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Three Essays on the Structure of Property Rights to Natural Resources

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in

Economics

by

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Abstract

Three Essays on the Structure of Property Rights to Natural Resources

Bryan Leonard

In this dissertation I study how the structure of property rights is shaped by the benefits and costs of defining and enforcing rights along various dimensions to inform current policy debates by better understanding the economic structure of the resource problems we face and saying something about the opportunity costs of policy proposals to alter resource use. I do this by combining formal models of natural resource use with detailed econometric analysis of novel historic and modern data sets which I build using GIS.

In Chapter 1, Gary Libecap and I analyze the economic determinants and effects of prior appropriation water rights that were voluntarily implemented across a vast area of the US West, replacing common-law riparian water rights. We model potential benefits and test hypotheses regarding search, coordination, and investment. Our novel dataset

of 7,800 rights in Colorado, established between 1852 and 2013 includes location, date, size, infrastructure investment, irrigated acreage, crops, topography, stream flow, soil quality, and precipitation. Prior appropriation doubled infrastructure investment and raised the value of agricultural output beyond baseline riparian rights. The analysis reveals institutional innovation that informs contemporary water policy.

In Chapter 2, Dominic Parker and I study how subdivision of land rights can affect natural resource use. Land contains multiple natural resources that are efficiently managed at different spatial scales, either concurrently or over time. We explain how subdividing the commons to promote one resource (agricultural land) inadvertently creates anticommons problems for another (shale oil). We provide empirical tests from a natural experiment on the Bakken, one of the world's largest booming oil fields. Before oil was discovered, U.S. land allotment policies created a mosaic of private, tribal, and fragmented ownership to shale on and around the Fort Berthold Indian Reservation. We compare horizontal drilling patterns across over 40,000 parcels on and off the reservation. We find that subdivision has caused economically significant delays in compensation to shale owners, as parcels surrounded by tribal lands are more quickly and fully exploited. The evidence demonstrates how subdivision can inadvertently delay spatially coordinated resource use and reduce resource rents.

In Chapter 3, Gary Libecap and I examine the emergence of spontaneous claims to inframarginal rents in open-access resources. Although early models of open-access in economics predicted full rent dissipation as homogeneous agents exploited the resource, later theory and empirical observations indicated persistence of inframarginal rents. The existence of inframarginal rents under open-access has been recognized in the literature, but agents incentives to invest in de facto institutions to protect rental streams from competitors has not been explored. These institutions include local property rights, specialized production, and restricted information sharing. Moreover, there has been no recognition of how these informal arrangements might contribute to observed resistance by inframarginal-rent earners to externally imposed schemes in order to reduce aggregate rent dissipation. Proponents are high-cost agents, who earn low or zero rents. High-cost agents ought to be able to compensate low-cost agents for a shift to a new property regime if the shift makes them better off than they were under open-access. Empirically, however, this appears not to happen and formal open-access persists. We develop a simple framework to show why "willingness to pay" and "willingness to accept" do not overlap and that institutional change is not Pareto-improving for those who have adjusted well to open-access. If agents are heterogeneous in search and production costs, and the resource is large and heterogeneous in quality, then low-cost parties search for the most productive locations and apply their superior skills and develop human and physical capital to earn inframarginal rents. We then apply this framework to historical experiences in oil and gas and fisheries.

Contents

Chapter 1

First Possession of Water in the American West

1.1 Introduction

Property rights are fundamental institutions for economic decisions and outcomes. They contribute to long-run economic growth (Acemoglu et al., 2001, 2005; Mehlum et al., 2006; Rodrik, 2008; Dixit, 2009; Besley and Ghatak, 2009a), facilitate greater investment when returns are uncertain or delayed (Besley, 1995; Jacoby et al., 2002; Galiani and Schargrodsky, 2010; Lin et al., 2010), allow for the development of markets (Greif et al., 1994; Dixit, 2009; Edwards and Ogilvie, 2012), and reduce rent dissipation associated with common-pool resources (Gordon, 1954; Scott, 1955; Wiggins and Libecap, 1985; Gaudet et al., 2001; Wilen, 2005; Costello et al., 2008).[1] Despite their

[1] The role of property rights in constraining rent dissipation in open-access resource has perhaps the largest literature. Other examples include Casey et al. (1995), Grafton et al. (2000b), and Bohn and Deacon (2000).

importance, the determinants of how property rights initially emerge and how the process frames subsequent economic behavior have received little attention.[2] The reason is that voluntary major shifts in property institutions are rare, reducing empirical observation for analysis. 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 arrangements (Libecap et al., 2011).

It is costly to set up a property rights system and once in place, owners (individuals or group members, depending on the institution) form expectations about the range of designated uses, conditions for exchange, investment opportunities, time frames, delegation of associated costs and benefits and hence, the flow of net rents from the asset. The property rights structure also defines political and social positions in societies. Accordingly, any important change in property rights imposes uncertainty and potential losses on incumbent owners and aspiring ones across a variety of margins with significant distributional and efficiency consequences. For these reasons, individuals and organizations within societies, economies, and political structures develop stakes in the prevailing property rights system, suggesting the high costs of replacing them and explaining their observed durability.

In this paper, we exploit the empirical setting of the westward settlement of the American frontier as a laboratory for institutional innovation. Settlers moved west across the continent after native claims had been swept aside. Migrants, seeking ownership of natural resources—land, timber, gold and silver, proceeded ahead of formal state and

[2]Demsetz (1967), Cheung (1970), 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 do not examine the forms property rights take in different settings or why.

territorial governments, bringing with them basic legal norms but confronting unfamiliar conditions that required new arrangements for successful economic development. These institutions appeared spontaneously via local collective action and persist today, determining contemporary actors and molding markets and policy.

Our focus is on the abrupt, deliberate shift from common-law riparian water rights that dominated in the eastern US and granted use of surface water to adjacent land holders as shares based on contiguous acreage, to prior appropriation that assigned ownership of water based on time, as first-possession claims.[3] Prior appropriation granted the right to divert a fixed amount of water for beneficial use at sites distant from a stream. It became the basis for large-scale investment in irrigated agriculture and the subsequent economic development of the West. Prior appropriation displaced riparian rights across an immense area of some 1,808,584 mi^2 (17 western states and 2 Canadian provinces).[4] Most prior appropriation rights were established between 1850 and 1920 when water was valued primarily as an input to irrigated agriculture, and today 40 to 80% of western water use remains in agriculture (Brewer et al., 2008).[5] Examination of the economic gains attributable to prior appropriation makes clear why it was adopted so broadly and

[3]First-possession ownership of natural resources has been criticized for encouraging a race among homogeneous agents that dissipates rents (Barzel, 1968, 1994; Lueck, 1995, 1998). This argument does not account for the ubiquity of first possession or its economic contribution. Indeed, when agents and the resource are heterogeneous, dissipation is reduced (Leonard and Libecap, 2015).

[4]Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, Wyoming, Alberta, and British Columbia. This system is often characterized by the phrase, "first in time, first in right." First possession in property rights allocation is discussed by Epstein (1978), Rose (1985, 1990), Ellickson (1993), and Lueck (1995, 1998).

[5]Prior appropriation water rights have been described by many, including Burness and Quirk (1979, 1980a,b), Johnson et al. (1981), Smith (2000), Howe (2005), Hanemann (2014), and Chong and Sunding (2006). Kanazawa (1996, 2015) 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. Ostrom (1953) and Ostrom and Ostrom (1972) discuss the replacement of riparian rights by prior appropriation.

so quickly as well as why it has persisted even after initial conditions changed.[6]

Our empirical analysis of the economic advantages of prior appropriation relative to riparian water rights begins with a model for deriving testable hypotheses. For the empirical analysis we develop a novel data set that includes the location, date, and size of 7,800 water claims along with measures of infrastructure investment, irrigated acreage, crops, topography, stream flow, soil quality, precipitation, and drought in Colorado, the state where prior appropriation was most completely implemented initially. We find that i) search by early claimants generated positive externalities, lowering costs for subsequent claimants; ii) secure, recognized property rights facilitated coordination among large numbers of heterogeneous agents by reducing uncertainty and providing an instrument for exchange; iii) coordination led to substantially higher levels of infrastructure investment, which led to iv) long-run increases in income per acre in agriculture.

While valuable in much of Colorado, we find that formal prior appropriation water rights were less critical in those parts of Colorado where water users were in close-knit, small, older Hispanic communities and relied upon shared norms in farming and irrigation decisions (Ostrom, 1990). Finally, we provide new empirical estimates of the contribution of irrigated agriculture made possible by prior appropriation to economic development in the western US. We conclude by emphasizing that once prior appropriation was put into place, it provided an on-going framework for water allocation, use, and investment decisions. This framework remains today, channeling how contemporary

[6]Related to the economic advantages we examine, is the ability to move water from one place to another that is possible only at very high cost with a riparian rights system. This transfer ability was the basis for the implementation of the Reclamation Service (Bureau of Reclamation) in 1902 and its multiple water storage and transfer infrastructures, as well as the transport of water to Los Angeles, San Francisco and other urban centers from remote water sources (Pisani, 2002).

water uses respond to new urbanization, environmental, and industrial demands. Our analysis extends the literatures on institutional change, property rights, first possession, and path dependency.

1.2 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, natural resources in the American West—farmland, timberland, mineral land, rangeland, and water—were open for first-possession claiming (Kanazawa, 2015; Libecap, 2007).[7] Examination of 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 (Clay and Jones, 2008).

Settlers sought to establish property rights with very limited information and understanding of the necessary conditions for successful enterprises. In the case of water, frontier migrants could observe relatively stable resource characteristics, such as topography, elevation, and stream location in their claiming decisions. Soil quality and variable

[7] Frontier resources, land, minerals, timber, and water were generally allocated via first possession (Umbeck, 1977, 1981; Libecap, 1978, 2007; Libecap and Johnson, 1979; Reid, 1980; Zerbe and Anderson, 2001; McDowell, 2002; Clay and Wright, 2005; Stewart, 2009; Gates, 1968; Allen, 1991; Romero, 2002; Getches, 2009). The federal government attempted to sell lands early in the century at a floor price of between $1.25 and $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.

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 provided 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 (Libecap and Hansen, 2002; Hansen and Libecap, 2004b,a).

The costs of establishing property rights to water were potentially high: learning about stream fluctuation, soil quality, and optimal farming techniques was time consuming and successful use of water required investment in major diversion infrastructure to move water from rugged and unproductive riparian terrain. The report on the Colorado Territory by Cyrus Thomas to the US 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, p. 150)

Each additional wave of settlers brought new competition but also created the potential for cooperation in the construction of critical diversion infrastructure.[8] These challenges had not presented themselves in settings where the riparian doctrine dominated—where land was more homogeneous with established ownership, the climate was better understood, farming practices were well established, and the terrain did not require water

[8]Hanemann (2014) points out that the key issue among migrants was raising capital for very capital-intensive agriculture.

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.[9] This property rights scheme, however, was ill suited to western water resources.

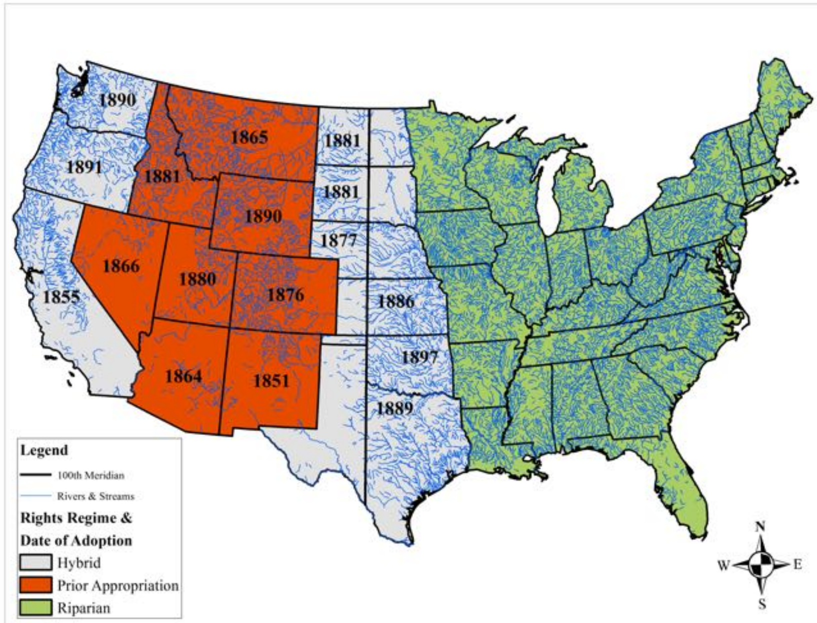
Figure 1.1 depicts the distribution of major streams and types of water rights in the United States to illustrate the dramatic nature of the shift in property rights regimes for water that occurred west of the 100th meridian. The figure shows states/territories with either riparian rights or prior appropriation or hybrids of both—those along the 100th meridian and those on the west coast. The dates are those of key constitutional, legislative, or judicial adoption of prior appropriation.[10] It is evident that populations in states with abundant water resources held to the riparian doctrine; those in states with both dry and wet regions maintained mixed systems; and those in the most arid states with lower stream density rapidly adopted prior appropriation. We explore the economic contributions of prior appropriation that led to this adoption.

Table 1.1 presents the results of a simple linear probability model for whether a state/territory adopted prior appropriation, replacing common-law riparian rights in the

[9] Rose (1990) discusses the early evolution of riparian water rights in the eastern United States.

[10] Mead (1901, p. 7-15) discussions the imperative to shifting from riparian to prior appropriation to promote irrigation in semi-arid regions. Dates of prior appropriation adoption: Arizona: Territory Arizona, Howell Territorial Code, Ch. LV, Hutchins (1977, p. 170); Colorado: Constitution art. XVI 5 and 6; *Coffin v. Left Hand Ditch Co* (6 Colo 443); Idaho: An Act to Regulate the Right to the Use of Water for Mining, Agriculture, Manufacturing, and Other Purposes (1881), Hutchins (1977, p. 170); Montana: *Mettler v. Ames Realty Co.*, 61 Mont. 152, 170-171, 201 Pac. 702, MacIntyre (1994, p. 307-8); New Mexico: Territorial Constitution Art XVI 2; Hutchins (1977, p. 228); Nevada: *Lobdell v. Simpson*, 2 Nev. 274, 277, 278; Hutchins (1977, p. 170-71); Utah: Utah Laws 1880, ch. XX; Wyoming: Constitution Art VIII 1-5; Hutchins (1977, p. 300); California: *Irwin v. Phillips*, 5 Cal. 40 (1855); Hutchins (1977, p. 181, 233-34); Kansas: 1886 Kans. Sess. Laws 154, ch. 115; Hutchins (1977, p. 170); Nebraska: Neb. Laws p. 168(1877); Hutchins (1977, p. 212); North Dakota: Terr. Dak. Laws 1881, ch. 142; Hutchins (1977, p. 213); Oklahoma: Terr. Okla. Laws 1897, ch. 19; Hutchins (1977, p. 171, 215); Oregon: Oregon Laws 1909, Ch. 216. Oregon Revised Stat. ch. 539; Hutchins (1977, p. 170); South Dakota: Terr. Dak. Laws 1881, ch. 142; Hutchins (1977, p. 170, 220); Texas: Tex. Gen. Laws 1889, ch. 88; Hutchins (1977, p. 170); Washington: Wash. Sess. Laws 1889-1890, p. 706; Sess. Laws 1891, ch. CXLII, Hutchins (1977, p. 170).

Figure 1.1: Property Rights Innovation



contiguous United States.[11] The dependent variable is equal to one for states/territories (or their sub-regions) that adopted prior appropriation and zero for areas that maintained the riparian doctrine.[12] This simple exercise underscores the impression in Figure 1.1 that inhabitants of states with lower stream density, less rainfall, and more rugged terrain were more likely to implement prior appropriation. These are states where agriculture would require diversion of water from streams that were sparsely and unevenly distributed across the rugged terrain.

[11]Stream density is aggregated perennial flow lengths divided by area; high-resolution data are from the National Hydrography Dataset (NHD). Precipitation is 30-year average annual rainfall data from PRISM Climate Group. Terrain Ruggedness Index (TRI) uses the Riley method and classification syntax are averaged over the area (see ArcGIS methods for TRI calculation below). Digital elevation model (DEM) used for TRI calculations from USGS, downloaded from GeoCommunity.

[12]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 northern and southern regions at the latitude of Lake Tahoe, defining much wetter and drier regions of these states.

Table 1.1: Adoption of Prior Appropriation

	Y = 𝟙(Prior Appropriation)		
Stream Density	−0.285***	−0.0875	−0.576**
	(0.0887)	(0.0592)	(0.225)
Roughness	0.000910***	0.000691***	0.000750***
	(0.000111)	(0.000118)	(0.000105)
Precipitation		−0.000507***	−0.000329**
		(0.000118)	(0.000136)
(Stream Density)^2			0.218**
			(0.0875)
Constant	0.152*	0.577***	0.539***
	(0.0888)	(0.148)	(0.141)
N	57	57	57
R^2	0.610	0.706	0.729

Robust standard errors in parentheses

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

To better understand the economic factors that led to the rise of prior appropriation, we 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 preexisting riparian water rights holders.[13] Colorado covers an area of some 66,620,160 acres containing over 107,000 miles of streams with elevations ranging from 3,317 to 14,440 feet.[14] 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.

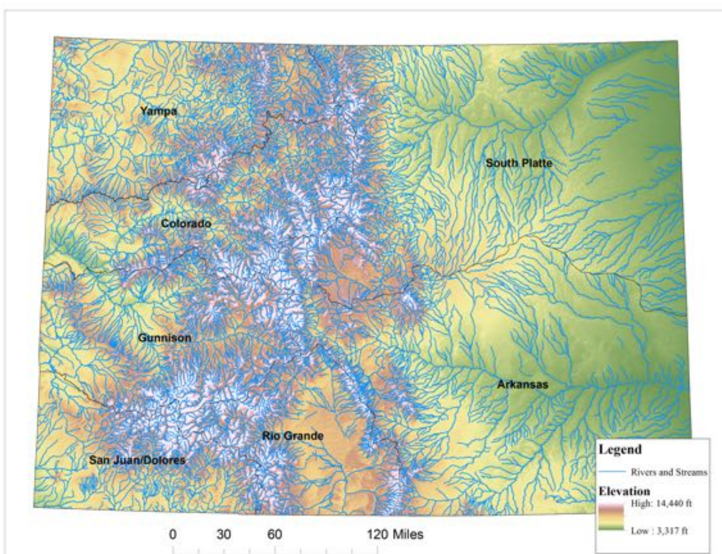
Prior appropriation emerged over a 20-year period, whereby more formal rights and supporting institutions were adopted as competition for water increased (Demsetz, 1967). Because the native population had been displaced and the federal government was remote,

[13]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, 1997).

[14]The 1900 population of Colorado was 539,500, implying a population density of 1 person per 123 acres.

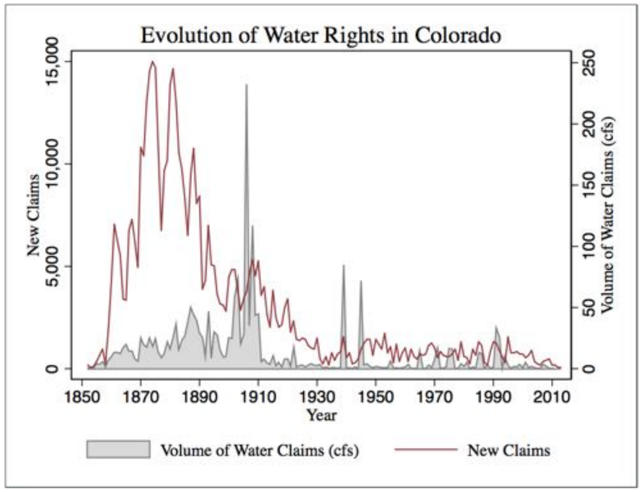
early migrants had a relatively open slate to define property institutions to frontier resources. Colorado migrants came primarily from the northeast and north-central US where there was little need for irrigation and riparian rights dominated (Colorado Water Institute, ND, 2; Dunbar, 1950, p. 42; Hobbs, 1997, p. 3; Romero, 2002, p. 527) In Colorado, however, irrigation of crop lands and investment in conveyance capital to move water to distant sites were required. As we show prior appropriation made these feasible. Figure 1.2 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.

Figure 1.2: Water Resources and Terrain in Colorado



The first Colorado Territorial Legislature in 1861 enacted legislation as a precursor to prior appropriation, allowing water to be diverted from streams to remote locations, abrogating common-law riparian principles that kept water on adjacent lands. A 1872 statute continued the move toward prior appropriation by granting right of way to irrigation ditch companies. In 1876 the Colorado Constitution formally proclaimed prior appropriation as the basis for water rights in the state. Statutes in 1879 and 1881 added administrative structures for measurement, monitoring, and dispute resolution. The state was divided into water divisions and subdivided into watershed districts with local water supervisors and courts. A state Hydrologic Engineer's Office was created and county clerks were to record appropriative claims that previously had been announced informally at diversion sites. Finally, in 1882 the Colorado Supreme Court in *Coffin v Left Hand Ditch Co* (6 Colo 443) rejected remnants of riparianism in favor of prior appropriation (Colorado Water Institute ND, pp. 3-8; Dunbar, 1950, pp. 245-60; Hobbs, 1997, pp. 6-9, 32; Romero, 2002, pp. 536-9). This legal infrastructure provided for the official definition and transfer of prior appropriation water rights and investment in irrigation capital. It has been described as the Colorado System, and it was adopted generally by most other western state legislatures, courts, or constitutions (Colorado Water Institute, ND, p. 1; Hess, 1916, pp. 652-6; Hemphill, 1922, pp. 15-8; Dunbar, 1983, 1985). Priority access to water was defined by stream, so that being the first claimant on a given watercourse granted the highest priority to water in any given year. Figure 1.3 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.

Figure 1.3: The Timing and Volume of Water Claims in Colorado



1.3 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 into the conditions under which prior appropriation is more efficient than riparian water rights and derive testable implications. We begin by characterizing the diverter's problem under prior appropriation and the aggregate rents generated by water claims under this system. Then, we present the diverter's problem under a share-based system that approximates a riparian regime in which shares are based on adjacent land ownership, and we compare the aggregate rents generated by each for a given number of users. Finally, we show that for a sufficiently large positive information externality from investment in establishing claims, prior appropriation is the efficient rights allocation mechanism.[15]

[15]Positive return-flow externalities also existed, whereby the diversion and subsequent runoff by upstream claimants smoothed out the natural flow of rivers and made more water available downstream

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 on the basis of 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.

1.3.1 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

$$\max_{x_i} \quad \mathbb{E}\left[\pi(x_i)\right] = \left[1 - F(p_i + x_i)\right] R(x_i) + \int_{p_i}^{p_i + x_i} R(t - p_i) f(t) dt - C(x_i). \qquad (1.1)$$

Expected profits can be broken into three parts. First, there is the revenue from

than had previously been the case (Crifasi, 2015). We note that these and other benefits existed but do not model them explicitly.

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

$$\begin{aligned}\frac{\partial \mathbb{E}\left[\pi(x_i)\right]}{\partial x_i} &= -f(p_i + x_i)R(x_i) + \left[1 - F(p_i + x_i)\right] R'(x_i) + f(p_i + x_i)R(x_i) - C'(x_i) = 0 \\ &= \left[1 - F(p_i + x_i)\right] R'(x_i) - C'(x_i) = 0. \end{aligned} \tag{1.2}$$

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 1.2 has a unique solution that defines an implicit function $x_i = x_i^{*PA}(p_i)$ and the profit function for user i under prior appropriation is[16]

$$\begin{aligned} V_i^{PA} = \mathbb{E}\left[\pi(x^{*PA}(p_i))\right] &= \left[1 - F(p_i + x^{*PA}(p_i))\right] R(x^{*PA}(p_i)) + ... \\ &... + \int_{p_i}^{p_i + x^{*PA}(p_i)} R(t - p_i) f(t) dt - C(x^{*PA}(p_i)). \end{aligned} \tag{1.3}$$

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

[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.

