimants in the previous year. Taken together, the coefficients on Follower and Lagged Claims are evidence against our prediction that users who choose to follow will divert more water than users who choose to search. Within a given watershed in a given year, users who follow others divert less water than those who search, and users tend to divert less as the number of prior claimants increases. We discuss the implications of this result below.

The results of the regressions on the volume of claims make intuitive sense but stand in contrast to the predictions from our model; claim sizes tend to decrease as the number of senior claimants on a given stream increases. Our simple model implied that in order for following to yield higher returns than searching, diversions for followers must exceed diversions for searchers. Several of the extensions to the model discussed about could change this particular prediction. In particular, our prediction is driven by the assumption of constant marginal costs. An upward-sloping marginal cost curve, combined with the positive externality described in the model, could produce a situation where followers establish smaller claims yet earn greater rents, particularly if the slope of the cost curve changes as a result of the externality. Adding an explicit resource constraint to the model or treating flows in each period as a random may also change this prediction, as in Burness and Quirk (1979). These considerations will guide our modeling efforts moving forward.

VI. Outcomes of Prior Appropriation as First Possession Property Rights.

A. Water Rights Trading.

Prior appropriation dramatically replaced common law riparian water rights. It was voluntarily adopted in a more or less independent manner across a very large area. Following Demsetz (1967) a property rights regime would be implemented when it was beneficial on net to do so. Given that first possession claiming was used to distribute rights to other resources, first possession could be implemented at transaction costs than if that demonstration effect had not been evident. Moreover, as we have described, prior appropriation allowed for the separation of water from land and the coordination of investment among rights holders in a manner similar to patterns observed by Ostrom (1990) under informal group rights to resources. In her case, non group members are excluded from participation, and in the case of prior appropriation rights, only rights holders could capture the benefits of water infrastructure investment. To illustrate, Table 4 shows selected prior appropriation diversion canals from the Cache La Poudre River, listed by position on the stream from the head. The data are from Hemphill (1922). The information reveals a number of aspects of the operation of prior appropriation property rights. First is the wide range of priorities, ranging from 3-100, on even a small river like the Cache La Poudre. Second, some ditches were based on original water rights claims of different date and priority assembled over time, most likely added as more irrigators secured land and joined in expanding the ditch to deliver water to their properties. Third, other ditches were filled by assembling water rights through trade. All of the source ditches are located further down stream. Their flow rights were purchased and diverted upstream by the owners of the canals in column 1.

The diverted water was then moved through the canal and lateral ditches to irrigate the lands of those who held ditch shares. At the same time, up to half the water placed in irrigation by the buyers flowed down to the lands of the selling ditch owners. This exchange process based on prior appropriation rights and not possible with riparian water rights not only provided more water to upstream ditches, but also provided more stable water supplies to downstream irrigators. Absent exchange, they would have diverted their often low-priority water early in the season when there were sufficient stream flows, but would have had little access to water later in the growing season when river flows were lower. Sale of the water and its early diversion by higher priority, upstream canal owners smoothed water supplies downstream because the returned water or tail water moved more slowly through the river system throughout the irrigation season.