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 Online Appendix A. 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 $N > N^{PA}$.

Under a riparian or other share-based system, users are able to divert shares of annual flow based on the size of their adjacent land holdings. For simplicity we assume equal shares.[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 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

$$\max_{x_i} \quad \mathbb{E}\left[\pi(x_i)\right] = [1 - F(Nx_i)]R(x_i) + \int_0^{Nx_i} \left[R\left(\frac{t}{N}\right) f(t)dt\right] - C(x_i). \tag{1.4}$$

The first two terms in Equation 1.4 are expected revenues for a user with diversion

[17] In practice, riparian systems require that other parties on the stream be 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 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.

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

$$[1 - F(Nx_i)]R'(x_i) - C'(x_i) = 0. \tag{1.5}$$

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. If we assume 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]

$$V_i^S = [1 - F\left(Nx_i^{*S}(p_i, N)\right)]R\left(x_i^{*S}(p_i, N)\right) + \int_0^{Nx_i^{*S}(p_i,N)} \left[R\left(\frac{t}{N}\right) f(t)dt\right] - C\left(x_i^{*S}(p_i, N)\right). \tag{1.6}$$

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

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

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

Proof: See Online Appendix A. 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 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 under which some users earn higher marginal returns than do 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. In contrast, 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

[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.

Online Appendix A). The fact that new arrivals cannot dissipate rents captured by earlier claimants not only creates incentives for early investment but 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.

1.3.2 Positive Information Externalities from Prior Claims

General uncertainty about resource conditions and high information and transportation costs characterized the western frontier and created the need for coordination among potential claimants. 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 from clustered claiming and settlement (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 in the presence of this positive externality is

$$\max_{x_i} \quad \mathbb{E}\left[\pi(x_i)\right] = \left[1 - F(p_i + x_i)\right] R(x_i) + \int_{p_i}^{p_i + x_i} R(t - p_i) f(t) dt - C(x_i) + \gamma p_i. \quad (1.7)$$

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 Online Appendix A. 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.

We assume that the positive externality exists only under prior appropriation for several reasons. 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 have 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.

1.3.3 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. We 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 (Figure 1.1).

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. For a new user to choose to follow prior claimants when other sites are available, the expected profits must be 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 Online Appendix A. Proposition 4 follows directly from Proposition 3 because, for aggregate rents to be convex in N, junior claimants must earn higher profits than the prior claimant so that aggregate profits are increasing at an increasing rate, due to the positive externality. This is true only 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, and hence have higher priority, 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.

1.3.4 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 is 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 information costs are an important determinant of behavior in allocating rights, we 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 observed directly—topography, current 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 establish rights to residual water only 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 users must 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 rightsholders because their expected water deliveries are more certain.

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 stronger determinants of claiming locations than are less apparent characteristics such as flow variability and soil quality

3. Fewer claims will be established during drought.

4. Users with higher priority are more likely to cooperate in investing in diversion infrastructure.

1.4 Empirical Determinants of Prior Appropriation Claims

1.4.1 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.[21] Colorado is divided into 7 Water Divisions that separately administer water rights, as depicted in

[21] GIS data on water rights were obtained directly from the Colorado Department of Water Resources. To our knowledge this is the first time such a comprehensive dataset has been compiled for water rights in any western state.

Figure 1.2. We focus on Divisions 1 to 3 (the South Platte (1), Arkansas (2), and Rio Grande (3)), which compose 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 i) the date and geographic location of original appropriation, ii) the name of the structure or ditch associated with the diversion, iii) the name of the water source, and iv) 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.[22] 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 1.4 shows a map of Divisions 1 to 3 with the original location of all claims in our data set, the major streams, and the grid squares used for the analysis.[23] Areas with productive soil are shaded in green.[24] 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 stream level 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), resulting in 311,364 total observations of which we are able to constructing overlapping

[22]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.

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

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

covariates for 248,745.

Table 1.2 provides variable names, definitions, and summary statistics for the stream-level data and Online 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, 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 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 to a larger spatial unit that is defined on the basis of underlying hydrologic variation rather than a more arbitrary partitioning of space.

Figure 1.4: Possible and Actual Claim Sites

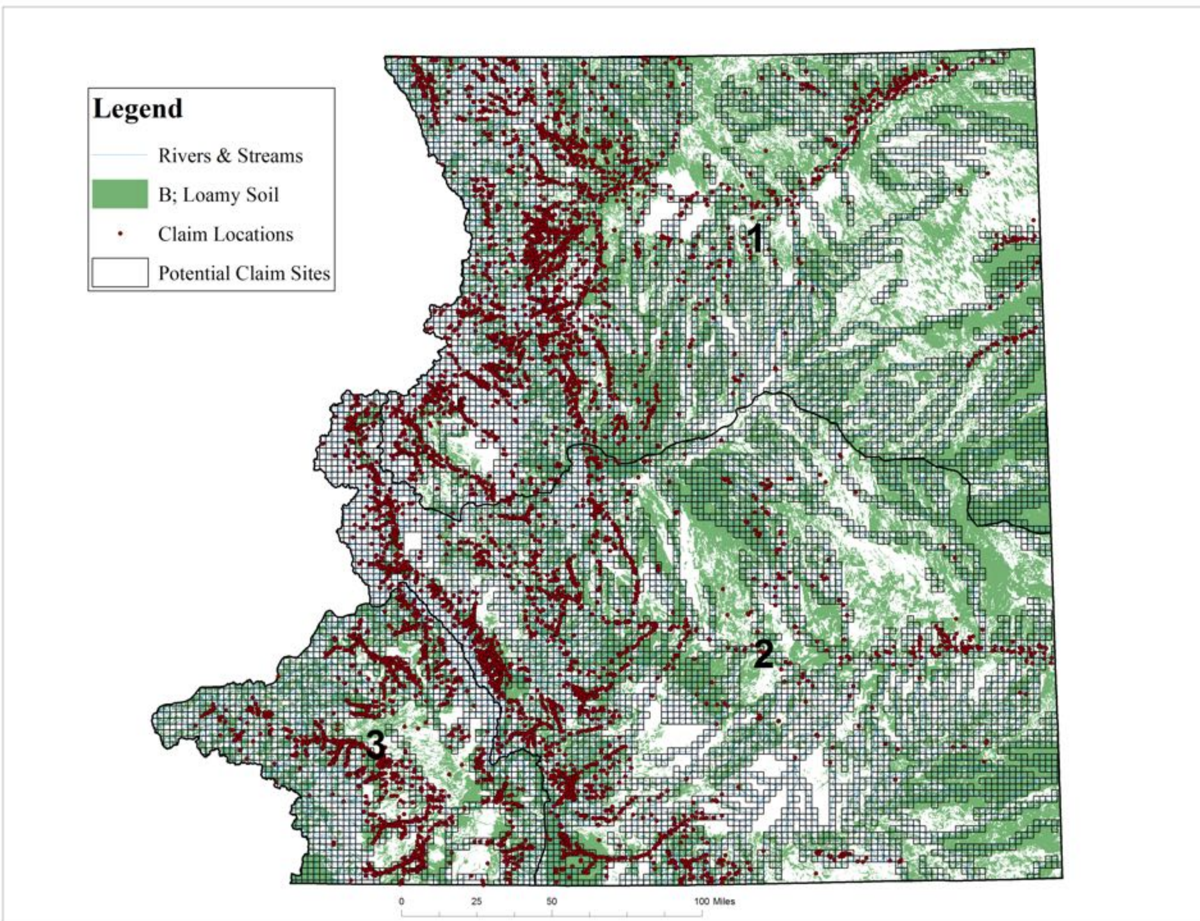


Table 1.2: Stream-Level Summary Statistics

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	S. D. of slope multiplied by average slope along stream j.
Flow Variability	250,452	5.761	56.22	0.00687	1,353	S. D. 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
Watershed Acres	311,364	5,460.68	187,325.2	18.43	8,215,323	Total size of watershed containing stream j
Acres Loamy Soil	311,364	367.29	3,973.91	0	173,086.5	Acres within 10 miles of stream j with loamy soil

Notes: 1) Data on homesteads were provided by Dippel et al. (2015) 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 be constructed only for a subset of data due to the availability of other variables used in the hydrologic model.

1.4.2 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 worse off and should make the arrival of subsequent claimants less likely unless a positive externality exists. Hence, we look for evidence of positive spillovers by estimating the effect of previous claims on a given stream on the probability and expected count of subsequent claims on that stream.[25] This gives our econometric model an inherently dynamic nature. We characterize the number of claims on stream j in year t, which has the properties of a count variable, using a Poisson distribution.[26] 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 instead to attribute the effect of these site attributes to positive spillovers. 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

[25] 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.

[26] 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.

mean

$$\mathbb{E}(y_{jt}|y_{jt-1},...,y_{j0},\mathbf{x_j},u_j) = u_j \exp(x_{jt}\beta + y_{jt-1}\rho), \tag{1.8}$$

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

$$u_j = \nu_j \exp(\delta y_{j0} + \gamma \mathbf{x_j}), \qquad \nu_j \sim \text{gamma}(\eta,\eta), \tag{1.9}$$

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 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 1.8 and the unobserved effect in Equation 1.9. 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.[27] Second, we must assume that ν_j is independent

[27]We perform a variety of simulations and confirm that the estimator is robust to alternative data

of $\mathbf{x_j}$ and y_{j0}. This requires that the random component of the unobserved heterogeneity in site quality be random and not dependent on observed covariates.[28] 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}.[29] 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 on the basis of what users in the previous period did and 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 effect 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.

1.4.3 Empirical Estimates of Claiming Externalities

Table 1.3 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.[30] All specifications control

generating processes for u_j.

[28]But note that the unobserved component of Equation 1.8—u_j—is allowed to depend on $\mathbf{x_j}$ and y_{j0}.

[29]This is implicit in Equation 1.8.

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

for stream size and variability (Summer Flow and Flow Variability), drought, land quantity 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 1.3 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, implying that the scarcity of the water and land endowments was linked.

Consistent with our intuition, several of the variables have no effect of the probability of new water claims on a stream. Long-term 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 1.3: 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 are 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 1.3 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%, meaning 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 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 by a general positive benefit of locating near other settlers on the frontier. In Section 1.5 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 a 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 initially 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 (Boyd, 1890).

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 stream 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 1.3 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 water of 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).

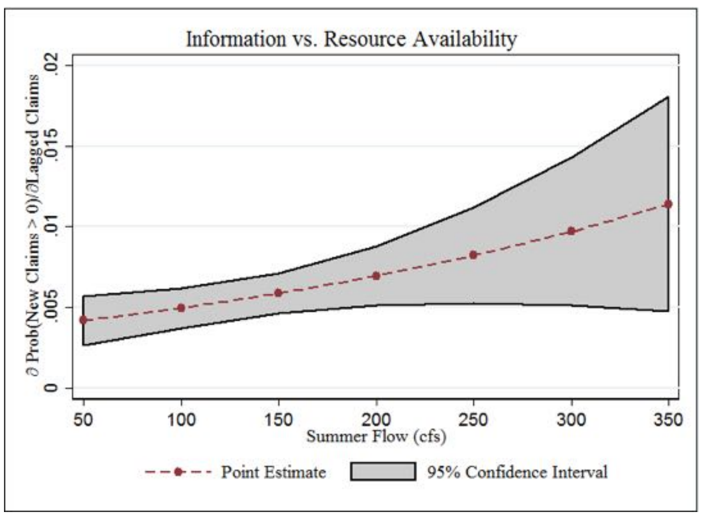
Reductions in available resources had a real effect on claimants' behavior, although the effect of water availability is quite small. This minuscule effect may be driven by claimants' lack of full knowledge of the legal volume of prior claims—the sum of "paper" water rights may not have been of primary concern to settlers as they observed 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 of 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 1.5.[31] The vertical axis is the estimated marginal

[31]We do this by including an interaction term between Lagged Claims and Summer Flow, which is present in all of the models whose marginal effects are presented in Table 1.3.

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 there being enough water for subsequent claimants.[33]

Figure 1.5: The Information-Resource Trade-Off

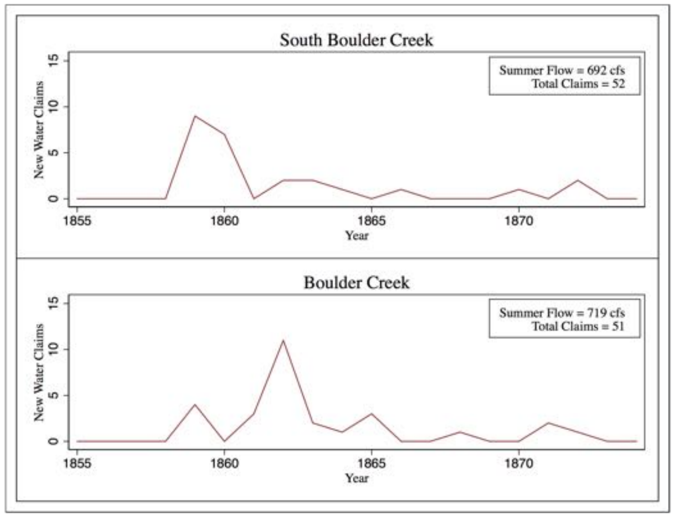


The development of water rights on South Boulder Creek near Boulder, Colorado, illustrates the economic behavior we identify in Table 1.3. The earliest claims on South Boulder Creek are associated with the Jones and Donnelly Ditch, which was established in 1859 to irrigate fertile land near the creek (Crifasi, 2015, p. 105). Seven other water

[32]Figure 1.5 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.

Figure 1.6: Evolution of Claims Near Boulder, Colorado



rights were established on South Boulder Creek in that same year. This prompted an additional eight claimants to follow suit and establish water rights the following year, 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 discovery prompted a subsequent wave of similar "high line" ditches on Boulder and South Boulder Creeks, including the north Boulder Farmer's Ditch, which would eventually supply much of the water for the city of Boulder (Crifasi, 2015, p. 187).

Eventually, claiming on both streams ceased as all available farmland and water was fully appropriated. Figure 1.6 depicts the early development of claims on Boulder and South 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

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

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

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. 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).

[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 Online 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 1.3, which should be interpreted as a lower bound on the magnitude of positive spillover effects from investment.

1.4.4 Robustness

We reestimate our model using a set of alternative estimators to evaluate the robustness of our identification strategy given the unique character of our data set. Three primary concerns could threaten identification. First, our data set contains a large number of 0s because in any year most streams receive 0 claims.[38] Second, the distribution of unobserved heterogeneity may be incorrectly specified in Equation 1.9 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. More broadly, we rely on a distributional assumption for identification and wish to show that our estimates are robust to alternative assumptions.

We address the first problem by reproducing the estimated marginal effects from Table 1.3 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 stream j in year t. The Probit is more robust to the presence of excess zeros because it is designed for 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,

[38] In any given year, most of the 1,922 streams in our sample do not receive new claims. Moreover, the identifying assumption for the random effects probit is slightly less restrictive for our setting in that it 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.

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

we restrict the data set to claims prior to 1950 and estimate the model by 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 0s in the dependent variable. Our results suggest attenuation bias in the presence of either complication, suggesting that our estimates are lower bounds on actual effect sizes.

1.5 Economic Implications of Prior Appropriation

1.5.1 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 1 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, 1929). We obtained GIS data on irrigation canals and ditches for Divisions 1 (South Platte) and 3 (Rio Grande) in addition to GIS data on crop choice and irrigated acreage by crop for certain historical years from the Colorado Department of Water Resources.[40] Each right has a unique identifier number that we use to match to ditches and irrigated lands, resulting in 550 rights for which we have complete data. Table 1.4 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 10 miles of the point of diversion in addition to the roughness of the terrain within a 10-mile radius of the point of diversion. We also calculate the total acreage of all 1-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 areas, we calculate the characteristics of irrigated lands 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 effect 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 associated with each right for which we have matching data, captured in the variable Irrigated Acres. Our irrigation data also tell us how many acres of which crops were irrigated with the water from each right. We use estimates of average yield per acre and prices for Colorado for each crop in our data set from the Census of Agriculture from 1936 and 1956 to estimate

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

the total value of irrigated agricultural output for each water right. The variable Total Income reports the crop income 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 Colorado.[41]

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

Table 1.4: Claim-Level Summary Statistics

Variable	N	Mean	S.D.	Min	Max	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	S. D. of summer flow from 1890 to 2000.
Roughness	6,479	142.7	107.7	0.0720	934.2	Avg. Slope*S. D. of Slope (within 10 miles 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 have complete elevation and flow data available.

In this section we document the role of formal property rights as a coordinating institution for resolving collective action problems associated with the development of natural resources. To do this, we estimate the effect of priority-differentiated water rights on coordination and investment in irrigation infrastructure in Colorado. 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. 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 do this using data on ditch investment and income per acre for Divisions 1 (South Platte) and 3 (Rio Grande), which comprised markedly different institutional settings for the development of prior appropriation.

1.5.2 Formal vs. Informal Institutions: Division 1 vs. 3

Differences in resource and user characteristics between Water Divisions 1 and 3 in Colorado provide a novel setting for analyzing the comparative advantages of formal property regimes relative to informal institutions for collective action. Broadly, conditions in Division 3 were consistent with the necessary conditions for successful common-pool resource management laid out by Ostrom (1990), whereas conditions in Division 1 were not. Differences in geography between Divisions 1 and 3 meant that there was much greater potential for entry of subsequent claimants in Division 1; the average number of potential riparian homesteads across all streams was 50 in Division 1 but just 28 in Division 3. Similarly, Division 1 was much more heavily settled than Division 3, increasing potential bargaining costs of water users. The average township in Division 1 had 84 homestead claims, compared to 11 homesteads per township in Division 3.

Division 3, composed mainly of the San Luis River Valley, had a predominantly Hispanic population living in small, close-knit communities with relatively long use of communal norms to govern ditch management and irrigation water allocation (Mead, 1901; Hutchins, 1928; Smith, 2016). Community-owned large ditches or *acequia madres*, were managed by ditch bosses or *mayordomos* who oversaw construction and annual maintenance contributions by local users, rotated water access, and arbitrated disputes.[42] This setting required little outside capital investment and the collective action problem was solved by custom (Hutchins, 1928; Meyer, 1984, pp. 64-73, 81; Smith, 2016). In contrast, Division 1 was comprised of larger numbers of heterogeneous migrants from elsewhere in the US (Hicks and Peña, 2003). In this setting, the legal doctrine of prior appropriation was the common denominator among parties seeking to form and finance an irrigation network (Hobbs, 1997, p. 4; Crisfasi, 2015). This key difference between the two jurisdictions allows us to assess the role of formal property rights as a coordinating mechanism with and without the presence of informal institutions.[43] Our prediction is that appropriative rights will generate larger benefits across a variety of outcomes in Division 1 than in Division 3.

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

[43]See Appendix Table C7 for a comparison of the two groups.

1.5.3 Property Rights Security and Coordination

First, we examine the determinants of cooperation, 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 1st and 2nd claimant is the same as the difference between being, say, the 14th and 15th 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 10 dummy variables—one for each decile. For example, if the 1st Decile Dummy is equal to 1, the associated water right was among the first 10% of claims along its stream and had high-priority access to water during drought. This approach 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 effect of priority on coordination among rightsholders in infrastructure investment, relying primarily on within-watershed variation for identification.[44] 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 1.5 presents the estimated marginal effects of each priority decile on the probability of cooperation, relative

[44]We use watershed fixed effects rather than stream fixed effects because coordination and spatial competition over irrigation works was often not limited to a single stream. Rather, development occurred based on what lands where arable, which varies by watershed.

Table 1.5: Marginal Effects of Priority on Cooperation

$Y = CoOp$	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

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

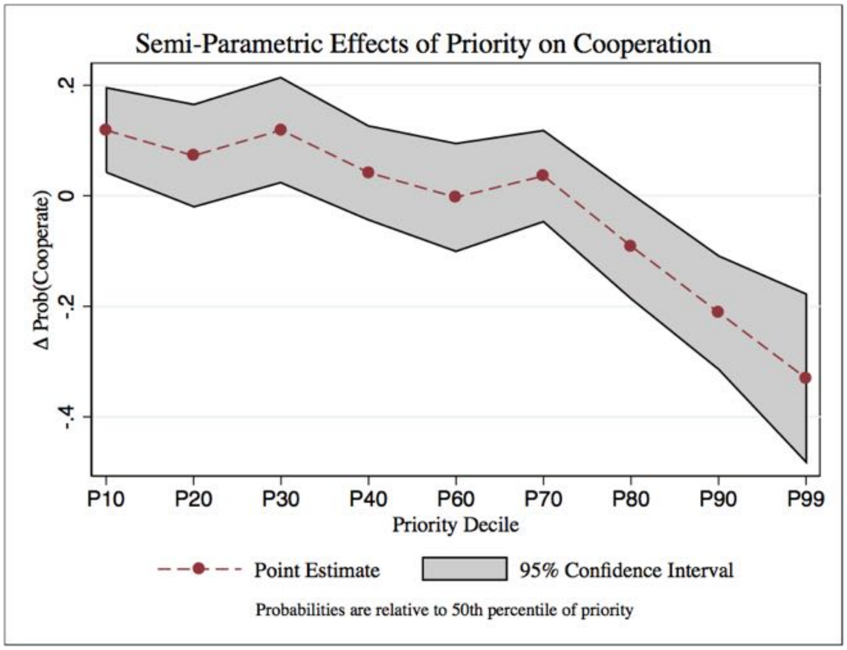
to the 5th decile.[45] Columns 1 and 2 are estimated jointly for all three divisions, whereas columns 3 and 4 report the results for Divisions 1 and 3 separately.

[45]Marginal effects are estimated at the median values of the controls, and standard errors are clustered by watershed.

We find a higher probability of coordinating for investment in infrastructure for rights above the 5th Decile and a lower probability of coordinating for rights below the 5th Decile. Figure 1.7 depicts the marginal effects of each priority decile on cooperation associated with the model in Column 2 of Table 1.5. Users with 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 are 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 were the most junior rightsholders. This general pattern holds within Division 1 and Division 3 separately, particularly with respect to the lowest-priority right-holders. As Figure 1.7 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 righsholders with the most variable water supply were the least likely to jointly invest in irrigation capital. By contrast, rightsholders 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 finding is consistent with that of Wiggins and Libecap (1985), who find that cooperation among oil field operators in oil

Figure 1.7: Marginal Effects of Priority on Cooperation



field coordination and investment becomes less likely as they become more heterogeneous.

1.5.4 Formal Coordination as a Basis for Investment

Next, we assess the extent to which ditch investment differed according to whether or not claimants coordinated with other water rightsholders. 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 for farming (Hayden, 1869). The costs of ditch investment had to be borne up front, before there was reliable information about the availability of water over time. Mead (1901, p. 8) estimated that private irrigation systems valued nearly at $200,000,000 (nearly $6 billion in 2015 $) were in place as of 1901 in the western United States. He also describes the complexity of raising capital and the coordination and consolidation among irrigation companies in the Cache La Poudre valley, one of the first areas in Colorado to be placed under large-scale irrigation.[46]

Coordination between water rightsholders could increase ditch investment because i) it allowed users to share these up front costs, ii) it 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 (Hanemann, 2014; Crifasi, 2015, p. 158). Users who cooperated still developed individual ditches known as laterals to bring water to their own particular fields (see Figure 1.9 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 development required security of ownership so that ditch builders could reap the rewards of their 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

[46] In the late 19th and early 20th centuries there were numerous investigations into irrigation in the western United States including Newell (1894), Mead (1901), Adams et al. (1910). Newell (1894) reports irrigation system values of $94,412,000 in 1890 in 11 western states. He also reports data on differences in ditch construction costs according to ditch width.

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; Libecap, 2011). Finally, having quantified, secure property rights made incumbent water users willing to accommodate and even transact with new arrivals because their senior claims were not threatened by new, junior claims. As previously noted, the additional benefits of these formal property rights are predicted to be lower in areas where informal institutions had already supplied a remedy for collective action problems, as in Division 3.

Table 1.6 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 a variety of controls for access to water and land resources, with complete results on the controls reported in Appendix Table C5.[47] Columns 1, 2, and 3 are estimated jointly across Divisions 1 and 3, while Columns 4 and 5 are estimated separately for each division.[48] In our preferred specifications we find that cooperative claimants' ditches are 10,198 meters longer than those of non-cooperative claimants' in Division 1 but that coordination does not affect ditch investment in Division 3.[49]

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

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

[49]One potential concern with our results on ditch investment is that investment and cooperation are jointly determined, making CoOp endogenous in Table 1.6. 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 the number of claims in the same month and same watershed as a given right as an instrument for CoOp and obtain similar estimates of key parameters. The number of claims in the same month and same watershed as a given right affects the probability of cooperation

Table 1.6: Effects of Coordination and Priority on Investment

$Y = DitchMeters$	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

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

Two possible alternative 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 1.5), makes it unlikely that legal status varied sharply between groups, pointing toward another explanation for differences in investment incentives. However, differences

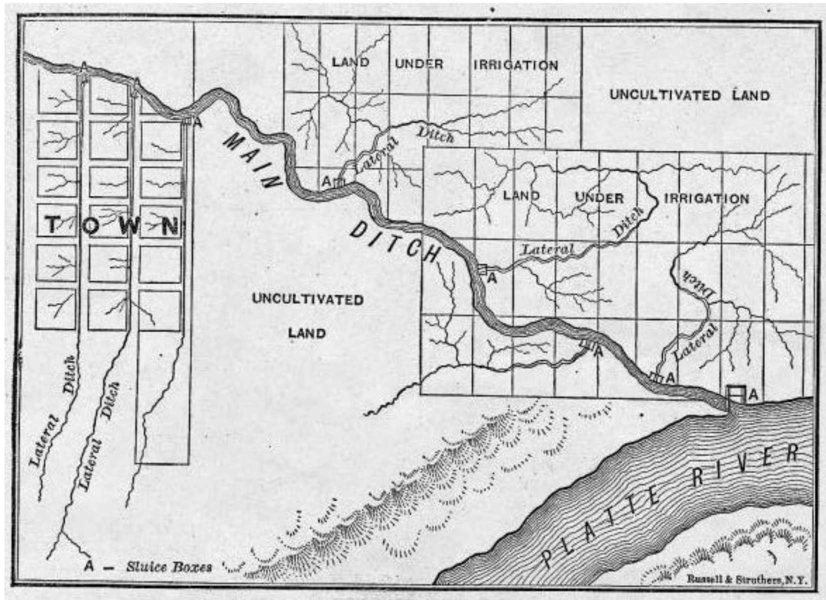
because rights established nearby other rights (in space and time) have more other claims with which to potentially cooperate. At the same time, the number of new claims in a given month should not directly affect the investment of any particular claim, except through its effect on the cooperative status of that claim. 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.

in wealth would result in less ditch building overall but should not reduce the role of formal coordination for projects that were undertaken. Instead, we argue that the differential role of formal coordination in Divisions 1 and 3 can be explained by the dominant communal norms in Division 3, which rendered formal property institutions less crucial in that area. In contrast, Division 1 required formal legal rights as a basis for coordination among many heterogeneous claimants.

To illustrate the role of priority on investment in Division 1, consider the McGinn Ditch on South Boulder Creek and north Boulder Farmer's Ditch on Boulder Creek. Both ditches were large, cooperative investments. 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 the Boulder Valley when it was constructed in 1862, costing $6,500 ($165,000 in 2015 dollars) and irrigated over 3,000 acres of land (Crifasi, 2015, p. 187). Even larger ditches followed. The Larimer and Weld Canal from the Cache La Poudre River, was constructed sequentially between 1864 and 1878 with the huge capacity of 720 cfs (5,400 gallons) and was 53 miles long to irrigate 50,000 acres (Hemphill 1922, p. 15; Dunbar 1950, p. 244). Construction costs for such ditches were financed either through forming non-profit mutual ditch companies among irrigators or through organizing commercial ditch companies with a broader group of investors, such as the Colorado Mortgage and Investment Company of London, England (Dunbar 1950, pp. 253-58, Libecap 2011, p. 73).

Figure 1.8, from the June 20th, 1874, issue of *Harper's Weekly*, depicts an arrangement typical for eastern Colorado and highlights the increase in arable land associated with coordinated development of irrigation canals.

Figure 1.8: Coordinated Investment



THE COLORADO SYSTEM OF IRRIGATION.

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

1.5.5 Irrigation and Income Per Acre

Ultimately the purpose of establishing a water right in Colorado was to provide water as an input to irrigated agriculture. Prior appropriation added value to agricultural endeavors by encouraging search and investment and by separating water rights from riparian land holdings, allowing for much greater and more productive areas to be irrigated than would have been possible under the riparian system. To estimate the magnitude these benefits, 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. We conservatively assume that land within a half mile of a stream or river could have been claimed and considered to be adjacent to the water for the purposes of assigning riparian water rights.

Figure 1.9 depicts riparian lands in eastern Colorado—indicated by cross hatch shading—and the location of loamy soils (hydrologic soil call B) best suited to farming—indicated with green shading—and reveals that the riparian doctrine would have both constrained the total area of land available for farming and have precluded the ability to irrigate some of the most productive soils in the region that were remote from streams. 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.

Figure 1.9: Riparian and Arable Land in Eastern Colorado

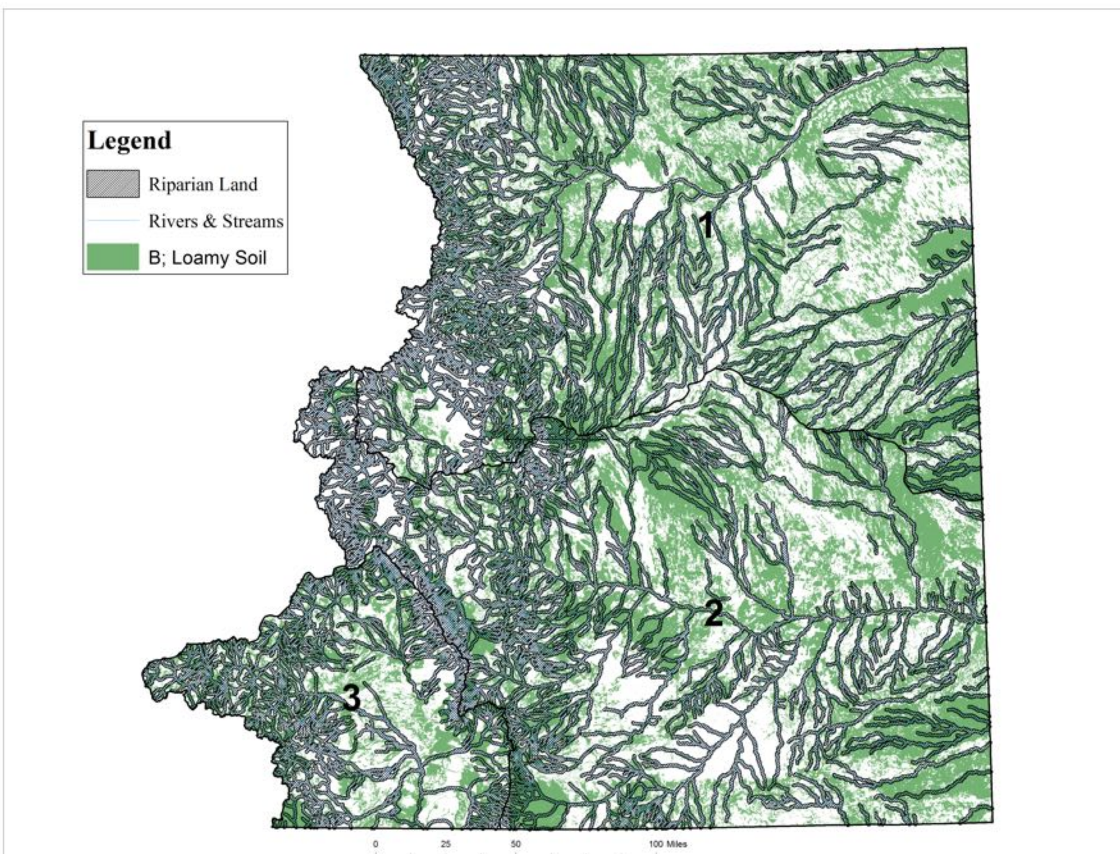


Figure 1.10 depicts riparian land and actual irrigated acreage in 1956 for Division 1 and 1936 for Division 3, the earliest years for which GIS data are available in each division.[50] We focus on these early years so that we can isolate the effect of access to surface water as from the effect of access to groundwater.[51] Roughly 45% of the irrigated land in Division 1 and 34% in Division 3 were riparian. The ability to claim water from streams and put it to use on non-adjacent land allowed for substantial growth in irrigated acreage in both divisions, resulting in an additional 546,552 acres of usable farmland—an increase of 133%.[52]

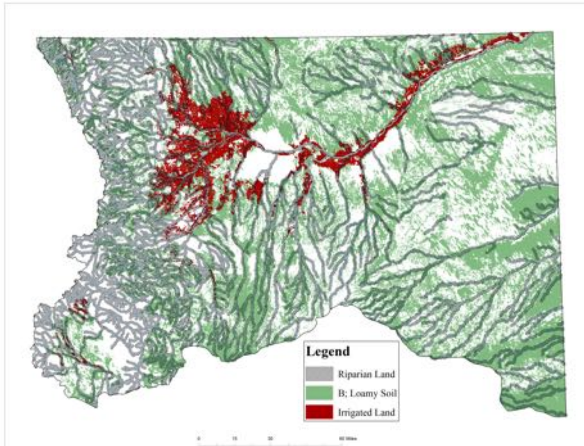
Focusing on per-acre returns allows us to better understand the contribution of prior appropriation to farm productivity. We combine our rights-level data on irrigated acres and crop choice with historical state-level data from the Census of Agricultural on prices and yields for each crop to estimate the value of production on riparian and non-riparian lands. These results are summarized in Table 1.7. 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

[50]Data for a contemporaneous cross-sectional or panel comparison are not available. To alleviate concern about the comparison over time, we collect county-level data on the number of farms, average farm size, and average farm value for both areas in 1935 and 1954 (the closest years to our sample years for which data are available) from the Census of Agriculture. We calculate the percentage change in each outcome between 1935 and 1954 and find no statistically significant difference in changes over time across divisions. The total number of farms fell in both divisions, while both average farm size and value increased. We also collect data on average yields for irrigated wheat in both periods in both divisions and find no statistically significant difference in the change in yield from 1936 to 1956 across divisions. These tests imply that economic conditions in agriculture in the two divisions moved in similar ways over the 20-year period.

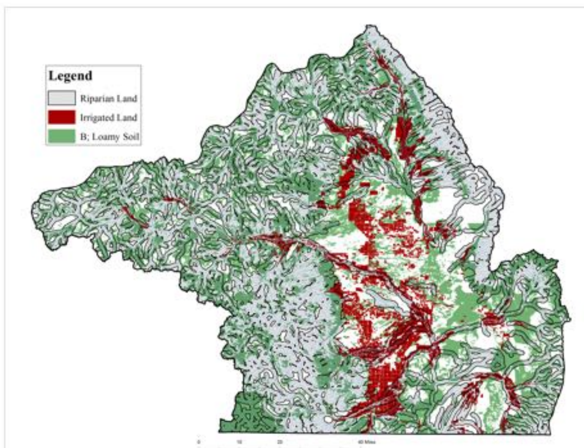
[51]Estimates from later in the 20th century are contaminated by the ability of farmers to supplement their surface water rights by pumping groundwater. The technology for groundwater pumping became widely available after World War II.

[52]These land-based estimates form an upper bound on the expansion of irrigated agriculture made possible by prior appropriation. The counterfactual 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.

Figure 1.10: Riparian and Irrigated Land



(a) Division 1



(b) Division 3

Colorado in our sample years by 134%.

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.[53] This suggests that non-riparian lands were more productive than riparian lands. This is consistent with the fact

[53]This difference is statistically significant at the 99% level. Newell (1894, p. 6) provides estimates for the value of irrigated agricultural production/acre at \$361/acre for all of Colorado (in 2015 \$).

Table 1.7: Irrigated vs. Riparian Land (2015 $)

	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
Median Farm Size	147	760	99	262
Average Income Per Acre	$527.50	$548.32	$601.67	$600.10
	(3.28)	(3.05)	(14.64)	(12.36)

Standard error of the mean reported in parentheses for Income Per Acre.

that users incurred substantial infrastructure costs to reach non-riparian lands and left much of the riparian corridor untouched.

Table 1.7 makes it clear that the riparian system would have constrained rightsholders to the more rugged terrain adjacent to streams and limited total farm size, assuming only riparian homesteads had access to water. This, in turn, would have precluded important 20th-century innovations in farming technology centered around the development of large, flat farms in the West (Gardner, 2009; Olmstead and Rhode, 2001). Previous studies of prior appropriation have emphasized the ability to separate water from streams as a necessary condition for irrigation in the arid West, but this does not explain fully why a first-possession mechanism was adopted. Another necessary ingredient for successful irrigation was an incentive structure to facilitate costly investment. Tables 1.5 and 1.6 suggest that first possession provided this incentive structure by granting a more secure property right and Table 1.7 confirms that nonriparian lands were in fact more productive and allowed for larger farms.

Taken together, these results suggest that formal coordination under the prior appropriation doctrine was an important determinant of per-acre income for farmers. Coordination facilitated ditch investment, which in turn provided access to more productive land and may have allowed for more efficient, larger farms and cooperation along other productive margins. Equation 1.10 summarizes the possible channels through which building a cooperative ditch could increase per-acre returns.

$$\frac{\mathrm{d}IPA}{\mathrm{d}CoOp} = \frac{\partial IPA}{\partial Acres}\left[\frac{\partial Acres}{\partial Ditches}\cdot\frac{\partial Ditches}{\partial CoOp}+\frac{\partial Acres}{\partial CoOp}\right]+\frac{\partial IPA}{\partial Ditches}\cdot\frac{\partial Ditches}{\partial CoOp}+\frac{\partial IPA}{\partial CoOp}. \tag{1.10}$$

We estimate a series of linear regressions using the GMM technique mentioned above to obtain each of the partial derivatives in Equation 1.10 and to construct the total effect of coordination on income per acre. Table 1.8 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. The first row of Table 1.8 reports 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 1.10, 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.

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. This exceeds the average difference in productivity for nonriparian vs. riparian farms reported in Table 1.7 by a factor of five. While reaching nonriparian lands did lead to greater

Table 1.8: 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)
SUR[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
* $p < .1$, ** $p < .05$, *** $p < .01$

income per acre, users who cooperated generated even greater benefits. This suggests that ditch investment was critical for productivity and that the ability to build longer ditches via formal cooperative arrangements (documented in Table 1.6) increased productivity substantially by granting access to the most productive lands.

In contrast, we find no effect of cooperation on income per acre in Division 3. This difference is driven largely by the fact that coordination promoted ditch investment in Division 1 but not in Division 3. Both divisions faced a classic collective action problem in the development of irrigation works. In Division 3 this problem was largely solved in a classic Ostrom (1990) manner with cultural norms and informal mechanisms, which worked well given the small number of homogeneous users. In this settings formal property rights added little value. Division 1 was rapidly settled by a large number of heterogeneous claimants, making a norm-based solutions untenable. Here, the collective action problem was solved by contracting based on formal, legal property rights.

1.5.6 Irrigated Agriculture and the Development of the West

By the late 19th century the role of irrigated agriculture in expanding economies was increasingly recognized (Newell, 1894). 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 1.9 presents our estimates of the value of irrigated crop production for western states in 1910 and 1930. We use data from Easterlin (1960) and from the Bureau of Economic Analysis on personal income by state and the 1910 and 1930 US Censuses of Agriculture to estimate the value of irrigated crops and report those estimates as a percentage of state or territory income.[54] 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.[55] This represents the estimated share of state income due to agricultural production that could not have taken place under the riparian doctrine.

Table 1.9 indicates that irrigation of non-riparian lands contributed 2% to 14% of

[54]Department of Commerce, BEA Survey of Current Business, May 2002 and unpublished data, "Personal Income and Personal Income by State, 1929-2001," provided to the authors by Robert A. Margo. State income values were calculated on a state basis by multiplying population by per capita income. Population data for 1910 and 1930 from US Agricultural Data, 1840-2010, distributed by the Inter-University Consortium for Political and Social Research (ICPSR). For 1910, per capita income was calculated by taking the mean of per capita income from 1900 and 1920. Per capita income from 1900 was taken from Easterlin 1960, Table A-3. Per capita income for 1920 and 1930 were taken from unpublished data from Easterlin and the BEA. The 1910 values of irrigated crops were calculated by summing individual crop values by state. Data from irrigated crop values were taken from the 1910 Census of Agriculture, Volumes 6 and 7. The 1910 Census of Agriculture notes that data for irrigated crops were taken from supplemental schedules, and the information is considered to be incomplete. Therefore, all available irrigated crop value data were summed. The 1930 values of irrigated crops were calculated by summing the eight most valuable crops according to state. The number of crops included in the calculation was chosen to be eight, as the 9th crop value added less than 5% to the total irrigated crop value. Data for irrigated crop values were taken from US Agricultural Data, 1930, distributed by ICPSR.

[55]We calculate a weighted average of the share of non-riparian income of 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.

Table 1.9: 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. %
AZ	$109,088,226	7.8%	4.4 %	$218,429,933	6.8%	3.9%
CA	$1,198,335,054	5.4%	3.1%	$4,730,240,019	6.6%	3.8%
CO	$955,887,896	15.4%	8.8%	$1,216,338,604	14.4%	8.2%
ID	$411,487,005	26.0%	14.8%	$1,176,322,174	38.2%	21.8%
MT	$357,644,113	12.9%	7.3%	$543,002,901	14.2%	8.1%
NV	$129,481,278	19.7%	11.3%	$199,548,712	18.5%	10.6%
NM	$132,129,974	9.2%	5.2%	$282,107,719	14.2%	8.1%
OR	$182,079,466	3.9%	2.2%	$425,281,996	5.2%	3.0%
UT	$355,860,090	15.1%	8.6%	$526,011,917	14.8%	8.4%
WA	$182,766,338	2.9%	1.7%	$896,351,083	6.2%	3.5%
WY	$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) Calculations are detailed in footnote 53.

state income in 1910 and 3% to 21% in 1930. These estimates understate the total impact on state income due to multipliers across the economy. Adelman and Robinson (1986), for example, estimate multipliers of 1.8 to 2.1 for every dollar of income from agriculture. Overall, irrigated agriculture 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 came from non-riparian lands.[56]

[56]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.

1.6 Conclusion

Prior appropriation encouraged socially-valuable search that lowered information costs regarding the most favorable diversion locations. Prior claims raised the probability of subsequent claims by 20%, an effect equivalent to a near doubling of stream size in attracting settlers. Denser settlement, in turn, brought agglomeration economies in the joint investment in large irrigation infrastructure. The ability to coordinate and combine formal, tradable prior appropriation rights along with greater certainty of water deliveries for high-priority rights holders facilitated joint development of canal systems. The top 10% of senior claimants were 40 percentage points more likely to form ditch companies than were those below the median priority. This cooperation in turn led to a doubling of average ditch length (about 10 km) that greatly expanded irrigable, high-quality land, especially in Division 1. Longer ditches brought more productive non-riparian land under irrigation, with the longest, cooperative ditches adding over $100 per acre to productivity. Prior appropriation water rights not only encouraged investment, but were exchanged routinely to consolidate and redirect water (Hemphill, 1922). There was no detectable effect, however, in Division 3 where formal rights appear not to have been required to coordinate effort. Overall, under prior appropriation between 3.5% and 20% of western state incomes by 1930 were directly attributable to irrigated agriculture, much of which would not have been feasible under the default riparian rights system. These estimates do not incorporate multiplier effects from higher agricultural incomes that might have doubled the economic impact in each state.

The value of any particular form of property right to a natural resource is its ability to align individual incentives to reconcile competing demands and to encourage innovation, investment, and reallocation. The western frontier provides a unique laboratory for analyzing the development or modification of property institutions. Prior appropriation emerged in response to new conditions in a setting where institutional change could occur at relatively low cost with high expected net returns. The migration of thousands of frontier claimants was fueled by anticipation of capturing resource rents that required a new property rights regime. Although migrants were numerous and dissimilar in many ways, they carried with them common notions of individual ownership of land and other natural resources and an ability to modify institutions as local conditions suggested. In case of prior appropriation of water, claimants applied existing first-possession allocation of agricultural and mineral land to water, rather than adhering to an eastern riparian system that offered lower returns under semi-arid conditions.

Once in place, prior appropriation molded expectations for the creation and distribution of net rents and the associated range of uses, exchange, time frames, and investment in water. These conditions remain today among property rights holders. In the face of new demands for water for environmental, urban, and industrial use along with more variable and possibly declining supplies, water rights will be exchanged and water reallocated (Brewer et al., 2008; Murphy et al., 2009; Culp et al., 2014). Such transfers can take place within the prevailing rights system. Doing so not only recognizes the long-term benefits associated with prior appropriation but reflects the economic, social, and political path dependencies associated with it. Recent policy discussions calling for a restructuring of water rights to shares of total annual allowable uses or to mandate instream environmental flows do not sufficiently consider the value of and stakes in the contemporary priority rights system. Unlike the earlier frontier setting, major uncompensated movement to any new institutional arrangement would not be at low cost.

1.7 Permissions and Attributions

The content of Chapter 1 is the result of a collaboration with Gary D. Libecap.[57]

[57]For helpful comments we thank Christopher Costello, Olivier Deschênes, Dick Startz, Louis Kaplow, Steve Shavell, and Henry Smith as well as participants at workshops at Indiana University, UC Santa Barbara, Arizona State University, Columbia University, Harvard, UCLA, Montana State University, the Society for Organizational and Institutional Economics, and the Western Economics Association. We also thank the Walton Family Foundation and the Sustainable Water Markets program at UC Santa Barbara for supporting this research. Excellent research assistance was provided by Cody Wilgas, Love Goyal, and A.J. Leon.

Chapter 2

Creating Anticommons: Historical Land Privatization and Modern Natural Resource Use

2.1 Introduction

Much of the world's indigenous populations lack formal property rights to land and many economists consider this a hindrance to development. The main argument is that informal rights are too insecure to encourage current users to invest in land improvements that would increase future income streams (see Demsetz (1967); Alchian and Demsetz (1973); Feder and Feeny (1991); Besley (1995); Goldstein and Udry (2008); Besley and Ghatak (2009b)). Land privatization programs attempt to address underinvestment problems in tribal areas of Africa, South America, and elsewhere, and are now being debated for indigenous populations in Canada (Flanagan et al., 2010; Brinkhurst et al., 2013). Through subdivision and codification of land rights, privatization programs seek to enclose the "commons", which are areas or resources for which individual users lack defensible exclusion rights (Gordon, 1954; Hardin, 1968; Barzel, 1997). In theory, having title over a specific parcel strengthens individual exclusion rights and hence makes future claims on prior investments secure (Alston et al., 1996).[1]

In this paper, we study an unintended consequence of strengthening individual exclusion rights via top-down privatization. Even when subdividing land successfully encloses the commons for one type of land use (e.g., agriculture), the process can create anticommons problems for other resources. Anticommons arise when too many exclusion rights are granted relative to the efficient scale of resource use, potentially causing underutilization and delays in resource exploitation (Heller, 1998; Buchanan and Yoon, 2000; Heller, 2010). Our concern is that subdividing land rights will raise the transaction costs of managing larger-scale resources such as shale oil and wind that are best managed at scales exceeding those required for agriculture (Lueck, 1989; Fennell, 2011; Bradshaw Schulz and Lueck, 2015). This is important because in some areas with large indigenous populations the value of large-scale natural resources—if managed well—may dominate the value of farming.