Table 4: Selected Cache La Poudre River Canals by Priority, Source, and Size

CANAL	PRIORITY DATES	PRIORITIES	SOURCES	SIZE Ft^3/SEC
Larimer County Canal	Mar 1,1862	5	Pioneer Ditch	10.77
	Sept 15,1864	12	Do.	13.89
	Mar 15,1868	28	Canyon Ditch	4.66
	Mar 20,1873	56	Do.	4
	Apr 1,1878	84	Smith Ditch	7.23
	Apr 25,1881	100	Original	463
			TOTAL	503.55
Jackson Ditch	June 10, 1861	3	Original	11.67
	Oct 21,1870	36	Original	14.42
	Sept 15,1873	67	Original	12.13
	July 15,1879	91	Original	12.7
			TOTAL	50.92
Larimer and Weld Canal	June 1,1864	10	No.10 Ditch	3
	Apr 1,1867	21	No.10 Ditch	16.67
	Sept 20,1871	45	No.10 Ditch	75
	Jan 15,1875	73	No.10 Ditch	54.33
	Sept ,1878	88	Original	571
			TOTAL	720
Greeley Union Colony Canal No.2	Oct 25,1870	37	Original	110
	Sept 15,1871	44	Original	170
	Nov 10,1874	72	Original	184
	Sept 15,1877	83	Original	121
			TOTAL	585
Greeley Union Colony Canal No.3	April 1,1870	35	Original	52
	Oct 1,1871	46	Original	41
	July 15,1872	50	Original	63.13
	May 15,1873	59	Original	16.66
			TOTAL	172.79

B. Investment in Irrigation Infrastructure.

Riparian water rights did not allow for the separation of water from the land or the trading of water rights. Common-law riparian water rights granted correlative rights to reasonable use of water to all owners of land appurtenant to streams so long as there was no harm to other riparians.[10] Under a riparian rights system there was no mechanism for aggregating water for investment, denying non participants, and moving the water elsewhere. With secure prior appropriation rights (Burness and Quirk 1978), however individual rights holders could combine diversion rights as a basis for investing in large canals, lateral ditches, and reservoirs to transport water from narrow river valleys to larger remote areas of flat farm land as shown in Table 4 above. The role of private property rights as a coordinating mechanism in addressing common-pool-resource problems has not been developed in the local commons literature (Ostrom 1990) where informal norms among small, homogeneous populations exploiting small-scale resources are emphasized. Yet, many important potential open-access problems involve larger numbers of parties competing for larger, heterogeneous resources, where there are few constraints on entry. In this frequent setting private property rights provide a basis for controlling entry and for joint, cooperative action.

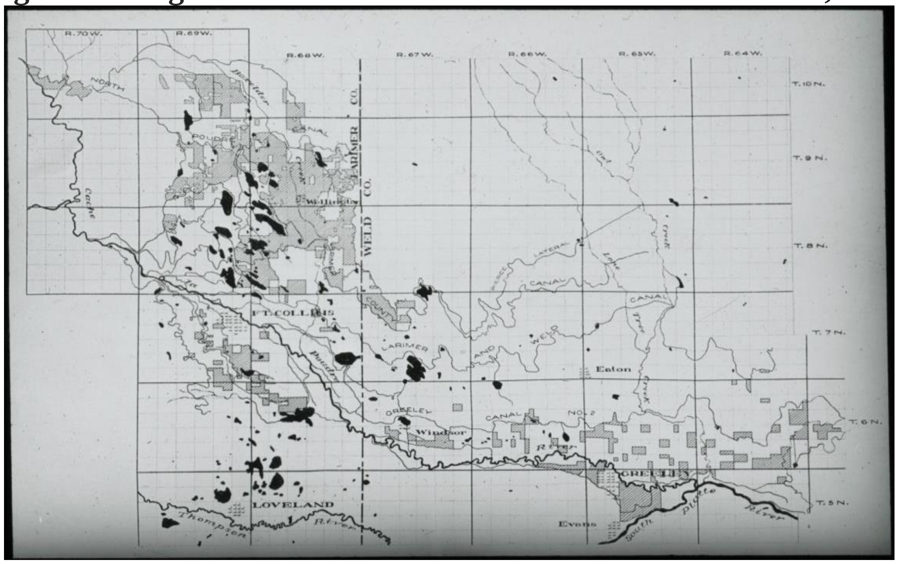
Cooperation around prior appropriation for irrigation is described by Hemphill (1922), Coman (1911, 7), Teele (1904, 169-72), Hutchins (1928, 1929,1930), and Bretsen and Hill (2006, 299-301). Adams (1910), Coman (1911), and Hemphill (1922) use the Greeley Union Colony Ditch from the Cache la Poudre River of the 1870s to illustrate the role of cooperative, unincorporated mutual ditch companies. The Cache La Poudre drains 1,915 square miles, drops 6,155 feet from its source to the confluence with the South Platte River and travels 140 miles before joining the South Platte as a tributary. Its drainage was the first area to be placed into large-scale irrigation in Colorado. The Union Colony Ditch No 2. Was 36 miles long and 32 feet wide.[11] 6-10 lateral ditches delivered water from the Union Colony to farm lands and 12 storage reservoirs (Hemphill 1922, 2-13). Over the entire drainage, some 375,000 acre feet of water was transported by canals to 225,000 irrigated acres (Hemphill 1922, 24). Boyd (1890) describes the formation of the Union Colony and investments in the mutual ditch company. Throughout the semi-arid West, unincorporated mutuals were the most common forms of water infrastructure and supply organizations, supplying some 46 percent of irrigated acreage in 1910 and 56 percent by 1978 (Bretsen and Hill 2006, Table 1, 293).