We study this issue by examining the legacy of the U.S. government's sweeping program for "allotting" Native American land over 1887-1934. During this period, roughly 41 million acres of Indian land was subdivided into 320, 160, 80, and 40 acre parcels

[1] Galiani and Schargrodsky (2012) review empirical studies on privatization. Most recent studies find that private ownership has stimulated productivity-enhancing investments in land and agriculture (see Banerjee et al. (2002); Field (2005); Do and Iyer (2008); Galiani and Schargrodsky (2010). But some studies fail to find significant improvements in agricultural investment after titling (Brasselle et al., 2002; Jacoby and Minten, 2007).

and allotted to individual Native American families with the goal of encouraging productive farming (Carlson, 1981).[2] Some allotted lands were fully privatized and others were not, with multiple family heirs retaining exclusion rights as we explain in section 3. Other tribal lands were never allotted and remain held in common by tribal members through their governments. The upshot is that modern Indian reservations are a patchwork of commonly owned land, individually owned parcels, and fractionated ownership of allotted trust lands (Trosper, 1978; Anderson, 1995; Banner, 2009). This patchwork enables comparisons of long-run investments under different tenure arrangements. Empirical research suggests that non-privatized Indian lands have less housing investment (Akee, 2009) and lower agricultural investments (Anderson and Lueck, 1992), as standard models of property rights and investment would predict.[3]

We contribute to literatures on land privatization, anticommons, land assembly, and path dependence by examining how exogenous variation in the subdivision of mineral ownership affects the timing and density of modern shale oil extraction focusing on one of the world's largest and currently booming oil fields.[4] Our empirical analysis is based on a detailed case study of drilling on and around North Dakota's Fort Berthold reservation and combines GIS files of land and mineral tenure with publicly available data on horizontal wells from the North Dakota Oil and Gas Commission. The parcels in our sample sit atop the highly productive Bakken oil field and represent a mosaic of tribal

[2] A less charitable interpretation is that land allotment policies were devised to transfer land from Native Americans to white settlers (see Carlson (1981); Banner (2009).

[3] A common challenge to identification in this literature is possible selection bias due to the fact that tenure is not exogenous to land characteristics (see Akee and Jorgensen (2014).

[4] Our study relates to a working paper by Holmes et al. (2015) who study agglomeration economies of density, also in the context of the Bakken. One key difference is that our study focuses to a greater extent on property rights and tenure, exploiting the different systems that exist on Forth Berthold.

land, allotted trust land, and fully privatized parcels. The history of land and mineral tenure on the Fort Berthold reservation, as described in section 3, almost guarantees that tenure is exogenous to shale quality and we provide evidence that this is true within oil field units.

Our focus on shale oil is important for three reasons. First, modern technology of oil extraction sometimes called horizontal fracking requires coordinated exploitation of a landscape's subsurface. This is because shale extraction is executed by drilling a horizontal line that extends up to three miles from a vertical well pad. Exploiting this technology in a subdivided landscape can generate large land assembly transaction costs.[5] Importantly, we argue that transaction costs are plausibly lower under tribally governed common lands.

Second, the spatial nature of horizontal drilling allows us to study how the economic use of a natural resource by one owner is affected by the property rights governing neighboring parcels. When exploitation requires coordination across parcels, even those parcels with advantageous bundles may not be able to utilize the resource due to the tenure of neighboring parcels. The cross-parcel development of horizontal wells in the tenure mosaic of Indian reservations provides a rich setting for identifying parcel-level spillover effects. In this way our study relates to Aragón (2015) who finds that property rights in one area can have local economic spillovers on other areas in the context of Canadian aboriginal lands.

A third reason for focusing on shale oil is that land allotment and the resulting tenure arrangements were exogenous to shale endowments. The ownership of shale was

[5] There would be 24 separate square 40-acre parcels along a three-mile line.

inadvertently subdivided in patterns determined by surface characteristics, primarily agricultural potential. Because of this exogeneity, we are able to credibly estimate the effects of property rights, parcel sizes, and parcel shapes on the speed and extent to which horizontal drilling has occurred.

We compare patterns of horizontal drilling across over 40,000 parcels off and on the reservation during the 2005 to present day oil boom. We find the timing and density of drilling under a parcel is negatively impacted by increases in the number of private parcels in a radius around a parcel: for example, an increase in subdivision within the radius by one standard deviation is associated with a 75 percent decline in the probability the parcel owner has been compensated for his shale and a 1,516 day delay in the time elapsed before his parcel is first penetrated by horizontal fracking line. The delays are longer for land that was subdivided into allotted trust tenure. In contrast, we do not find a negative neighbor effect for neighboring tribal parcels, which share a common owner and hence do not require spatial coordination amongst additional owners with exclusion rights. Our back-of-the-envelope estimates suggest the costs of tribal shale subdivision, in terms of delayed oil-royalty earnings, exceeded the overall income earned by American Indians on Fort Berthold in 2010 under reasonable discounting assumptions.

We also find that a parcel's size and shape has large effects on the timing and probability of oil development, with larger and more rectangular parcels exploited before smaller squares. This finding complements studies that detail how the "wrong" parcel allocation (at least for one type of resource use) can impair current productive use because rights and resource use are path dependent (Libecap and Lueck, 2011; Bleakley and Ferrie, 2014; Hornbeck and Keniston, 2014).[6]

Our study also provides context to Kunce et al. (2002), who argue that conventional, vertical natural gas drilling was more costly on U.S. federal land when compared to neighboring private parcels.[7] On one hand, our evidence is consistent because it suggests that oil developers avoid placing the vertical portion of horizontal wells on tribal and government lands. On the other hand, we find that extending horizontal lines through additional tribal lands causes less delay than the extension through private parcels. This finding suggests the marginal contracting cost of horizontal drilling, per unit of distance, is lower in areas with contiguous government ownership and our supplementary estimates of drilling delays on and around federal and state land on the Bakken support this interpretation. This is an economic rationale for government ownership of shale that we return to in the paper's conclusion.

2.2 Exclusion, Commons, and Anticommons

In this section we articulate a fundamental tension in the design of property rights over land harboring large and small scale resources with different physical attributes. It is not possible to simultaneously match the scale of property rights with the optimal management scale of all resources unless use and exclusion rights are unbundled for every resource (Lueck, 1989; Barzel, 1997; Fennell, 2011; Bradshaw Schulz and Lueck, 2015).

[6] Our study also contributes to the literature on how historical, top-down imposed institutions imposed on indigenous societies has affected modern economic outcomes. This literature includes Feir (2013), Dippel (2014), Akee et al. (2015), Akee (2009), Cookson (2010), Anderson and Parker (2008), Dimitrova-Grajzl et al. (2014), Cornell and Kalt (2000), Anderson (1995), Anderson and Lueck (1992), Carlson (1981), and Trosper (1978) among others.

[7] The study was retracted due to data errors (Gerking and Morgan, 2007).

We study the case where the privatization of a tract of land is bundled, meaning the surface owner also obtains some combination of use and exclusion rights to the subsurface (e.g., oil reservoirs, ground water, coal, shale oil).

2.2.1 Land Subdivision and Enclosure of the Commons

The "commons" is often conceptualized as an agricultural landscape on which a group of N individuals have use rights. The group can exclude outsiders, but each individual lacks the right to exclude other members.[8] The inability to exclude leads to overuse of a fixed, congestible resource such as grazing land because each user bears only $1/N$ of the long-run costs of his current use but accrues the full current benefit. Similarly, the inability to exclude can result in under-investment in crops and other commodities for which there is a time lag between labor and capital investments and the flow of output. The incentive problem is that the individual investor bears the full current cost but expects to accrue only $1/N$ of the returns on investment in later periods.[9]

Two solutions to these problems involve privatizating the landscape. The first is to grant ownership to one individual by vesting her with a single use and single exclusion right. The enclosure movement of eighteenth century England is a leading empirical example. Access to communally used fields was restricted and land was converted to large private farming estates (Smith, 2000). The second solution is to subdivide the landscape into individual parcels and assign a single exclusion and single use right per

[8] Group exclusion distinguishes common property from open access (Dietz et al., 2003; Ostrom, 1990).

[9] Merrill (1998, p. 730) argues that the ability to exclude is crucial for private property: "Give someone the right to exclude others from a valued resource, i.e., a resource that is scarce relative to human demand for it, and you give them property. Deny someone the exclusion right and they do not have property."

parcel. Examples of privatization schemes like this include homesteading in the United States, Canada, and Australia during 18th and 19th century (Allen, 1991), programs in modern sub-Saharan Africa (Mwangi, 2006), and the allotment of Native American lands during 1887-1934.

Sole private ownership of the landscape is a useful theoretical construct that we return to below, but we focus on subdivision because it is the empirically dominant form of privatization.[10] In the Mathematical Appendix we present a model that compares agricultural productivity generated from a landscape of size L by N users under common property with agricultural productivity from the same landscape when it is subdivided into L/N private parcels. Suppose that constant returns to scale in land dominate for parcels larger than L_A and that $N < \frac{L}{L_A}$ so that each user experiences constant returns to scale.[11] In the appendix we prove that 1) aggregate agricultural investment under the subdivided regime depends on land area and output and input prices only—it is not a function of N, and 2) productivity is the same under subdivided parcels or sole ownership.

In summary, when considering only agriculture, subdivision is a politically feasible (and empirically dominant) alternative to sole ownership that can solve the tragedy of the commons as long as parcels are not too small. Next, we examine potential drawbacks

[10] There are several reasons why subdivision may dominate sole ownership as a solution to the tragedy of the commons. First, vesting ownership of an entire resource to a single individual is politically unpopular. The enclosure movement in England generated widespread political backlash and prompted a generation of classical economists including Adam Smith and David Ricardo to consider "land rents" as a fundamental source of economic value. Second, sole ownership over a landscape creates principle-agent problems because tenant farmers are not the resource owners (see (Smith, 2000; Barzel, 1997; Allen and Lueck, 2003).

[11] This follows from the assumption that there is some minimum efficient scale $\frac{L}{L_A}$, but that constant returns to scale are operative above this minimum farm size.

to subdivision.

2.2.2 Subdivision and the Creation of Anticommons

Whereas common property problems are due to the lack of exclusion rights, anticommons problems are caused by too many exclusion rights. Heller (1998) draws attention to the problem by describing the puzzle of underused Russian resources in the wake of post-Soviet privatization. The problem, according to Heller, was that the post-communist privatization scheme allocated exclusion rights to too many people, creating prohibitively high contracting costs to resource use. Buchanan and Yoon (2000) formalize Heller's reasoning with a theoretical model intended to demonstrate how the under-use of a fixed resource worsens with the number of owners holding exclusion rights.

Buchanan and Yoon (2000) argue that an anticommons is essentially a pecuniary externality, caused by an input assembly problem. If multiple agents have the right to exclude others from the use of a required resource, each will fail to consider the effect on others when setting their own use fee. The result is an aggregate price that is economically too high; hence underutilization of the resource relative to sole ownership.[12]

Subdivision solves the commons problem for agriculture described above and it does not in general create an anticommons *for agriculture* because the scale of exclusion rights matches the scale of profitable agricultural use, by design. In our empirical case, for example, land was typically subdivided into square parcels that varied in size with rainfall conditions in an effort to create individually profitable units based on historical farming

[12]This argument assumes the sole owner does not have monopoly power in the consumption or use market.

technology. Subdivision can, however, create an anticommons for any resource that requires coordinated agreement across multiple parcels. When the resource is too finely subdivided, an investor or entrepreneur must contract with each owner thereby slowing the use of resources requiring large scale coordination (see Brooks and Lutz 2016).

The problem is perhaps best illustrated using the parking lot example from Buchanan and Yoon (2000). There are two parking lots, one near and one distant. A tragedy of the commons arises if no one holds exclusion rights for the nearer parking lot and it becomes congested to the point where its value is dissipated entirely. In contrast, the tragedy of the anticommons occurs if multiple users hold exclusion rights to the entire lot, so that anyone wishing to park must purchase a ticket from each exclusion-right holder. Sole ownership of the lot averts both tragedies. To extend the analogy to the case of subdivided ownership, imagine users are allocated property rights to individual parking stalls so there is a single use and exclusion right per stall. This solution solves both problems because the scale of use and exclusion rights match, *at the scale of resource use* (a single stall).

The problem we study arises when a new use for the resource is discovered that exceeds the spatial scale of subdivision. Suppose a developer wishes to convert the parking lot to an office building or a public park. Though the tragedy of the parking commons was solved by privatizing parking stalls, doing so created an anticommons at the scale of the lot itself. To undertake lot-scale investment, the developer must contract with each stall owner because each holds an exclusion right.

2.2.3 Constraints on Subdivision for Optimal Resource Use

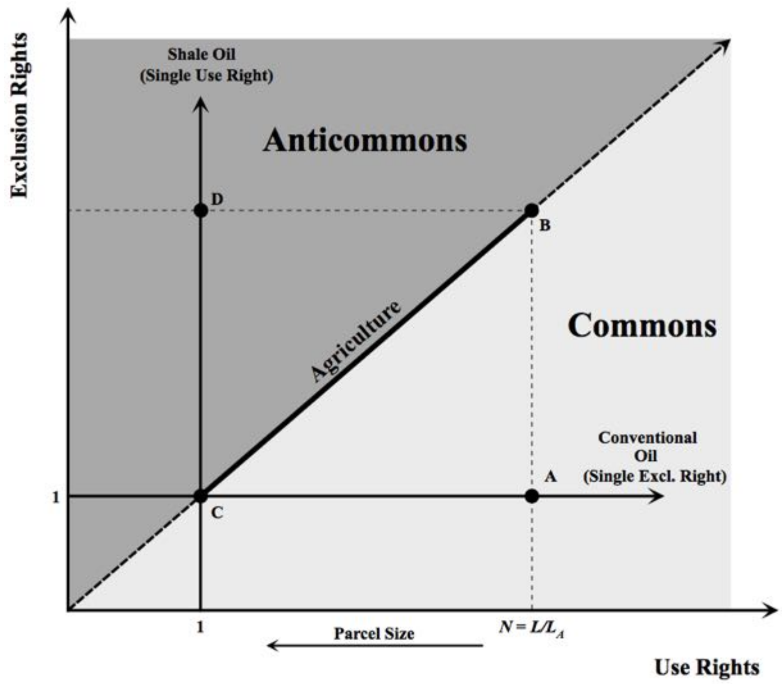
The tension we study can be defined with reference to two constraints that interact to determine optimal ownership for different land-based natural resources. The first is the incentive-based set of rules necessary for avoiding economic dissipation due to commons and anticommons discussed above. This constraint requires a property rights system that delineates one and only one use right for each exclusion right. The second constraint is defined by the physical and technological characteristics of the resource.

Figure 2.1 plots the number of use rights against exclusion rights for a resource, or landscape, of size L. Parcel size is increasing towards the origin because increasing the number of rights via subdivision of a fixed land area results in smaller parcels. The 45 degree ray characterizes the set of subdivision schemes for which the number of use rights matches the number of exclusion rights. This is the incentive-based constraint on the property rights system. Whereas the commons is characterized by an abundance of use rights relative to exclusion rights (lightly shaded area), the anticommons is characterized by an abundance of exclusion rights relative to use rights (heavily shaded area). The classic agricultural tragedy of the commons occurs at point A, where there is a single (group level) exclusion right and N use rights. Subdivision of the landscape forces a move to point B by creating N exclusion rights (one for each use right).

The physical/technology constraint varies by resource, and over time with technological changes. For agriculture, subdivision beyond $\frac{L}{L_A}$ creates parcels that are smaller than the minimum efficient scale for agriculture, violating the physical/technology constraint for optimal ownership.[13] Hence, the set of subdivision schemes that achieve the efficient

[13]Bleakley and Ferrie (2014), for example, explain how the 19th century subdivision of parcels that

Figure 2.1: Use vs. Exclusion Rights



outcome for agriculture lies along the CA line.

The physical/technology constraint on optimal ownership is more restrictive for large-scale resources such as shale oil and conventional oil. To illustrate, we plot the physical/technology constraint for both types of oil in Figure 2.1. Subsurface shale oil is tightly trapped and relatively immobile. Profitable extraction of it requires the exploitation of a large contiguous subsurface area via horizontal drilling and fracturing. If we assume that L is the size of a commercially feasible fracking project, the physical/technology constraint implies that only one user can profitably engage in fracking. This means the *de facto* use rights for shale oil will lie along the vertical line of Figure 2.1 at one, *regardless of the de jure property rights regime.* Hence, full subdivision of the landscape

were too small for productive agriculture in the U.S. state of Georgia necessitated difficult contracting in order to combine the small parcels into larger, economically viable parcels.

into N parcels moves the property rights regime for shale oil to point D. This point is an anticommons because there are many exclusion rights (i.e., each parcel owner) but only one use right can be effectively exercised.

The physical/technology constraint on conventional oil implies that subdivision also fails to incentivize its efficient use, but for a different reason. Oil in conventional reservoirs can migrate across property lines, making exclusion rights to it costly to enforce.[14] For a reservoir of size L, oil mobility implies only one *de facto* exclusion right, resulting in the constraint depicted by the horizontal line at 1 in Figure 2.1. Subdivision above the reservoir grants multiple use rights but only a single exclusion right is feasible, resulting in a commons at point A. The upshot is that, for shale oil or conventional oil, the only intersection between the incentive constraint (the use = exclusion nexus) and the resource/technology constraint is sole ownership at point C. Conventional oil and shale oil pose symmetric problems—commons and anticommons—with the same solution: sole ownership.

More generally, spatial anticommons can arise when subdivision fails to anticipate a larger scale (and shape) of technologically feasible and economically profitable resource use in the future and inadvertently raises future costs of transitioning to the new uses. Square 160 acres parcels, for example, do not match well with the optimal scale of land use for horizontal shale drilling, wind energy from a line of turbines, and linear biking trails.[15]

[14]One landowner can deplete the resource without physically accessing the subsurface below his neighbor's land by sucking oil from under his neighbor's parcel (Libecap and Wiggins, 1984; Wiggins and Libecap, 1985).

[15]One might alternatively refer to spatial anticommons as spatial externalities, which are ultimately caused by a too fine subdivision of property and include a broad array of problems studied by environmental and urban economists. Hansen and Libecap (2004a), for example, show that the prevalence of

2.3 Inadvertent Subdivision of Shale: Natural Experiment on the Bakken

To assess the importance of anticommons, we study the subdivision of the Bakken shale.[16] It sits beneath the Fort Berthold Indian Reservation and surrounding North Dakota land. The historical subdivision of these lands creates an ideal natural experiment for two reasons. First, the "allotment," homesteading, and later flooding of Fort Berthold created three types of tenure with different exclusion rights per parcel. Second, the subdivision of shale was inadvertent to the intentional subdivision of farm land, which occurred long before shale was profitable to extract and even before conventional oil was discovered in North Dakota. The resulting patterns of modern parcel sizes, shapes, and tenure types are largely exogenous to the quality of shale that only recently became valuable via horizontal drilling.

2.3.1 Background on Land Allotment

The allotment of Fort Berthold during the late and early 19th centuries was governed broadly by the U.S. Allotment Act of 1887. It authorized the U.S. government to sequentially subdivide communal Indian reservations and allot parcels to families and individuals (see Figure 2.2). Allotment was promoted to encourage agricultural investment[17] and,

small farms limited private contracting solutions to controlling wind erosion and contributed to the Dust Bowl of the 1930s.

[16]The Bakken, which began to boom around 2005, is one of the world's largest oil fields. Because of it, by 2012, North Dakota had surpassed California and Alaska to become the second largest oil producing state after Texas. By the end of 2012, the Bakken accounted for 10 percent of the entire nation's oil production (Zuckerman, 2013).

[17]The sponsor of the Act, Senator Henry Dawes, argued that under communal ownership Indians had not "got as far as they can go because they own their land in common, and under that [system] there

consistent with this claim, research indicates the scale and timing of allotment across reservations was determined primarily by agricultural land quality (Carlson, 1981).

The Act allotted land to Indians with the intention of granting private ownership including the right to alienate after 25 years or once the allottee was declared "competent." The distribution of acreages for arable land was as follows: 160 acres to each family head, 80 acres to each single person over 18 and orphans under 18, and 40 acres to each other single person under 18. On reservations for which total acreage exceeded that necessary for allotments, the surplus land was privatized and opened for white settlers.

Through a combination of land sales once allotment owners were declared competent, and through the declaration of surplus land, millions of reservation acres are now fully privatized parcels, many owned by non-Indians.[18] The Indian Reorganization Act (IRA) of 1934 halted further privatization, declaring those acres not already alienated to be held in trust by the Bureau of Indian Affairs. Allotted lands not privatized prior to 1934 are held in trust to this day, and interests in the land are divided among the heirs of the allottee. Hence, the "allotted trust" parcels on Indian reservations today often have multiple owners with exclusion rights, sometimes more than 100 (Russ and Stratmann, 2014). On the Fort Berthold reservation, a study reported the following breakdown of ownership: 13 percent of allotted trust tracts had two owners; 38 percent had 3-10 owners; 26 percent had 11 to 25 owners; 14 percent had 26 to 50 owners; and 8 percent had more than 50 owners (U.S. Government Accounting Office 1992).

Figure 2.2 shows that many reservations that were allotted overlap shale deposits,

is no enterprise to make your [land] any better than that of your neighbors." The quote is cited from Ambler (1990, p. 10).

[18]Some of the land cleared for fee simple ownership remains owned by Native Americans, but there are no systematic sources on how much this is.

Figure 2.2: Timing and Distribution of Allotted Reservations

Notes: This map is based on our digitization of an 1890 Office of Indian Affairs map of 97 reservations that were west of the Mississippi River and clearly visible in the original map. With the exception of the Osage Reservation, we exclude Oklahoma because reservations in that state are no longer federally recognized. The data on surplus land and the timing of allotment come from Indian Land Tenure, Economic Status, and Population Trends prepared by the Office Indian Affairs of the U.S. Department of Interior in 1935. Based on that report, 68 of the reservations in our sample were allotted to some extent, and surplus land was given to white settlers in 21 reservations. Of the 68 reservations that were allotted, some land was alienated and sold out of trust on 56 reservations. The spatial definitions of shale basins and plays come from the U.S. Energy Information Administration.

but agricultural quality, rather than shale, was the main determinant of cross-reservation allotment (Carlson, 1981).[19] Allottees on Indian reservations, settlers who acquired surplus lands, and homesteaders before 1916 also acquired subsurface rights to oil, even if it was not yet discovered. After 1916, the Stock-Raising Homestead Act split oil ownership, reserving subsurface rights to the federal government on new homesteads. For

[19]The Allotment Act mimicked the 1862 Homestead Act, which promoted settlement of the U.S. West (Allen, 1991). The Homestead Act granted to settlers 160 acre parcels except that certain parcels near railroad lines were 80 acre grants. To promote the settlement of less productive agricultural land, homestead acts of 1909 and 1916 raised the size of homesteads from 160 to 320, and then to 640 acres.

reservations not yet allotted at this time, subsurface rights under future allotments were often reserved for tribes by specific laws.[20] In general, only reservations allotted after the mid-1910s have their communal mineral interests fully intact today. Most reservations, including the Fort Berthold, are mosaics of subdivided subsurface tenure.

2.3.2 Shale Ownership under Fort Berthold and Surrounding Counties

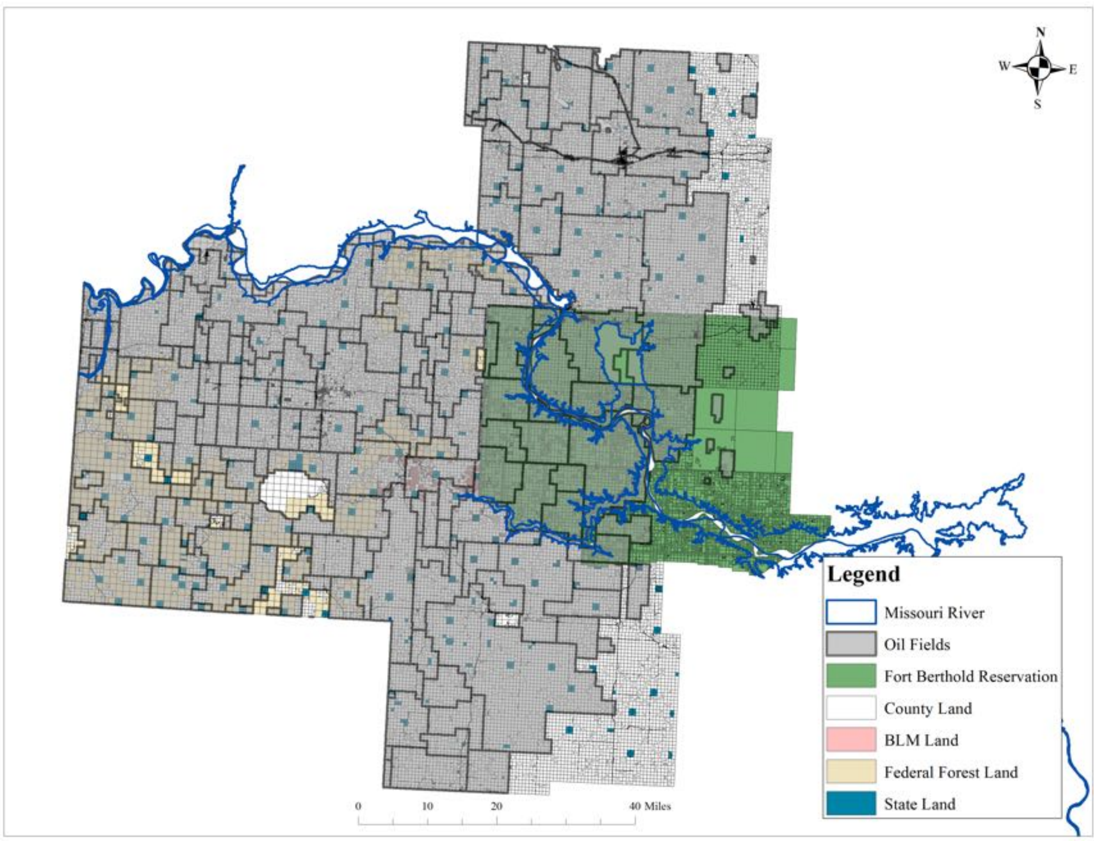
Figure 2.3 shows our study area, which is the Fort Berthold reservation and the surrounding shale-endowed counties of Dunn, McKenzie, and Mountrail. Today, there are several active shale oil fields in this area as defined by the North Dakota Oil and Gas Commission. These are relatively homogenous areas of terrain beneath which shale can be extracted in amounts that justify drilling. Figure 2.3 also shows that some land in our study area is owned by North Dakota, the U.S. forest service, and the U.S. Bureau of Land Management (BLM). The state trust lands were granted from the federal government in 1889 and are typically sections 16 and 36 of every township. The forest service and BLM land comprise failed homesteads, many that were purchased back during the 1930s. The forest service land mostly comprises the Dakota Prairie Grasslands: it is managed for wildlife and recreation and drilling for oil there is constrained.

Fort Berthold was established in 1851 by treaty. Though the treaty established a reservation of over 12 million acres for three tribes—the Arikara, Mandan, and Hidatsa—subsequent policies reduced the reservation to its contemporary size of 988,000 acres.

[20]These reservations include Blackfeet in 1919; Crow in 1920; Fort Peck in 1920 and 1927; Fort Belknap in 1921; Northern Cheyenne in 1926; and Wind River in 1928 (Ambler, 1990).

Congress approved Fort Berthold for allotment in 1894, and the northeastern section was opened for surplus homesteading settlement in 1910. The surface and subsurface rights in the surplus section were quickly privatized (see Figure 2.4).[21] The majority of Fort Berthold was allotted but not released from trust. Some allotted parcels were later privatized (Figure 2.4).

Figure 2.3: Study Area: Fort Berthold and Surround Counties with Oil Fields



Notes: This map depicts parcel boundaries and present-day oil fields on the Fort Berthold Indian Reservation and surrounding counties. The surrounding counties are Dunn, McKenzie, and Mountrail. Data on oil fields come from the North Dakota Oil and Gas Commission.

[21] Land in the surplus section was closer to a late 19th century railroad line, and it has a gentle slope, suggesting it was of higher agricultural value than the rest of the reservation. Although not the focus of our present study, this observation is consistent with studies of land privatization which emphasize the endogenous selection of lands for privatization (Besley, 1995; Galiani and Schargrodsky, 2010; Field, 2005; Akee and Jorgensen, 2014).

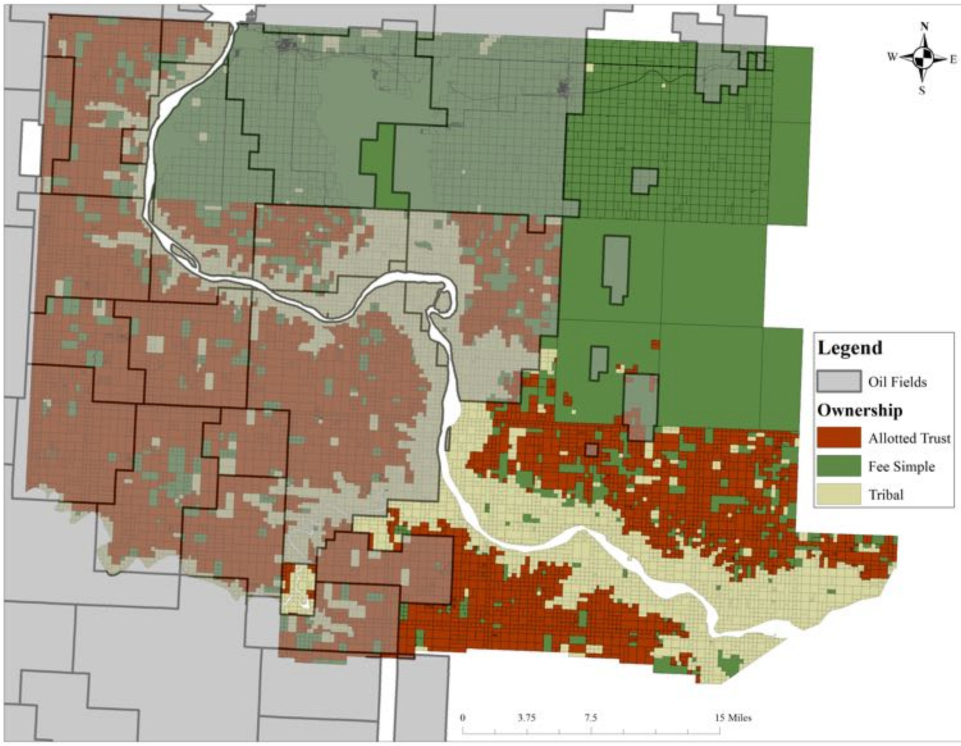
After the allotment era, 150,000 acres of land reverted back to tribal ownership when the reservation was flooded for an Army Corp of Engineers dam project in 1951. This Garrison Dam project was controversial and it forced the relocation of families off of allotted trust land near the Missouri River and into other areas of the reservation. The Garrison Dam episode explains why so much of the tribally owned shale today is by the river (Figure 2.4); some of the land is dry now but it was in the original flood basin. Today, the reservation is a mosaic of tenure—privatized parcels (i.e., "fee simple"), allotted trust, and tribal. Within the part of the reservation that is on an oil field, there are 285,651 acres of allotted mineral tenure, 176,820 acres of fee simple tenure, and 109,016 acres of tribal tenure.

The variation in Fort Berthold parcel sizes and tenure are plausibly exogenous to the quality of shale beneath because this variation resulted from historical processes that were unrelated to shale oil, which became profitable only recently. Moreover, the reservation was established, allotted, and opened for surplus settlement long before even conventional oil and gas was discovered. As Ambler (1990, p. 42-43) notes: "When it surveyed [Fort Berthold] in the 1910s, the U.S. Geological Survey found no oil and gas potential, which is not surprising because oil and gas was not discovered in the state until 1951." The Garrison Dam project was approved in 1947, also before the discovery of oil.

2.3.3 Statistical Comparisons of Ownership and Shale Quality

Although ownership patterns were not intentionally selected based on shale endowments, the process may have unintentionally biased some patterns towards higher quality

Figure 2.4: Parcels and Mineral Tenure on Fort Berthold Reservation



Notes: This map depicts parcel boundaries, oil fields, and mineral tenure types on the Fort Berthold Indian Reservations. The surrounding counties are Dunn, McKenzie, and Mountrail. The data sources are described in Table 2.2. The areas lacking parcel boundaries are areas for which parcel level data are lacking.

shale. We investigate this possibility empirically by examining how shale thickness and depth correspond to tenure, parcel sizes, and shapes. In general, thicker shale holds more oil. Shale depth can be important too, because drilling costs tend to rise with greater depth. For these reasons, we follow the lead of Weber et al. (2014), by measuring the economic quality of shale with its thickness-to-depth ratio at the parcel level. We first multiply thickness by 100 to reduce the number of decimal places in the regression below. For parcels within an oil field, this variable ranges from 0.13 to 1.82 with a mean of 0.98. Off of oil fields, the variable has mean of 0.85.[22]

[22]The thickness and depth data come in the form of contour lines. To convert those data to numerical values, we employed the "Topo to Raster" interpolation tool in ArcGis. Shale thickness for parcels on

Panel A of Figure 2.5 shows the depth of the Bakken formation. Darker areas indicate deeper shale formations. Lighter areas in panel B indicate thicker shale. The visual evidence in Figure 2.5 indicates there is variation in the quality of shale within and across tenure types. Visually, it is difficult to detect any clear patterns of bias but we note the following. First, the western part of the reservation has deeper but thicker shale than the eastern part. Second, the northern part of the reservation covers relatively thick shale.

To evaluate the exogeneity of shale quality, we run parcel-level regressions with thickness-to-depth as the dependent variable. The full data set consists of 51,083 parcels but we constrain our attention to the 41,979 parcels on oil fields, which are depicted in figures 2 and 3. For the reservation, we obtained parcel-level GIS data on mineral tenure for allotted and tribal parcels from the Bureau of Indian Affairs (BIA) in addition to GIS data on which areas of the reservation have fee simple mineral rights. Because the BIA does not identify the parcel boundaries for fee parcels, we overlapped the reservation tenure files with GIS data on parcels for Dunn, McKenzie, and Mountrail counties to fill in the missing parcel boundaries. We explain the data set and sources in more detail in section V.

We estimate Equation 2.1 using OLS, where i indicates the parcel and j is one of the 203 oil fields spanning the 41,979 parcels. The variable Tenure encompasses allotted trust, fee simple, forest service, BLM, and state lands. The variable Acres represents the size of the parcel. The variable Longside is a measure of parcel shape. It is the length of

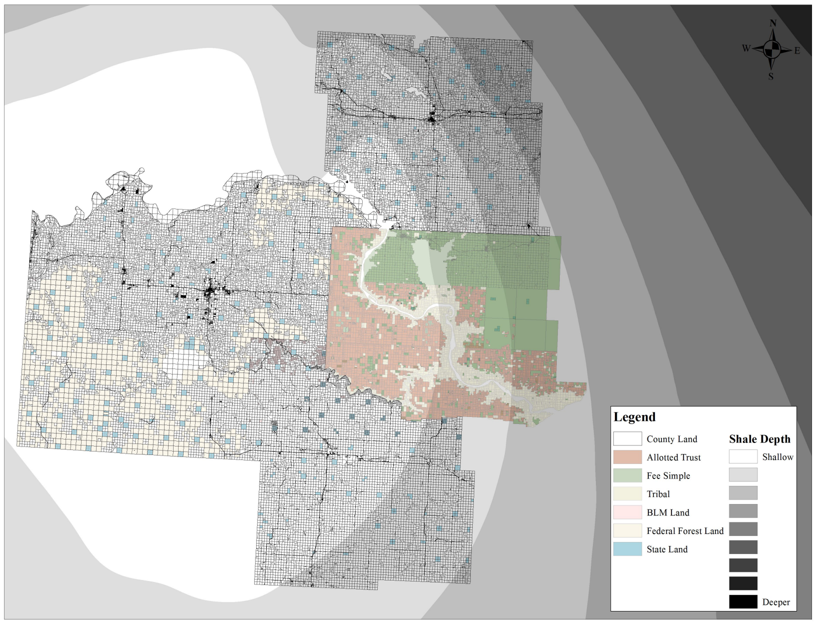
an oil field ranges from 10.6 to 141.9 with a mean of 78.4 feet. Shale depth ranges from 5,494 to 8,644 feet with a mean of 8,070.

the parcels' longest side, in miles. Holding constant parcel acres, an increase in Longside means the parcel is skinnier (e.g., progressively more linear than square).

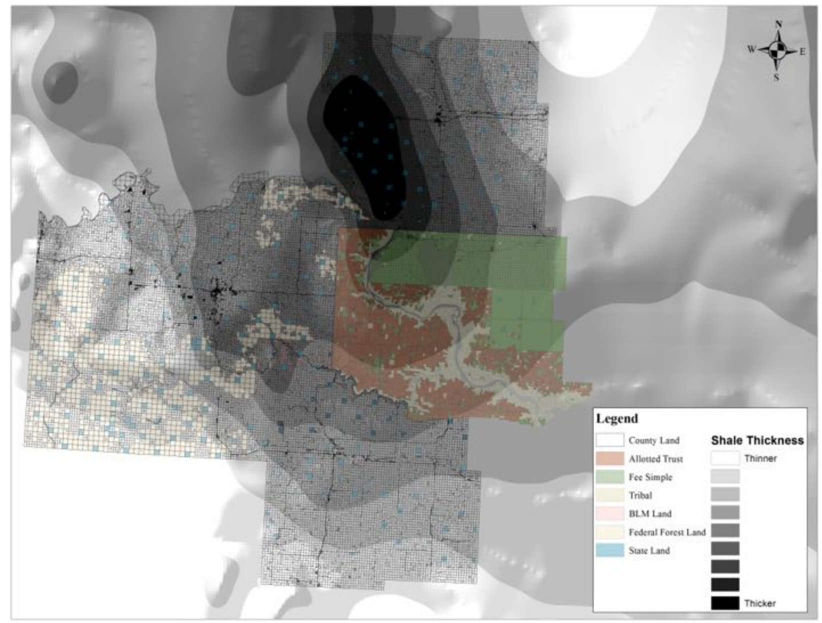
$$Thick - to - Depth_{ij} = \alpha_j + \gamma Tenure_{ij} + Acres_{ij} + Longside_{ij} + \varepsilon_{ij} \qquad (2.1)$$

Table 2.1 presents the estimates. The even numbered columns include oil field fixed effects and the odd numbered columns do not. The omitted category in the odd-numbered columns is private parcels off the reservation. The omitted category in the even numbered models is a private parcel, off reservation, in oil field 1.

Figure 2.5: Shale Depth and Thickness



(a) **Shale Depth**



(b) **Shale Thickness**

Notes: Panel A (on the left) depicts the depth of shale in the Bakken formation, with the darker shades indicating thicker shale. Panel B (on the right) illustrates the thickness of the shale, with lighter shades indicating thicker shale. The data are based on GIS data provided by the U.S. Energy Information Administrative office.

Table 2.1: **Correlations between Thickness-to-Depth and Parcel Characteristics**

	Across Fields (1)	Within Fields (2)	Across Fields (3)	Within Fields (4)	Across Fields (5)	Within Fields (6)
Fee	0.348***	0.0259			0.325***	0.0236
	(0.0882)	(0.0185)			(0.0823)	(0.0195)
Allotted Trust	0.139**	0.0241			0.134**	0.0224
	(0.0535)	(0.0175)			(0.0517)	(0.0182)
Tribal	0.181***	0.0235			0.165***	0.0205
	(0.0555)	(0.0159)			(0.181)	(0.0107)
State	0.00875	-0.001			0.043	0.00236
	(0.0348)	(0.00574)			(0.0358)	(0.00627)
U.S. Forest Service	-0.316***	-0.00164			-0.181***	0.0107
	(0.0744)	(0.00467)			(0.0687)	(0.00838)
U.S. BLM	0.0208	0.0104			-0.00636	0.00736
	(0.0452)	(0.0127)			(0.0452)	(0.0126)
Parcel Acres			-0.000516***	-0.0000311	-0.000277***	-0.0000378
			(0.000123)	(0.0000216)	(0.000102)	(0.0000269)
Longside			-0.0937**	-0.00596	-0.0748**	-0.00455
			(0.0426)	(0.00751)	(0.035)	(0.00770)
Constant	0.937***	0.255***	1.066***	0.279***	0.993***	0.271***
	(0.0471)	(0.0047)	(0.046)	(0.0130)	(0.0507)	(0.0103)
Oil Field Fixed Effects	No	Yes	No	Yes	No	Yes
N	41979	41979	41979	41979	41979	41979
Adjusted R^2	0.121	0.955	0.052	0.955	0.138	0.955

Standard errors are clustered by oil field and reported in parentheses.
* $p < .1$, ** $p < .05$, *** $p < .01$

The results in the odd numbered columns reveal systematic relationships between shale quality and ownership across oil fields. The results in columns 1 and 5, for example, suggest that average shale quality on the reservation exceeds average quality off the reservation, and that fee parcels tend to be endowed with the highest quality shale. Columns 3 and 5 show that larger, skinnier parcels sit above lower quality shale

By contrast, results in the even numbered columns demonstrate no statistically significant relationships within oil fields, which are relatively homogeneous spatial units by design. This is an important consideration for testing hypotheses about the causal effects of ownership on oil drilling patterns. In our tests, which appear in section V, the empirical specifications that include oil field effects are most credible.

To summarize, the inadvertent subdivision of shale created variation in tenure, parcel sizes, and parcel shapes that we expect to influence the speed and probability of horizontal drilling, based on anticommons logic. Moreover, the variation is verifiably exogenous to a critical measure of shale quality, within oil fields. We exploit these natural experiments in shale ownership in the section V tests.

2.4 Theoretical Motivation for Empirical Tests

In this section we integrate the anticommons literature (section II) with details about contracting for horizontal drilling in order to formulate hypotheses about the effects of subdivision and tenure on drilling in our study area. We begin with a description of drilling, in order to define the technologically optimal length of a horizontal line, h^*. This concept is analogous to L in section II, in that both refer to the scale of profitable extraction.

2.4.1 Technological Costs

Although hydraulic fracturing (fracking) and horizontal drilling were experimented with on a small scale for several decades, their large-scale use did not emerge in the United States until about 2005 (Zuckerman, 2013). The technology makes oil trapped in tight shale formations profitable. A well is first drilled vertically from a main well pad to the depth of the shale, which runs approximately parallel to the surface and holds the trapped oil. The well line is then turned horizontally and driven for typically several thousand feet through the shale. When hydraulic fracturing is added to horizontal drilling, as is the case in the Bakken, a liquid solution is pumped at high pressure through the well. The pressure fractures the shale, thereby facilitating oil drainage. Oil is pumped out of the well until the area around the horizontal portion of the well is mostly drained. At that time, the well is either plugged, or drilling at a different depth within the shale commences.

The economic costs of horizontal drilling comprise two main components, aside from leasing. First, there is a large fixed cost of drilling the well associated with employing the necessary labor and capital (a drilling rig) and creating the necessary infrastructure (e.g., pipeline, waste water impoundment facilities, compression stations).[23] Second, there is a marginal cost of extending horizontal distance into the shale. This marginal cost increases with distance, at least on a per unit of oil drained basis (see Syed 2014). One reason is that it becomes increasingly difficult to "steer" the line with increased distance. The second reason is that steering and capturing oil requires an increasing amount of pressure as horizontal distance increases.[24]

To set the stage for understanding contracting costs, we consider a simple benchmark for optimal line length in a world of zero transaction costs. Consider a linear landscape

[23]This cost is roughly in the range of about $10 million for a well in the Bakken formation.

[24]We are simplifying the technology; in reality production per horizontal foot generally declines with distance (Syed, 2014), but we argue this can be modeled as rising marginal costs per unit of oil captured because the decline in productivity can be offset by increased input use (such as care, time, fluids, energy usage, etc.) There is also a marginal cost of drilling depth that we ignore here. This marginal cost tends to increase linearly with depth (Syed, 2014).

endowed with shale of distance D. Assume constant production per unit distance, denoted by q. The oil extracted is homogeneous in quality and sells for an exogenously determined and constant unit price, p. Profit maximization involves choosing the number of wells to drill (w), which implicitly involves choosing horizontal line length per well (h). Profit is given by: $\pi = pqD - w(k + c(h))$, where k is the fixed cost per well and $c(h)$ is a cost function of line distance that is increasing at an increasing rate. The convexity of the cost function implies a solution for length per well, h^* that trades-off the fixed cost of drilling additional wells versus the rising marginal cost of line length. In this framework, the length of line that minimizes total costs (h^*) increases with the fixed cost. Drilling will occur if $\pi(h^*) > 0$.

To motivate why some areas of shale are drilled before others, we imagine J different sections of shale, each of length h^*. The areas of shale differ in quality, such that $q_{j \neq q_m}$, for $j \neq m$. If $q_j > q_m$, then $\pi_j(h^*) > \pi_m(h^*)$. If a fixed capital input is scarce in supply (e.g., large drilling rigs),[25] there is a positive time discount rate on profits, and $\pi_j(h^*) > 0$, then drilling should occur in shale area j before shale area m.

2.4.2 Number of Exclusion Rights

Oil companies need to contract with shale owners, and this will raise the oil developer's costs of drilling and lower his realized revenue. The contracting costs are critically related to N, the number of exclusion rights holders over the horizontal line. Holding constant the length of the line, h^*, the number of exclusion rights depends on the degree of subdivision

[25] Our discussions with oil industry experts indicate that drilling rigs are in scarce supply on booming oil fields.

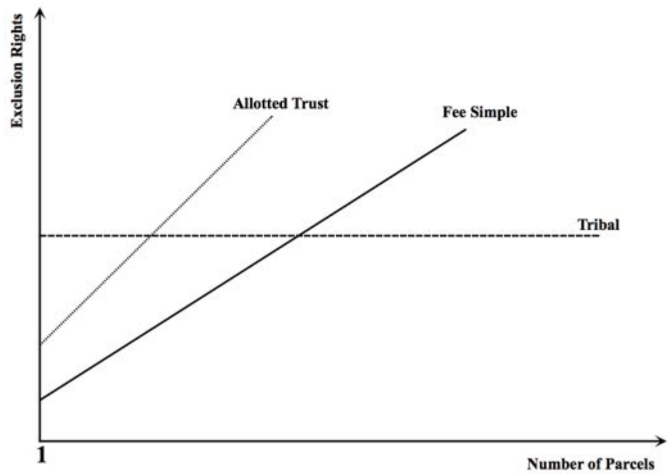
and on tenure type. As fee simple parcels become smaller, the number of exclusion rights increase by one owner for each parcel added. Assuming there are on average z owners per allotted trust parcel, each additional allotted trust parcel requires contracting with an additional z users. In contrast, adding tribal parcels to a project already taking place on tribal land adds zero new holders of exclusion rights to contract with.

Figure 2.6 illustrates how the number of exclusion rights over h^* increase with the number of parcels. The slope of the fee simple line is one, representing our assumption that fee simple parcels have one owner. The slope of the allotted trust line is steeper, because the average allotted trust parcel has $z > 1$ owners. The slope of the tribal line is zero, because tribal parcels share a common owner so that "parcelization" does not add exclusion rights.

The vertical intercepts in Figure 2.6 depict the number of excluders for whom consent would be needed if the entire horizontal line was under a single, large parcel. To think about this issue, it is useful to consider the collective action problems of government decision making, and the fact that many agencies are often involved in granting drilling permits such as the Bureau of Indian Affairs, the U.S. Bureau of Land Management, and the North Dakota Oil and Gas Commission (Regan and Anderosn, 2014; Kunce et al., 2002). Importantly, drilling the vertical portion of a horizontal well disturbs the surface in ways that may extend jurisdiction over permitting to more agencies.