Figure 7 shows canal and reservoir investment in the Cache La Poudre Basin by 1898. [more discussion to be added about role in expanding irrigated acreage and land values and overall economic development]

[10] For discussion, see Rose 1990, Getches 1997, and Smith 2008).

[11] https://www.yourwatercolorado.org/cfwe-education/water-is/climate-and-drought/2-uncategorised/587-irrigation-and-the-union-colony; http://caringforourwatersheds.com/usa/colorado/watershed-information/

Figure 7: Irrigation Infrastructure in Cache La Poudre Basin, 1898.



C. **Evidence of Over Investment as Stream Flows Unexpectedly Fall.**

To be added. 1904 JPE, 1911 AER, Irrigation census data—over investment and over extraction. Dissipation. If rights were secure, how could this be? Add data precipitation patterns. Drought not evident until later part of settlement period. Parties overestimated mean stream flow. More variable than expected. Excessive rights allocation based on this. More paper rights than water. Not due to weak administration, but rather to incomplete climate information.

D. **Expansion in Irrigated Agriculture and Increases in Land Values.**

To be added from census data.

VIII. Concluding Remarks

We analyze the economics of first-possession property rights to a large heterogeneous resource allocated under incomplete information and competitive claiming by agents. Our focus is on prior-appropriation surface water rights used in 18 western US states and generally in at least 3 western Canadian provinces, with specific attention to Colorado, 1852-2013. Prior appropriation was an institutional innovation, replacing common-law riparian rights, in a setting where water supplies were scarce, unevenly distributed, and remote from production sites where water was a key input. Prior appropriation emerged very rapidly because of its large net economic advantages relative to the incumbent property rights regime, riparianism. Voluntary, large-scale property rights changes are unusual empirically. Prior appropriation was both efficient and fair relative to feasible alternatives. It granted ownership by time of discovery; announcing a diversion location and amount; and placing the claimed water into beneficial use, which constrained claims to productive size. Prior appropriation encouraged valuable search and narrowed the information required to establish ownership to that described in immediate water diversion rather than an entire river basin. It thereby also lowered individual bounding and enforcement costs. At the time of claiming water there was little information about water source characteristics, and the process of claiming revealed such information. Hence, there was a tradeoff between claiming at a particular time or waiting. We model the process of first possession claiming, derive hypotheses, and confront the hypotheses with data for Colorado. In general we find that claimants follow earlier searchers when the latter provide valuable new information on the location of diversion sites. Additionally, all else equal, new property claims tend to be toward the stream head and subsequent claims are further from the stream head. Claims also are more responsive to easily observed covariates, especially critical summer stream flow. Finally, claimants who follow initial searchers establish rights to smaller amounts of water than do those who came earlier. 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. These rights endure, affecting the distribution of water ownership and exchange. Assessment of the prior appropriation's welfare effects requires accounting for its role in generating property rights to water, investment, production, and the transaction costs of water exchange.

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