Turning back to Figure 2.6, we argue the number of exclusion rights governing the vertical portion tends to be greatest for tribal parcels and lowest for private, fee parcels. For fee parcels, the parcel owner must grant permission and a permit is required by North

Figure 2.6: Number of Exclusion Rights over Horizontal Line of Length h^*



Dakota.[26] For allotted parcels, multiple owners of the single parcel must grant permission and permits are required by multiple federal agencies.[27] For tribal parcels, multiple tribal agencies may be involved—especially if there are archaeological and cultural considerations regarding surface disturbances—and permits are required by multiple federal agencies.

2.4.3 Contracting Costs of Horizontal Drilling

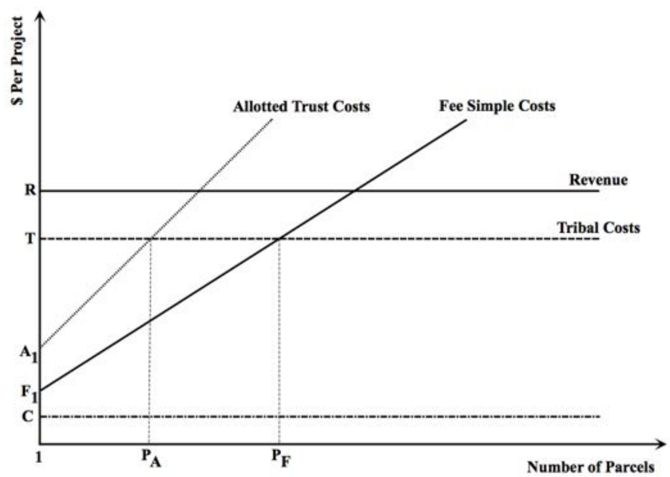
To motivate our empirical tests, we connect the number of exclusion rights holders just described to the costs of contracting with those holders. To develop this connection, we assume that contracting costs rise with the number of exclusion rights holders (N) over

[26]Although surface owners have no legal standing to stop a drilling project, they typically must be negotiated with because the oil developer needs to place infrastructure such as pipelines, compressor stations, and water impoundment facilities next to the main vertical well pad. Payments for allowing this infrastructure one-time payments that can be large; in some areas of horizontal gas fracking development, for example, landowner payments for compressor stations has ranged from hundreds of thousands to millions of dollars and payments for water impoundment construction has ranged from $40,000 to $70,000 (Boslett et al., 2014).

[27]Drilling under allotted trust land does not formally require permission from the state of North Dakota but the oil and gas regulations of the state and the permitting process is generally followed.

shale length h^*. Contracting costs include title searches to find owners, and legal costs of writing and recording formal leases.[28] These costs should increase with N, plausibly in a linear way as drawn in Figure 2.7. The vertical axis shows revenue and total costs per drilling project. The technological costs of drilling the well are $C = k + c(h^*)$. The labels F_1 and A_1 refer to the cost of a project contained within a single large fee and allotted trust parcel, respectively. The total costs of drilling rise with subdivision, which is characterized in Figure 2.7 by increases in parcels per h^* on the horizontal axis. The revenue line assumes homogeneous shale quality and a fixed output price paid for oil.

Figure 2.7: Revenue and Costs Per-Drilling Project of Length h^*



In Figure 2.7, whether or not a project is inherently profitable, net of contracting costs, depends on tenure and subdivision. There are P_A profitable projects under allotted land and P_F profitable projects under fee lands. All projects under tribal land are profitable by assumption. The economic rent available from each drilling project is the vertical distance between the revenue and cost lines. If we assume a competitive oil industry,

[28]These costs are typically borne via payments to so-called "landmen." These are agents whom oil companies hire to find rights holders and negotiate leases with them.

then rents are earned by shale owners, in this context through their negotiations of higher royalty payments. Note that contracting costs that rise with N dissipate rents rather than simply redistributing them across oil companies and shale owners.

Assuming there is a scarce input (e.g., drilling rigs) and positive time discounting, Figure 2.7 allows us to predict the timing of oil drilling projects. As long as oil companies receive a small epsilon percentage of the available rent, they will drill the least subdivided fee parcels first, starting with the single fee parcel case and ending when the height of the "fee simple cost" line reaches A_1. After this point, drilling between areas of fee and areas of allotted parcels will oscillate until the Allotted Trust Costs and the Fee Simple Costs reach the height of T. Once the fee land is sufficiently subdivided such that the Fee Simple Costs exceed Tribal Costs, drilling will exclusively take place under tribal land. The logic is that drilling will be prioritized over sections of shale for which aggregate rents are highest. Contracting costs prevent or delay drilling by lowering the aggregate available rent.

In addition to reducing aggregate available rents, subdivision may encourage shale owners to engage in wasteful competition over the distribution of rents. The problem is that each shale owner has holdup power to leverage in bargaining over his individual royalty amount. Royalty payments vary depending on an owner's success in negotiating, but have averaged around 17% in North Dakota in recent years (Brown et al., 2015). Holding out for a higher royalty percentage may be individually rational, but it is collectively wasteful if holdups raise the aggregate, well-level royalty rate demanded by owners to a level above the rate a profitable drilling project can bear. In this case, the shale would not be drilled even though available rent is positive, leading to an anti-commons problem of underutilization as in (Buchanan and Yoon, 2000), but stylized to the context of horizontal drilling by a competitive oil industry.

To conclude, subdivision and allotted trust tenure can prevent and delay shale drilling for two reasons. First, by raising the number of exclusion right holders; available aggregate rents will fall due to higher contracting costs and make projects with more owners less desirable. This is a sufficient condition for delays and drilling prevention as illustrated in Figure 2.7. Second, if holdup incentives increase with N, then competition over the distribution of rents may cause requested royalty rates to rise with N, which could be modeled as steepening the fee simple and allotted trust cost lines in Figure 2.7. With a competitive oil industry, however, the aggregate royalty rate paid to shale owners cannot rise with N.

Finally, before proceeding, we note there have been two institutional responses to the contracting problems we describe here. First, forced pooling laws are in force in North Dakota and in other U.S. states. Forced pooling compels minority mineral owners into horizontal drilling projects if a majority of neighboring acreage in an oil drilling unit has already been leased. State-level forced pooling laws do not generally apply on sovereign Indian reservations (see Slade et al. (1996)). Second, a 1998 federal law specific to the Fort Berthold requires the consent of only a majority of owners of allotted trust lands before a mineral lease can be executed. We view these institutional responses as decreasing but not eliminating contracting costs and holdup problems because they reduce the number of contracting parties, but not down to the level of sole ownership.

2.5 Parcel-Level Empirical Tests

In this section we test for the importance of contracting costs using parcel-level data. In the next section we employ oil well-level data. The main advantage of using parcel-level data is that it allows us to exploit information contained in the "zeroes" (i.e., the parcels above shale that have not yet been drilled). We explain the relative advantages of using the well-level data below.

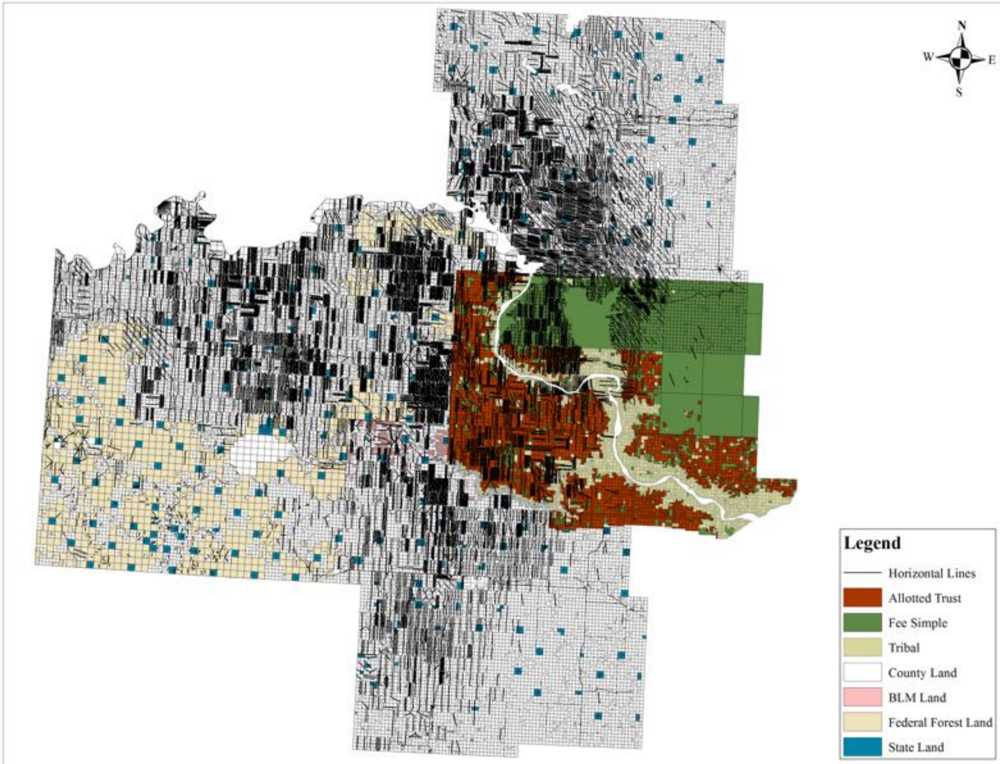
2.5.1 Parcel-Level Data

The parcel-level data set, as displayed in Figure 2.3, spans Fort Berthold and neighboring counties. We trim the initial sample of 50,572 parcels to the subset of parcels located on oil fields. This criterion reduces the sample size to 43,166.

The source for data on drilling is the North Dakota's Oil and Gas Commission website. It contains GIS data for every horizontal well bore, and for every horizontal well line, that has been drilled in the state. Figure 2.8 shows the location of well bores which are the vertical portion of a horizontal well. It also shows the location of horizontal lines. We downloaded these data in May 2015, and they represent the accumulation of wells completed as of May 1, 2015. We have also obtained data on the date in which each well was completed, with the drilling boom roughly spanning 2005 to the present. During this 10-year period, 7,864 horizontal wells were drilled in our study area spanning 12,017 line miles.

Table 2.2 shows summary statistics of the parcel-level outcome variables that we have constructed and Figure 2.9 illustrates our mapping from the spatial data to the

Figure 2.8: Location of Horizontal Well Bores and Lines in Study Area



Notes: This map depicts the location all horizontal oil wells ever drilled, and lines emanating from horizontal wells, based on data from the North Dakota Oil and Gas Commission.

variables. The outcome variables measure the timing and extent to which a parcel has been exploited. Approximately 41.6 percent of the sample parcels have been cut by at least one horizontal line. Having a horizontal line is our best proxy for whether or not the owner(s) have received financial payment for their shale.[29] The first line crossed each parcel an average of 2,324 days after January 1, 2005, conditional on the parcel having at least one line through it by May 1, 2015. We measure the extent of drilling through a parcel by the miles of horizontal lines. Some parcels are drilled multiple times from

[29]In some unusual cases, it is possible for an owner to receive compensation if a line does not cross his parcel. Compensation is based on membership in an oil drilling unit, and sometimes a line does not cross every member's parcel. Lines usually cross every parcel in a unit, with the exception of very small parcels. We discuss unitization in more detail below.

multiple directions or at different depths. The mean number of line miles per parcel is 0.27. The presence of a well bore on the parcel is an indication that the surface owner has received payment for accommodating drilling infrastructure. Approximately 7.9 percent of the parcels have at least one well bore.

We include measures of parcel size, shape, and tenure to proxy variation in contracting costs. The variable Parcel Longside measures the length of a parcel's longest side. Holding constant the parcel's acreage, an increase in the longside means the parcel has a longer and skinnier shape. The other variables indicate the ownership and tenure of the parcel.[30] Not included in the summary statistics are indicators for parcels owned by the U.S. forest service, the U.S. Bureau of Land Management, and the state of North Dakota. These categories collectively comprise 4.7 percent of the sample parcels.

To assess the effects of subdivision and tenure mixes around a parcel, we focus on parcels within a 1-mile radius of each parcel's centroid (see Figure 2.9). We choose the 1-mile radius because lines from well bores typically extend 1 to 2 miles but our results are robust to other distance choices.[31] Within the 1-mile radius, the number of

[30]The parcels represent oil ownership on the Fort Berthold reservation. The parcels off the reservation represent surface ownership, because we do not have data on off-reservation mineral rights. Surface and mineral ownership were generally aligned before oil development, because much of the land in North Dakota was settled before the Homestead Act of 1916, which reserved subsurface mineral rights to homesteaded land settled thereafter to the United States.

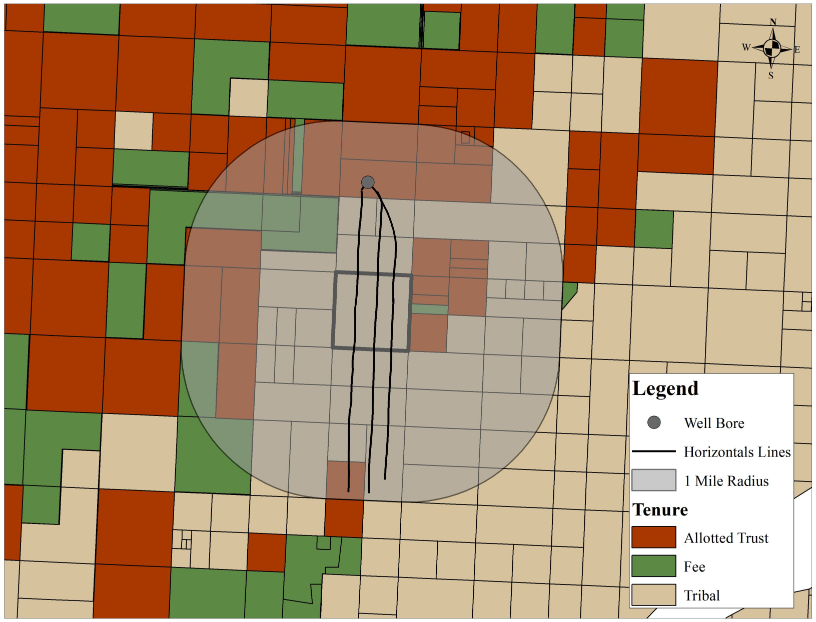
[31]An alternative approach is to conduct analysis at the level of an oil spacing unit. Unitization laws require the driller to define a "unit," which is a contiguous area of minerals that will be exploited. Royalty compensation to each mineral owner is determined by their percentage of acres in a unit. While analyzing unitization data from the North Dakota Oil and Gas Commission, we discovered that these are not good candidates for our spatial observations because their definition is highly endogenous. Unit sizes vary in size over time; from a low of 160 acres to a high of 5120 acres. As of 2015, the most prevalent unit sizes were 1280 acres and 640 acres. These units are typically rectangular rather than square, reflecting the fact that wells are drilled over long narrow swaths of space. However, oil units are highly fungible on the Bakken and they change definitions frequently, as new parcels are appended and other parcels eliminated. Most parcels in the Bakken have been part of multiple units over time, sometimes as many as 20. This fungibility of units in the case of horizontal shale drilling is much different than unitization over traditional oil reservoirs (Libecap and Wiggins, 1984; Wiggins and Libecap, 1985).

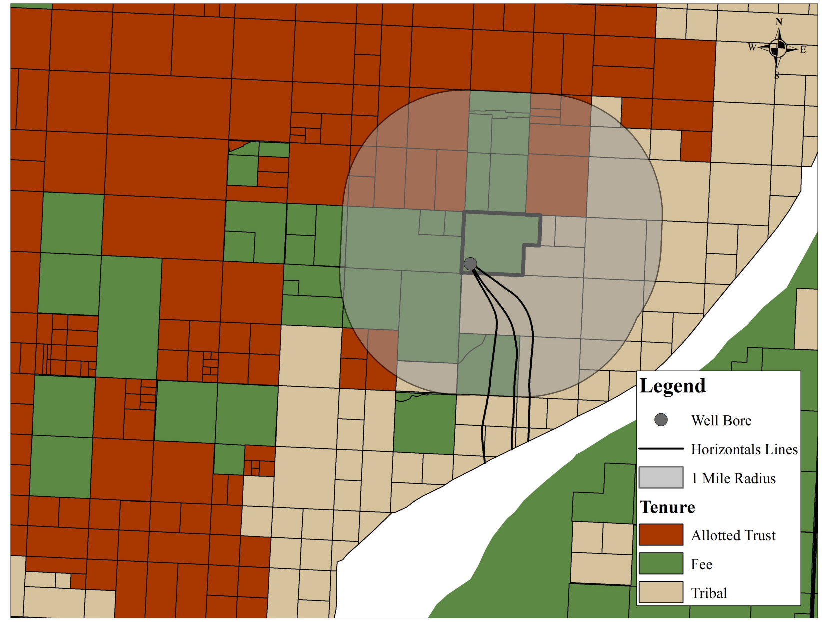
neighboring parcels ranges from 4 to 1000. Note that the data sets treat government tracts, including tribal tracts, as multiple separate parcels, even though the tracts have a single government agency owner. Some mineral parcels are under a body of water, based on the high flood lines of the Missouri River. We control for this in the regressions, to account for special rules governing drilling under water.

We create a variable to measure the mix of tenure types around a parcel. The variable "Extra Tenure Regimes" is the number of tenure types represented by the block of parcels adjacent to the parcel. For example, a fee-simple parcel adjacent to fee, tribal, and allotted trust land has two extra regime types in its neighborhood. Figure 2.9 illustrates.

Finally, we have collected data to measure a variety of parcel-level factors that may influence the net value of extracting oil. One of these variables is the shale's thickness-to-depth ratio discussed above. We have created a "topographical roughness" variable to account for potentially higher costs of drilling through rough terrain. We have also created variables measuring the distance from each parcel's centroid to the nearest body of water (zero if the parcel is under water), and to the nearest railroad. We measure infrastructure in the neighborhood around a parcel with the miles of roads in a 1 mile radius. Finally, although not shown in Table 2.2, we include the spatial X-Y coordinates of a parcel in some specifications to control for possible South-North and West-East patterns in drilling.

Figure 2.9: Examples of our Mapping from Spatial Data to Empirical Variables





Notes: These images illustrate how we have constructed our empirical variables. For the parcel-level analysis, parcel i is in bold. The dependent variables include the timing of the first line under parcel i, the miles of line penetrating parcel i, and indicators for whether or not a vertical well bore is found on parcel i. In the Ffgure on the left, there are lines through parcel i but not a well bore. In the figure on the right, there are lines and a well bore on parcel i. The number of neighboring parcels includes all parcels that are contained within or touch the exterior boundary of the radius. The number of extra regimes is measured by the count of different tenure types that are directly adjacent to parcel i. For the well-level regressions, the key dependent variables measure the date in which the entire well (bore plus lines) was completed. The other dependent variable in the well-level regressions measures the total length of the lines emanating from the well bore. The key right-hand side variables in the well-level regressions measure the tenure of the parcel containing the well bore, and the number and tenure of the parcels through which the well lines penetrate. The images above do not show all of the wells and lines in the area, in order to keep the images more simple and informative. Figure D1 in the appendix shows the same images, along with other lines and wells in the mapped areas.

Table 2.2: Summary Statistics from Parcel-Level Data Set

Variable Names	Mean	S.D.	Min	Max	Definition
Outcome Variables					
Days until First Horizontal Line[a]	3168.96	857.56	13	3772	Days elapsed between January 1, 2005 and date of first line; censored at 3772 days if no line
Horizontal Line Indicator[a]	0.4163	0.4929	0	1	=1 if the parcel was cut by at least one horizontal line as of May 1, 2015, otherwise = 0
Miles of Horizontal Lines[a]	0.2784	0.5584	0	10.47	The total length (miles) of horizontal lines cutting a parcel as of May 1, 2015
Horizontal Line Miles/100 Acres[a]	0.4008	3.6415	0	515.87	The total length (miles) of horizontal lines cutting a parcel as of May 1, 2015, per 100 square miles
Well Bore indicator[a]	0.0796	0.2701	0	1	=1 if the parcel had at least one (vertical) well bore as of May 1, 2015, otherwise = 0
Well Boresa	0.1822	0.8412	0	30	The number of (vertical) well bores as of May 1, 2015, otherwise = 0
Parcel Size, Shape, and Tenure					
Parcel Acres[b,c]	79.402	98.197	5.16E-09	1259.9	Area of the parcel, in acres
Parcel Longside[b,c]	0.4273	0.3553	9.25E-06	8.046	The length of a parcel's longest side, in miles
Reservation Parcel Indicator[b]	0.2419	0.4283	0	1	=1 if the parcel is on the Fort Berthold Indian reservation, otherwise =0
Fee Parcel Indicator[b]	0.0991	0.2988	0	1	=1 if the reservation parcel is fee simple, otherwise =0
Allotted Trust Parcel Indicator[b]	0.0911	0.2877	0	1	=1 if the reservation parcel is allotted but not alienated from trust, otherwise =0
Tribal Parcel Indicator[b]	0.0517	0.2988	0	1	=1 if the reservation parcel is tribally owned, otherwise =0
Neighbor Parcels (1-mile radius)					
No. of Neighbors	153.92	251.22	4	1000	Number of parcels within 1 mile radius around parcel
St. Deviation of Neighbor Size	9.9673	9.3553	0.0196	119.27	Standard deviation of parcel acreage within 1 mile radius around parcel
Off Res. Neighbors[b,c]	104.66	212.27	0	993	Number of private parcels, off the reservation, within 1 mile radius around parcel
Fee Neighbors[b,c]	37.307	165.8	0	1000	Number of fee parcels within 1 mile radius around parcel
Allotted Trust Neighbors[b,c]	5.7433	14.327	0	131	Number of fractionated parcels within 1 mile radius around parcel
Tribal Neighbors[b,c]	4.0566	12.073	0	104	Number of tribal parcels within a 1 mile radius around parcel
Neighbors Underwater[f]	4.9241	14.869	0	119	Number of parcels under a body of water within 1 mile radius around parcel
Extra Tenure Regimes[b,c]	0.2805	0.57	0	6	No. of extra tenure types adjacent to parcel (off res, fee, fractionated, tribal, USFS, BLM, state)
Other Covariates					
Thick-Depth Ratio[d]	0.0098	0.0034	0.0013	0.0182	Shale thickness divided by shale depth
Topographic Roughness					Std. Dev. of slope multiplied by average slope
Feet to Water (000s)[f]	12.231	10.313	0	43.759	Euclidean distance (in 000s of feet) from parcel centroid to nearest body of water
Feet to Railroad (000s)[f]	14.078	11.851	0	57.403	Euclidean distance (in 000s of feet) from parcel centroid to nearest railroad line
City Indicator	0.1042	0.3056	0	1	= 1 if the parcel is within a city boundary, otherwise = 0
Road miles in 1-mile radius[f]	8.7415	18.626	0.0967	57.4	Number of road miles within 1 mile radius of parcel centroid, divided by area

Notes: This table summarizes data for all parcels over an oil field. N = 43,166 for all variables except the Thick-Depth Ratio, which is N = 41,376. Data sources are: a) North Dakota Oil and Gas Commission website, b) U.S. Bureau of Indian Affairs, c) Real Estate Portal, d) U.S. EIA website e) Authors calculations from a National Elevation Dataset, and f) Authors calculations from North Dakota GIS Portal data.

2.5.2 Tests for Effects of Subdivision on Drilling Delays

We begin by estimating the following latent-variable regression model, using the parcel level data set.

$$Days_{ij} = \alpha_j + \phi Acre_{ij} + \mu Longside_{ij} + \beta No.Neigh_{ij} + \delta Std.Neigh_{ij} + \lambda Res + \gamma X_{ij} + \varepsilon_{ij} \tag{2.2}$$

The dependent variable is the number of days elapsed since January 1, 2005 until a line penetrated the parcel. Because this variable is censored at 3,772 days, we use a Tobit estimator. Here i = parcel, j = oil field, the notation α_j represents the 203 oil field fixed effects, and the notation X_{ij} indicates the covariates. We include oil field fixed effects because our Section 2.3 analysis indicates that shale ownership is more plausibly exogenous to shale quality within rather than across oil fields.

The coefficient estimates of ϕ, μ, β, and δ are of key interest. We expect $\phi < 0$ and $\mu < 0$. In words, we expect shorter delays on larger, rectangular parcels because oil companies can limit the number of contracting parties by focusing first on these parcels. We expect $\beta > 0$, meaning the length of drilling delays will increase with greater parcel subdivision in the radius around parcel i. We anticipate $\delta > 0$ if more heterogeneity in parcel sizes raises the costs of negotiating leases with heterogeneous resource owners.[32] For identification of these coefficients, we rely on the exogeneity of parcel size, shape, and tenure, conditional on the covariates and oil field fixed effects (see Section 2.3).

[32] In her studies of common pool resource use, Ostrom (1990) argues that heterogeneity in resource users raises the transaction costs of agreements.

Table 2.3: Parcel-Level Estimates of Days Elapsed between Start of Fracking Boom and First Horizontal Line

	Tobit Estimates Y = Days elapsed between Jan. 1, 2005 and first horizontal line (as of May 1, 2015)				*OLS Estimates* Y = 1 if at least one horizontal line cuts parcel	
	(1)	(2)	(3)	(4)	(5)	(6)
Parcel acres	-5.746***	-5.293***	-5.570***	-5.801***	0.0015***	0.0016***
	(0.618)	(0.59)	(0.633)	(0.737)	(0.0001)	(0.0001)
Parcel longside	-797.4***	-757.0***	-779.8***	-739.7***	0.212***	0.203***
	(103.9)	(94.53)	(95.7)	(95.01)	(0.0284)	(0.0292)
No. of neighbors	1.655***	6.389***	6.160***	6.042***	-0.0012***	-0.0012***
	(0.465)	(1.426)	(1.303)	(1.724)	(0.0002)	(0.0002)
St. dev. of neighbor size	26.03***	30.01***	27.72***	23.69**	-0.0062***	-0.0054**
	(6.844)	(7.452)	(7.006)	(9.525)	(0.0016)	(0.0022)
Reservation parcel indicator	450.7***	325.9***	117.5	96.01	0.0232	0.025
	(128.9)	(119.3)	(147.9)	(232.5)	(0.0351)	(0.0502)
Covariates						
Thickness-to-depth ratio	-102918***	-97947***	-152927***	-112904**	41.84***	33.12***
Feet to water (000s)	32.88***	34.65***	25.97***	33.11*	-0.00523***	-0.0107**
# Neighbors underwater	13.93***	12.25***	10.92***	13.55***	-0.00242**	-0.00349**
Topographic roughness	1.215*	1.179**	1.255**	0.747	-0.000363**	-0.000253*
City indicator		368.2**	275.0*	417.7**	0.00652	-0.057
Feet to railroad (000s)		7.676	8.286	24.72**	-0.000348	-0.00560*
Road density in radius		-68.66***	-62.80***	-63.92***	0.0134***	0.0139***
x coordinate of parcel			0.634***		-0.0003***	
y coordinate of parcel			0.333*		-0.00005	
Oil field fixed effects	No	No	No	Yes	No	Yes
Constant	4813.4***	4661.0***	-13655.6	5536.3***	3.353	0.123
Pseudo R-squared	0.038	0.04	0.041	0.05		
Adjusted R-squared					0.257	0.309
Observations	27,480	27,480	27,480	27,480	27,480	27,480
Censored at 3772 days	16,687	16,687	16,687	16,687	NA	NA

Notes: We do not show some standard errors in order to save space. A parcel's neighborhood includes all parcels touching a one-mile radius extending from the parcel's exterior boundary. All specifications control for the slight variation in the total area of the one mile radius, due to variation in the size of parcels on the exterior of the radius. Standard errors are clustered by oil field and shown in parentheses. * $p < .1$, ** $p < .05$, *** $p < .01$

Table 2.3 shows coefficient estimates. In all specifications we drop from the sample any parcel for which the 1-mile radius includes parcels owned by the USFS, the BLM, or the state of North Dakota. We drop these 13,792 parcels in our baseline specifications because rules on public lands—particularly the forest service tracts—limited fracking during our time period of analysis. Later we show the results are robust to keeping all government parcels in the sample. We also show that patterns of drilling on and around government parcels are similar to patterns on and around tribal parcels, suggesting our tribal findings may generalize to other governments. All of the standard errors in Table 2.3 are clustered by oil field but the results are robust to models that allow for other spatial error structures as discussed below.

Focusing first on columns 1-4 in Table 2.3, there are significant relationships between days elapsed and parcel acres, longside, number of neighbors, and the standard deviation of neighbors that are consistent with contracting cost rationales. The coefficients are also relatively insensitive to the inclusion or omission of different covariates and to oil field fixed effects, but our preferred estimates are in column 4. In terms of magnitude, the column 4 coefficient of -5.80 on parcel acres implies that a one standard deviation increase above the mean (i.e., from 79 to 177 acres) is associated with a 568 day decrease in time until drilling. The longside coefficient of -739.7 means a one standard deviation increase implies a 263 day decrease in time until drilling. The coefficient on the number-of-neighbors variable, which is 6.04, means that a one standard deviation increase implies a 1,516-day drilling delay. We quantify the meaning of delays in terms of foregone royalty income below, in Section 2.6.

The signs on the other coefficients in columns 1-4 are mostly as expected. Parcels with greater thickness-to-depth ratios were drilled earlier in time as were parcels in areas with greater road infrastructure. Parcels close to water were drilled later in time, if at all, as were parcels within city boundaries. These findings make sense because regulatory rules dissuade oil drilling in urban areas and in areas near bodies of water. The reservation parcel indicator is insignificant in columns 3 and 4, suggesting that being on the reservation is not, in general, a cause of drilling delays.

In columns 5 and 6 we estimate the probability that a parcel had at least one horizontal line by May 2015. The column 6 coefficient of -0.0012 means that a one standard deviation increase in the number of neighbors around a parcel i reduced the probability that the parcel would have a line by 30.1 percentage points. For perspective, 40.0 percent of the sample parcels had a line drilled by May 2015. Hence, an increase in one standard deviation in our measure of subdivision is associated with a 75.3 percent decline in the probability that a shale owner has been compensated.

2.5.3 Tests for Subdivision Effects Across Tenure Types

To test for different subdivision effects across tenure types, we now include four separate variables that decompose the Number of Neighbors variable into each tenure type: off reservation neighbors, fee neighbors, allotted trust neighbors, and tribal neighbors. We also decompose the reservation indicator variable into three separate indicator variables, one for each tenure type. We also include the Extra Tenure Regime variable, and estimate the following regression model.

$$Days_{ij} = \alpha_j + \phi Acres_{ij} + \mu Longside_{ij} + \beta_O OffNeigh_{ij} + \beta_F FeeNeigh_{ij} + ...$$

$$... + \beta_A ATrustNeigh_{ij} + \beta_T TribNeigh_{ij} + \delta StD.Neigh_{ij} + \rho XtraReg_{ij} + \lambda Fee_{ij} + ...$$

$$... + \lambda_A ATrust_{ij} + \lambda_T Trib_{ij} + \gamma X_{ij} \varepsilon_{ij} \quad (2.3)$$

The estimates of β_O, β_F, β_A, β_T, and ρ provide the tests. We expect $\beta_T < \beta_O \leq \beta_F < \beta_A$ and also expect $\beta_T = 0$ and $\beta_{-T} > 0$ for each of the non-tribal tenure types. To understand why we expect $\beta_T = 0$ and $\beta_T < \beta_O \leq \beta_F < \beta_A$, recall that our main theoretical argument is that divided shale ownership will delay and repress horizontal extraction because divided ownership raises contracting costs. The allotment of Fort Berthold resulted in three types of tenure with different numbers of exclusion rights per parcel. Based on our Section 2.4 discussion, we expect contracting costs to rise most quickly as the horizontal fracking line expands into allotted trust parcels, because the number of contracting parties increases at the fastest rate under this tenure system. At the other end of the continuum, adding tribal parcels to a project already taking place on tribal land adds zero new holders of exclusion rights to contract with and hence we predict that it does not raise contracting costs or delay drilling.

There is also contracting rationale motivating the prediction that $\beta_O \leq \beta_F$. As discussed in Section 2.4, off reservation parcels are subject to North Dakota forced pooling but on-reservation parcels may not be forced into pools. If fee owners on the reservation cannot be forced into drilling pools, then contracting costs of an additional fee neighbor should exceed the contracting costs of an additional off reservation neighbor.

We also expect $\rho > 0$, meaning that extra tenure regimes should cause delays. Contracting across tenure types—e.g., fee and tribal—could raise transaction costs relative to contracting within regime types for two reasons. First, contracting across regimes may require the involvement of the Bureau of Indian Affairs to approve permits and drilling plans (Regan and Anderosn, 2014). Second, contracting across regimes creates a fixed learning cost; for example to research the rules governing fracking under the alternative regimes.

The λ_F, λ_A, and λ_T coefficients measure the extent to which the tenure of parcel i influences delays conditional on the degree of neighborhood subdivision and the tenure compositions of neighbors. In this set of estimates, for which the dependent variable measures delays with respect to getting a horizontal line, the λ coefficients are of secondary interest. If the tenure of parcel i changes total contracting costs by a small amount, conditional on the composition of neighbors, then we expect $\lambda \approx 0$ for all tenure types.[33]

Table 2.4: Parcel-Level Estimates of Days Elapsed with Mineral Tenure Variables

	Tobit Estimates Y = Days elapsed between Jan. 1, 2005 and first horizontal line (as of May 1, 2015)				***OLS Estimates*** Y = 1 if at least one horizontal line cuts parcel	
	(1)	(2)	(3)	(4)	(5)	(6)
Parcel acres	-5.598***	-5.316***	-5.560***	-5.808***	0.00154***	0.00163***
	(0.613)	(0.603)	(0.637)	(0.722)	(0.000135)	(0.000156)
Parcel longside	-802.9***	-770.4***	-786.6***	-749.2***	0.214***	0.203***
	(100.1)	(95.44)	(96.33)	(97.57)	(0.0289)	(0.0294)
St. dev. of neighbor size	26.70***	30.19***	28.01***	27.70***	-0.00566***	-0.00609***
	(7.914)	(7.725)	(7.157)	(7.942)	(0.00193)	(0.00202)
Fee parcel indicator	214.9	301.8*	98.54	131.5	0.016	0.00781
	(172.2)	(178.1)	(223.2)	(245.2)	(0.0508)	(0.0521)
Allotted trust parcel indicator	-56.99	27.56	-125.4	15.95	0.0565	0.0286
	(141.8)	(145.6)	(172.3)	(213)	(0.0463)	(0.0539)
Tribal parcel indicator	-74.39	43.11	-77.52	32.94	0.00964	-0.00777
	(203.7)	(199.9)	(206.8)	(228.2)	(0.0513)	(0.056)
<u>Neighbor Variables</u>						
No. of tenure regimes	115.8***	109.8**	109.3***	106.5**	-0.0243**	-0.0266***
	(42.83)	(44.59)	(41.96)	(42.11)	(0.0103)	(0.00987)
Off reservation neighbors	1.162*	5.947***	6.400***	8.058***	-0.00116***	-0.00179***
	(0.6)	(1.642)	(1.513)	(1.701)	(0.000382)	(0.000373)
Fee neighbors	2.269***	6.069***	6.292***	7.283***	-0.00122***	-0.00164***
	(0.47)	(1.382)	(1.286)	(1.355)	(0.000302)	(0.000293)
Allotted trust neighbors	10.34***	11.19***	10.98***	14.92***	-0.00190**	-0.00334***
	(2.269)	(2.674)	(2.725)	(3.113)	(0.000788)	(0.000868)
Tribal neighbors	7.592	6.673	3.968	0.2	0.00136	0.00165
	(8.996)	(7.601)	(6.995)	(8.318)	(0.00107)	(0.00112)
<u>Covariates</u>						
Thickness-to-depth ratio	-107468***	-99180***	-153020***	-111286**	42.81***	34.61***
Feet to water (000s)	35.13***	35.21***	26.36***	36.28**	-0.00563***	-0.0118**
No. Neighbors underwater	13.02*	13.73**	13.59**	20.52***	-0.00401***	-0.00575***
Topographic roughness	1.281*	1.196**	1.246**	0.662	-0.000382**	-0.000241*
City indicator		373.2***	270.8*	382.7**	-0.00439	-0.0533
Feet to railroad (000s)		7.294	7.721	23.23**	-0.000355	-0.00498*
Road density in radius		-0.0637***	-0.0658***	-0.0867***	0.0000124***	0.0000205***
x coordinate of parcel (000s)			6.413***			-0.00276***
y coordinate of parcel (000s)			3.237*			-0.000569
Oil field fixed effects	No	No	No	Yes	No	Yes
Pseudo R-squared	0.039	0.04	0.041	0.05		
Adjusted R-squared					0.259	0.312
Observations	27,480	27,480	27,480	27,480	27,480	27,480
Censored at 3772 days	16,687	16,687	16,687	16,687	NA	NA

Notes: We do not show some standard errors in order to save space. A parcel's neighborhood includes all parcels touching a one-mile radius extending from the parcel's exterior boundary. All specifications control for the slight variation in the total area of the one-mile radius, due to variation in the size of parcels on the exterior of the radius. Standard errors are clustered by oil field and shown in parentheses.

[33] Below we explain why the tenure of parcel i is likely more impactful on well bore drilling.

Table 2.4 shows estimates of the empirical model in (3). The sequence of specifications and covariates mimics those of Table 2.3. In column 4 of Table 2.4, which is our preferred specification, the point estimates indicate $\hat{\beta}_T = 0.2 < \hat{\beta}_F = 7.3\hat{\beta}_A = 14.9$. This ordering follows our predictions, and the differences between coefficients are statistically significant.[34] Note that adding an allotted trust neighbor doubles delay time, relative to adding a fee neighbor. Adding a tribal neighbor does not increase delay time as predicted.

With respect to the Extra Tenure Regimes variable, we find evidence that a tenure mosaic immediately adjacent to a parcel has discouraged drilling through that parcel. The column 4 point estimate of $\hat{\rho}$ indicates that adding another tenure regime around parcel i is associated with a 106 day drilling delay. The column 6 coefficient of -0.026 is striking. This estimate indicates that adding one extra tenure regime decreases the probability that a shale owner has been compensated for his shale by 65 percent.

To summarize the results in Table 2.4, parcel owners wait longer to be compensated for their shale with increases in the number of exclusion rights holders in the surrounding one-mile radius. Delays increase especially with the number of allotted trust parcels and, to a lesser extent, with the number of fee parcels in the radius. By contrast, we find no evidence that delays increase with an increase in the number of tribal parcels in the radius. Table D1 in the appendix shows the results are robust to estimates that include both parcel X-Y coordinates and oil field effects, to subsamples that omit parcels in cities or parcels that have neighboring parcels in cities, and to the use of the full sample that includes federal and state government parcels. Table D2 indicates that our main

[34] The coefficient runs counter to our reasoning that the neighbor effect off reservation should be smaller, due to forced pooling. These coefficients are not statistically different from each other , however, and they are sensitive to the inclusion of parcels within cities in the sample. When we omit city parcels, the relationship flips so that as expected (see appendix Table D1).

inferences are also robust to the use of a linear model that allows for arbitrary spatial correlation in the error structures following Conley (2008) and Hsiang (2010).

To assess whether the empirical patterns might generalize, Table D3 in the appendix compares private subdivision versus government ownership for the sample of off-reservation parcels. Off the reservation, government parcels are managed by the state of North Dakota, the U.S. BLM, and the USFS. These government parcels are sometimes situated within oil fields alongside privately owned parcels (Figure 2.3). Regression results in Table D3—which employ the same specifications as Table 2.4—show that days elapsed prior to line penetration increase with the number of private neighbors within the 1-mile radius. By contrast, increases in the number of BLM neighbors have no effect on timing, and increases in the number of neighboring state-owned parcels actually reduce the number of days elapsed. Both findings are consistent with one of our main arguments, that private subdivision around a parcel reduces the parcel owner's leverage in attracting oil development. We do not emphasize drilling patterns around and on USFS parcels because the USFS Dakota Prairie Grassland area in our sample has unique drilling restrictions. The observed timing of drilling on and around BLM and state parcels, however, are similar to those on and around tribal parcels suggesting the tribal results generalize to other forms of collective ownership.

2.5.4 Estimates of Other Outcome Variables

Table 2.5 present tests for the effects of subdivision and tenure on the extent to which a parcel has been drilled, measured by the length of lines penetrated a parcel.

This outcome variable is important because a parcel's shale can often be drilled multiple times, enabling parcel-owner compensation for multiple drilling projects.

The Table 2.5 estimates employ the same set of independent variables as those used in Table 2.4. We estimate the Table 2.5 coefficients using a Tobit estimator that is censored at zero for approximately 60.7 percent of the parcels (i.e., those lacking any horizontal lines). Whether drilling extent is measured by total line length (columns 1 and 2) or by line length per acre (columns 3 and 4) we find the same pattern of effects as those reported in Table 2.4. In the case Table 2.5, parcel acres and longside correlate positively with line miles. As in Table 2.4, an increase in the number of neighbors in the 1-mile radius is also associated with decreases in line miles, unless the neighbor's tenure type is tribal.

In Table 2.6 we estimate the effects of subdivision and tenure on whether or not parcel i has a well bore, and on the number of bores. Recall that a bore is the vertical portion of a horizontal well. It's placement on a particular parcel is important because the surface owner of that parcel is positioned to benefit financially for allowing well-pad infrastructure to be housed on his land. The Table 2.6 estimates in columns 1-2 employ a linear probability model for $Y = 1$ if the parcel has a well bore. The estimates in columns 3-4 use a Poisson model to estimate the count of well bores, which ranges from 0 to 30 across parcels.

The two most noteworthy results in Table 2.6 are the coefficient estimates on λ_T and λ_F in column 2. These coefficients indicate that tribal parcels are less likely to have well bores, and that fee parcels are more likely to have them when compared to the omitted, off-reservation private parcel category. The column 2 coefficients are large.

Relative to the mean probability of 7.96 percent, the $\hat{\lambda}_T = -0.037$ point estimate means the probability of having a well bore decreases by 46.5 percent on tribal parcels. The $\hat{\lambda}_F = 0.032$ point estimate means the probability of having a well bore increases by 40.2 percent on fee parcels. This finding suggests that oil companies prefer to locate on-reservation well bores on fee and not tribal land, presumably because negotiating a surface access contract with the tribe entails a higher cost when compared with the cost of negotiating with a private surface owners.

To summarize the parcel-level results in tables 2.3-2.6, they suggest that subdivision and allotted trust tenure reduce the probability that a parcel owner has been compensated for her shale, and also delay drilling where it has occurred. Oil companies seem to prefer to place well bores on fee simple parcels, but they also apparently prefer to run horizontal lines through contiguous tribal tracts, or through swaths of private land that have not been finely subdivided. These findings draw attention to the following question: is there a threshold amount of subdivision that makes drilling exclusively through tribal land more attractive to oil companies than drilling exclusively through private parcels? We address this question in the next section, using well-level data.

Table 2.5: Parcel-Level Tobit Estimates of Extent and Density of Horizontal Lines

	Y = Linear Miles of Horizontal Lines		Y = Linear Miles per 100 Acres	
	(1)	(2)	(3)	(4)
Parcel acres	0.00569***	0.00591***	0.00418***	0.00450***
	(0.000273)	(0.000307)	(0.000873)	(0.00101)
Parcel longside	0.236***	0.209***	0.534***	0.570***
	(0.0391)	(0.0381)	(0.168)	(0.176)
St. dev. of neighbor size	-0.0136***	-0.0105*	-0.0283***	-0.0320***
	(0.00497)	(0.00584)	(0.00940)	(0.0100)
Fee parcel indicator	0.0251	0.0683	0.167	0.0698
	(0.0970)	(0.0856)	(0.216)	(0.254)
Allotted trust	0.123	0.0802	0.406*	0.198
parcel indicator	(0.0989)	(0.110)	(0.229)	(0.259)
Tribal parcel indicator	0.0398	0.0213	0.347	0.150
	(0.118)	(0.119)	(0.300)	(0.288)
No. of tenure regimes	-0.0550**	-0.0595**	-0.110**	-0.110**
	(0.0242)	(0.0247)	(0.0514)	(0.0544)
Off reservation neighbors	-0.00160*	-0.00264***	-0.00238	-0.00680*
	(0.000952)	(0.000871)	(0.00358)	(0.00378)
Fee neighbors	-0.00199***	-0.00264***	-0.00341	-0.00656**
	(0.000764)	(0.000695)	(0.00305)	(0.00312)
Allotted trust neighbors	-0.00496***	-0.00673***	-0.00717*	-0.0132**
	(0.00184)	(0.00217)	(0.00429)	(0.00564)
Tribal neighbors	0.00177	0.00271	-0.000982	-0.00535
	(0.00345)	(0.00365)	(0.0129)	(0.0138)
Covariates				
Thickness-to-depth ratio	108.6***	70.46***	242.8***	146.6***
Feet to water (000s)	-0.0159***	-0.0230***	-0.0217***	-0.0354**
No. Neighbors underwater	-0.00802***	-0.0103***	-0.0139	-0.0165
Topographic roughness	-0.000901**	-0.000496	-0.00207**	-0.00137
City indicator	-0.0896	-0.176**	-0.268	-0.361
Feet to railroad (000s)	0.00243	-0.0125**	-0.000866	-0.0283
Road density in radius	0.0154	0.0290***	0.0247	0.0776*
x coordinate of parcel (000s)	-0.00660***		-0.0174**	
y coordinate of parcel (000s)	-0.00212**		-0.00659***	
Oil field fixed effects	No	Yes	No	Yes
Pseudo R-squared	0.247	0.313	0.053	0.074
Observations	27,480	27,480	27,480	27,480
Censored at 0	16,682	16,682	16,682	16,682

Notes: We do not show some standard errors in order to save space. A parcel's neighborhood includes all parcels touching a one-mile radius extending from the parcel's exterior boundary. All specifications control for the slight variation in the total area of the one mile radius, due to variation in the size of parcels on the exterior of the radius. Standard errors are clustered by oil field and shown in parentheses. * $p < .1$, ** $p < .05$, *** $p < .01$

Table 2.6: Parcel-Level Estimates of the Probability and Number of Horizontal Well Bores

	OLS estimates of Y = 1 if parcel has a horizontal well bore (1)	(2)	Poisson Estimates of Y = No. of horizontal well bores (3)	(4)
Parcel acres (100s)	0.04786***	0.04668***	0.3362***	0.3349***
	(0.005376)	(0.005514)	(0.05412)	(0.05695)
Parcel longside	-0.008175	-0.01033	0.03533	0.05411
	(0.009072)	(0.009452)	(0.1263)	(0.1308)
St. dev. of neighbor size	-0.001856***	-0.001607*	-0.03108***	-0.02719***
	(0.0006303)	(0.0008656)	(0.008889)	(0.008916)
Fee parcel indicator	0.03231*	0.03202**	0.1873	0.1546
	(0.01871)	(0.01452)	(0.1795)	(0.1921)
Allotted trust parcel indicator	0.01836	0.02382	0.3390	0.1909
	(0.02049)	(0.01696)	(0.2831)	(0.2754)
Tribal parcel indicator	-0.04978***	-0.03791**	-1.5861***	-1.6604***
	(0.01560)	(0.01631)	(0.4406)	(0.4439)
No. of tenure regimes	0.0005092	-0.0004315	0.03530	0.03388
	(0.004955)	(0.004892)	(0.09659)	(0.09267)
Off reservation neighbors	-0.0006307***	-0.0007883***	-0.01312***	-0.01665***
	(0.0001340)	(0.0002202)	(0.003168)	(0.003860)
Fee neighbors	-0.0006228***	-0.0007358***	-0.01265***	-0.01538***
	(0.0001072)	(0.0001717)	(0.002528)	(0.002963)
Allotted trust neighbors	-0.001604***	-0.001467***	-0.02214***	-0.02211***
	(0.0003020)	(0.0004127)	(0.004877)	(0.006652)
Tribal neighbors	-0.0005451	-0.0005099	-0.007279	-0.0001790
	(0.0003628)	(0.0004410)	(0.01159)	(0.01064)
Covariates				
Thickness-to-depth ratio	3.5450**	2.3342	113.49***	24.724
Feet to water (000s)	-0.002142***	-0.003572**	-0.03152***	-0.05262***
No. Neighbors underwater	-0.0007712**	-0.0009464**	-0.01393	-0.01964**
Topographic roughness	-0.00006101	-0.00002546	-0.0004564	0.0004475
City indicator	0.009665	0.0001227	-0.4851	-0.7611
Feet to railroad (000s)	0.0002839	0.0005732	0.007782	0.001662
Road density in radius	0.0007139***	0.0009311***	0.0001238***	0.0001730***
x coordinate of parcel (000s)	0.00006507		-0.004853***	
y coordinate of parcel (000s)	0.0002370**		-0.0002760	
Oil field fixed effects	No	Yes	No	Yes
R-squared	0.056	0.075		
Observations	27,480	27,480	27,480	27,480

Notes: We do not show some standard errors in order to save space. A parcel's neighborhood includes all parcels touching a one-mile radius extending from the parcel's exterior boundary. All specifications control for the slight variation in the total area of the one mile radius, due to variation in the size of parcels on the exterior of the radius. Standard errors are clustered by oil field and shown in parentheses. * $p < .1$, ** $p < .05$, *** $p < .01$

2.6 Well-Level Estimates, Delay Costs, and Qualifications

In this section we test theory with well-level data. These tests have the following advantages relative to parcel-level tests: 1) well-level coefficients are more intuitive to interpret, 2) the well-level estimates measure the delays based on the drilling path actually taken, rather than equally weighting all of the drilling paths that might be taken as in our one-mile radius variables, and 3) the well-level estimates better facilitate the monetization of delay costs. Monetizing delay costs helps us understand the estimates' economic significance.

2.6.1 Well-Level Estimates of Delay

Table 2.7 summarizes the well-level data. The data set comprises the 6,554 horizontal wells for which we were able to match the bore with the horizontal lines emanating from the bore.[35] The number of lines emanating from a single bore ranges from 1 to 12, with some lines radiating like rays from the bore and others extending in opposite directions from the bore (see Figure 2.8). The mean total length of all lines from a single bore is 2.22 miles. The number of tenure regimes penetrated by lines from a single well range from 1 to 3, but 91 percent of the lines from a well are contained within a single tenure regime.[36] The maximum number of parcels cut by lines from a well is 85, and the mean is 7.3 parcels. Figure 2.9 illustrates an example of how our well-level variables map to

[35] We match well bores to horizontal lines by matching first on API number and then using proximity.

[36] There are 1261 wells on the reservation in this sample, with 61 percent penetrating multiple regimes.

the spatial attributes of a well.

Using the well-level data, we estimate the following empirical model

$$\begin{aligned} Days_{wj} = \alpha_j + \lambda_F Fee_{wj} + \lambda_A ATrust_{wj} + \lambda_T Trib_{wj} + \beta_O OffParc_{wj} + ... \\ ... + \beta_F FeeParc_{wj} + \beta_A ATrustParc_{wj} + \beta_T TribParc_{wj} + \rho Regimes_{wj} + \gamma X_{wj} + ... \\ ... + \psi Linemiles_{wj} + \varepsilon_{wj} \end{aligned} \tag{2.4}$$

The dependent variable is the number of days elapsed before the well was drilled. Here w = the 6,554 wells, j = oil fields, the α_j notation represents the 203 oil-field fixed effects, and the notation X_{wj} indicates the covariates, measured at the parcel containing the well bore. We also control for line length in some specifications with length growing slightly over time due to changing technologies. Controlling for length makes the estimates consistent with our theoretical reasoning, which holds constant line length (at h^*).

Table 2.7: Summary Statistics from Well-Level Data Set

Variable Names	Mean	S.D.	Min	Max	Definition
Drilling Date and Distance					
Day when Drilled[a]	2315.3	740.8	13	3772	Days elapsed between January 1, 2005 and date in which the line was drilled
Lines from Well Bore[a]	2.2223	0.6212	1	12	Number of horizontal lines stemming from well bore
Miles of Horizontal Line[a]	1.8892	0.5094	0.0002	8.1336	The total length (miles) of horizontal lines from the well bore
Location of Well Bore					
Fee Parcel Indicator[a,b]	0.0871	0.282	0	1	=1 if the well bore is on fee simple parcel, otherwise =0
Allotted Trust Parcel Indicator[a,b]	0.0981	0.2975	0	1	=1 if the well bore is on allotted trust parcel, otherwise =0
Tribal Parcel Indicator[a,b]	0.0072	0.0844	0	1	=1 if the well bore is on tribal parcel, otherwise =0
Off Res. Parcel Indicator[a,c]	0.772	0.4195	0	1	=1 if the well bore is on an off reservation, private parcel, otherwise =0
No. of Parcels Well Lines Cut					
Tenure Regimes[a,b]	1.1017	0.3514	1	3	Number of different tenure regimes that all lines from a well penetrate
All Parcels[a,b,c]	7.2723	3.7111	1	85	Number of parcels that all lines from a well penetrate
Off Reservation Parcels[a,c]	5.9049	4.4169	0	85	Number of off reservation private parcels that all lines from a well penetrate
Fee Parcels[a,b]	0.5383	1.7638	0	28	Number of fee simple parcels that all lines from a well penetrate
Allotted Parcels[a,b]	0.6352	1.9301	0	15	Number of allotted trust parcels that all lines from a well penetrate
Tribal Parcels[a,b]	0.1939	1.1154	0	16	Number of tribal parcels that all lines from a well penetrate

Notes: This table summarizes data for all horizontal wells in our study area that were drilled between 2005 and May 2015 that we could spatially match the well bores with the lines emanating from the bore. N = 6,544 for all variables. Data sources are: a) North Dakota Oil and Gas Commission website, b) U.S. Bureau of Indian Affairs, c) Real Estate Portal. d) Authors calculations.

Table 2.8: Well-Level OLS Estimates of Duration between Jan. 1, 2005 and Drilling of a Horizontal Well

	(1)	(2)	(3)	(4)	(5)	(6)
Location of Well Bore						
Fee	206.8**	309.9***	233.4***	306.4***	306.9***	347.8***
	(94.67)	(85.61)	(89.27)	(79.64)	(87.28)	(78.65)
Allotted Trust	226.4**	299.8***	260.6***	306.8***	308.2***	330.2***
	(89.78)	(89.18)	(84.69)	(83.20)	(79.86)	(83.82)
Tribal Trust	280.0	346.0	342.4	385.2*	367.0*	386.0*
	(257.7)	(228.7)	(247.5)	(230.2)	(212.9)	(201.8)
No. of Parcels Cut by Lines						
Tenure Regimes	94.49**	82.44	99.02*	86.90	70.84	60.21
	(47.81)	(56.98)	(52.75)	(60.64)	(58.49)	(64.82)
Off Res. Parcels	16.69***	14.56***	5.150	3.625	14.42***	12.33***
	(4.387)	(3.077)	(5.103)	(4.596)	(4.721)	(3.260)
Fee parcels	21.73***	21.21***	9.132	9.808	11.63	11.53
	(7.990)	(8.115)	(8.080)	(8.943)	(7.947)	(9.335)
Allotted parcels	43.45***	36.12***	25.71***	19.93**	27.20***	23.12**
	(9.180)	(9.952)	(9.802)	(9.922)	(8.848)	(9.094)
Tribal parcels	19.15	16.96	-1.572	-2.152	2.211	2.220
	(18.81)	(17.62)	(20.03)	(19.23)	(16.79)	(15.54)
Line Distance and Number						
Miles of Lines			171.3***	166.7***	281.7***	268.9***
			(54.77)	(54.02)	(54.36)	(54.85)
Lines from Well					-258.8***	-232.5***
					(23.52)	(21.56)
Covariates	Yes	Yes	Yes	Yes	Yes	Yes
X and Y coordinates	Yes	Yes	Yes	Yes	Yes	Yes
Field Effects	No	Yes	No	Yes	No	Yes
Observations	6545	6545	6545	6545	6545	6545
Adjusted R-squared	0.095	0.234	0.104	0.242	0.141	0.270

Notes: The regressions include all horizontal oil wells for which we could identify the completion date. The tenure variables represent the total number of parcels from each tenure type through which lines from a single horizontal well project penetrate. Covariates are measured at the well-bore and include: thickness-to-depth, roughness, feet to water, feet to railroad, and road density.

Standard errors are clustered by oil field and shown in parentheses. * $p < .1$, ** $p < .05$, *** $p < .01$

Table 2.8 presents results. We focus here on columns 2, 4, and 6, which include oil field fixed effects. In those columns, $\hat{\lambda}_T$, $\hat{\lambda}_F$, and $\hat{\lambda}_A$ are all positive, meaning that having a vertical bore on reservation land is associated with a delay, relative to wells with bores off the reservation, on private land. The estimates of $\hat{\lambda}_T$ are largest, which is consistent with the fixed cost of surface access being highest for wells emanating from tribal land. With respect to the $\hat{\beta}$ coefficients, the main patterns are $\hat{\beta}_A > \hat{\beta}_F > \hat{\beta}_T$ and $\hat{\beta}_T = 0$ as expected.[37] The column 2 point estimate of $\hat{\beta}_A = 36.1$, for example, means that drilling delays increased by 36.1 days for each allotted parcel penetrated by a well. By contrast, $\hat{\beta}_T = 0$ means that penetrating an additional tribal parcel is not associated with longer delays.

Figure 2.10 graphically represents the results, based on the column 6 coefficient estimates. Focusing first on the left panel, the height of the vertical intercepts denote the point estimates of $\hat{\lambda}_T$, $\hat{\lambda}_F$, and $\hat{\lambda}_A$. As we move right along the horizontal axis, the oil well penetrates a greater number of parcels (P). Hence, the total delay is $\hat{\lambda} + \hat{\beta}P$ for each tenure category.[38] As the graph demonstrates, a drilling project through allotted trust parcels takes longer to execute than a project through tribal tenure if the well will penetrate three or more allotted trust parcels. A drilling project through fee simple parcels takes longer to execute than a project through tribal tenure if the well will penetrate four or more fee parcels.

The graph on the right side of Figure 2.10 puts these estimated delays in the context of scenarios in which formerly communal (tribal) land is subdivided into 1280, 640, 320, 160, 80, 40, and 20 acre parcels. We treat the 1280 acre scenario as the benchmark, single-parcel case because the most prevalent oil drilling unit on the Bakken is 1280 acres. This implies that a 1280 acre parcel can fully accommodate most modern oil wells. When the landscape is subdivided into 640 acre parcels, Figure 2.10 assumes the well must

[37]The differences in coefficients are not all statistically significant.

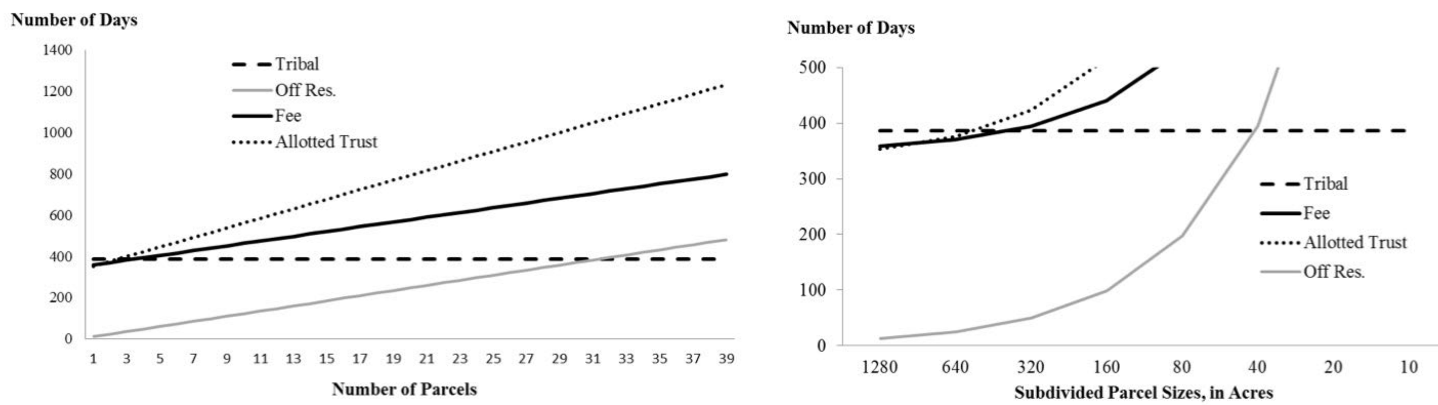
[38]Figure 2.10 is drawn under the assumption that the statistically insignificant $\hat{\beta}_T$ coefficient is zero, but that the statistically insignificant $\hat{\beta}_F = 11.5$, because the latter coefficient is more precisely estimated.

penetrate two parcels.[39] When the landscape is subdivided into 320 acre parcels, the well must penetrate four parcels. When subdivision involves 160 acre parcels, the well must penetrate eight parcels and so on.

Applying the Table 2.8, column 6 estimates to the subdivision scenarios just described yields the Figure 2.10 plots. These simple illustrations demonstrate that, once subdivision is finer than 320 acre plots, there are delays associated with fee simple and especially allotted trust parcels. For private land off of the reservation, the delays become longer than delays under tribal ownership once subdivision is 40 acres. Under the 40 acre scenario, 32 parcels must be consolidated to create a 1280 acre unit, although forced pooling rules in North Dakota requires the consent of only half of the owners.

[39] Other common oil unit sizes are 640 and 2560 acres.

Figure 2.10: Delays from Drilling Projects, Based on Well Level Estimates



Notes: The graph in the left panel plots the coefficient estimates of $\hat{\lambda} + \hat{\beta}P$ from Table 2.8, column 6 for each tenure type. Here the notation P indicates the number of parcels a well intersects. For tribal tenure, the plots assume that $\hat{\beta}_T = 0$ because this point estimate is imprecisely estimated. The right panel represents the results in the left-side panel for common subdivision scenarios, assuming that a well is fully contained within a single 1280 parcel, which is the most common oil unit drilling size on the Bakken. The right-side panel assumes a well must intersect two 640 acre parcels, four 320 acre parcels, eight 160 parcels, 16 80 acre parcels, and 32 40 acre parcels.

2.6.2 Monetizing Delay Costs

We monetize the cost of delays using back-of-the-envelope approaches. Our calculations are based on the monthly productivity of a typical well in the Bakken, as estimated by Hughes (2013, p. 57). According to his estimates, a typical well produces 213,488 barrels during the first 48 months. Production from the well declines rapidly at first, and then the decline rate slows. For example, 19 percent of the 213,488 barrels are extracted during the first 3 months, 47 percent are extracted during the first year, and 70 percent during the first two years. We fit a hyperbolic decline-curve function (see Satter et al. (2008)) to the Hughes numbers in order to extend the production estimates from 4 to 29 years, which is a predicted length of production (see MacPherson (2012)2). This process leads us to estimate total production of 396,395 barrels in 29 years, which is a conservative estimate of well productivity on the Bakken.[40]

To monetize expected impacts of delays on royalty earnings, we take the following steps. First, we multiply monthly production of barrels by the average price per barrel over 2005 through May 2015, which was $78.89.[41] Second, we discount monthly revenue by annual rates of 1, 3, and 5%. Third, we multiply this discounted revenue by a royalty rate, assumed to be 17 percent based on Brown et al. (2015)'s reported averages for the Bakken.

Table 2.9 shows the monetized costs per well under the different discounting scenarios. With no delay and a 3% annual discount rate, the expected stream of royalty payments

[40]Note that this "typical" well from Hughes (2013) is less productive than other estimates. MacPherson (2012), for example, reports that a typical well produces 540,000 barrels.

[41]This is the West Texas Intermediate Price, downloaded from the U.S. Energy Information Administration website at `www.eia.doe.gov/dnav/pet/TblDefs/pet_pri_spt_tbldef2.asp`.

has a present value of \$4.47 million. If this royalty earning is shared across 7.3 mineral owners, which is the mean number of parcels penetrated by a well in our sample, then the present value is \$614,665 per parcel. A one year delay under this 3% discounting scenario leads to an expected aggregate royalty loss of \$131,905 or \$18,144 per parcel. The one-year delay represents a loss of 2.95% of royalty value, compared to the no-delay benchmark scenario. The other cells in Table 2.9 can be interpreted in the same way.

Table 2.10 monetizes the expected royalty delay costs of subdivision, which we illustrate in terms of days in the graph on the right-side of Figure 2.10. Table 2.10 employs the 3% discounting scenario. Here we highlight the subdivision scenario that best matches the observed mean size of parcels over oil fields in our sample area today, which is 79.4 acres. Rounding up to 80 acres, consider the delay costs associated with subdividing a 1280 acre oil unit of communal tribal minerals into 16 separate, 80 acre plots. The per-well expected delay costs, in terms of the present value of foregone royalties, are \$197,718-\$143,382 = \$54,336 for subdivision into fee simple. The per-well delay costs are \$260,064-\$143,382 = \$116,682 for subdivision into allotted trust.

How large are these royalty delay costs in aggregate? Consider there are 592 wells with bores on fee land in our well-level sample and 660 wells with bores on allotted land. Under the 80 acre subdivision scenario, this suggests the expected aggregate delay costs of fee simple subdivision were in the range of $592 \times \$54,336 = \$32.2$ million. The aggregate delay costs of subdivision into allotted trust parcels were in the range of $660 \times \$116,682 = \$77.0$ million. Fort Berthold had an American Indian population of 6,341 in 2010. Hence, the aggregate per-capita delay costs were in the range of \$5,073 for fee simple subdivision and \$12,145 for allotted trust subdivision. For perspective, the

Table 2.9: Costs of Drilling Delays for a Typical Horizontal Well

	Aggregate Royalties from Well			Royalties Per Parcel		
	r=1%	r=3%	r=5%	r=1%	r=3%	r=5%
Royalty $s, No Delay	$4,993,516	$4,468,611	$4,062,254	$686,866	$614,665	$484,324
Delay cost (% of Total)						
1 Month	4,158	11,144	16,856	572	1,533	2,319
				(0.08)	(0.25)	(0.48)
3 Months	12,463	33,348	50,358	1,714	4,587	6,927
				(0.25)	(0.75)	(1.43)
6 Months	24,895	66,447	100,092	3,424	9,140	13,768
				(0.50)	(1.49)	(2.84)
1 Year	49,666	131,905	197,717	6,832	18,144	27,196
				(0.99)	(2.95)	(5.62)
2 Years	98,837	259,917	385,811	13,595	35,752	53,069
				(1.98)	(5.82)	(10.9)

Notes: The notation r refers to the annual discount rates. The columns showing royalties per parcel are based on the mean number of parcels penetrated by a horizontal well, which is 7.27 (see Table 2.3). We assume that each parcel in the drilling unit is equal in size so that each parcel owner is paid a 1/7.27 or 13.76% share.

2010 American Indian per capita income on the Fort Berthold reservation was $13,543, based on U.S. Census data. Hence, the per capita delay costs from subdivision of $17,218 exceeded per capita income.

The back-of-the-envelope simulations are rough, and there are reasons why they might overstate or understate actual delay costs. The simulations might overstate delay costs because they assume 1280 acre oil units, but some units were smaller. If we assume an oil unit size of 640 acres, then the per capita delay costs were $1,874 for fee simple subdivision and $4,994 for allotted trust. The simulations might understate delay costs because they hold constant oil prices at the sample period mean of $78.89. However, oil prices fell after our sample period ends, from $59 per barrel in May 2015 to $37 per barrel in December 2015.[42] The declining price of oil raises the delay costs for owners of parcels that were not drilled prior to our sample period, and it highlights an important

[42]See `https://research.stlouisfed.org/fred2/series/DCOILWTICO/downloaddata`.

issue that we do not consider here. If excessive supply of oil from horizontal fracking has driven down world prices, then areas of shale burdened by subdivision and suboptimal tenure will face larger delay costs than our estimates imply. Finally, the simulations hold constant royalty rates at 17 percent but the royalties paid on projects in oil units with subdivided and allotted trust parcels may have been lower. We lack data on royalty rates so we cannot directly address this contention. Our theoretical reasoning in Section 2.4, however, implies that these projects must pay lower royalty rates if the oil drilling industry is competitive.

Table 2.10: Monetized Delay Costs from Different Subdivision Scenarios (r=3%)

		Cost of Delay per Well (Present Value of Delayed Royalties, in $s)			
Parcel Acres	Parcels in Oil Unit	Tribal	Fee	Allotted Trust	Off Reservation
1280	1	143,382	133,475	131,243	4,580
640	2	143,382	137,758	139,831	9,160
320	4	143,382	146,324	157,007	18,320
160	8	143,382	163,455	191,359	36,640
80	16	143,382	197,718	260,064	73,281
40	32	143,382	266,245	397,472	146,562
20	64	143,382	403,297	672,290	293,123
10	128	143,382	677,401	1,221,926	586,246

Notes: The calculations monetize the days of delay in Figure 2.10 using the discounting procedure summarized in Table 2.9, for the r = 3% discounting scenario.

2.6.3 Alternative Interpretations, Caveats, and Generalizations

We focus on a contracting cost mechanism through which subdivision delays drilling, but alternative causal channels are possible. If smaller parcels have higher surface quality, conditional on oil field fixed effects, and drilling through shale damages surfaces, then our estimates might be capturing systematic resistance from small-parcel owners due to environmental damage concerns. We do not think this alternative mechanism is driving the results for two reasons. First, environmental damages from shale drilling whether perceived or real - spill across neighboring parcels and are not generally contained to surface areas above a particular section of drilling line (see, e.g., Olmstead et al. (2013), Muehlenbachs et al. (2015)). This implies an owner of a small parcel cannot prevent exposure to external effects from drilling simply by trying to prevent drilling beneath his parcel. On the contrary, contracting costs caused by subdivision can actually prevent neighbors from joining together to prevent oil drilling at a scale large enough to eliminate exposure to adverse effects. This argument is similar to Hansen and Libecap (2004a), who explain how high contracting costs among small landowners exacerbated environmental pollution during the U.S. dust bowl era.

We focus on a contracting cost mechanism through which allotted trust tenure has delayed drilling relative to fee simple but alternative causal channels are possible. If the average American Indian owner of allotted trust is more resistant to drilling than the average non-Indian fee simple owner, for cultural reasons, then differences in preferences might explain longer delays associated with allotted trust. A test for this alternative could compare drilling uptake on fee parcels with uptake on allotted trust parcels with only a single owner, but we lack data on parcel-specific allotted trust ownership numbers. In any case, an explanation focused on preferences rather than contracting is difficult to reconcile with the observation that the tribal government on Fort Berthold which is democratically elected - has aggressively pursued drilling. Moreover, our interpretation that contracting costs rather than preferences explain the slower uptake of drilling in allotted trust areas align with assessments by local experts, such as Ogden (2011), who asserts that because of a "highly fractionated [allotted trust] land base it is almost impossible for companies to gather the approval of all the landowners of any given tract." Even if differences in the timing of drilling on fee simple versus allotted trust parcels reflected cultural preferences, preferences would not explain differences in drilling through allotted trust versus tribal parcels.

Finally, our study might be criticized on the grounds that the findings narrowly apply to the Fort Berthold reservation, and to the peculiar institution of allotted trust tenure. While a fuller investigation of other settings is outside the scope of our study, we think the contracting cost and anticommons logic should apply to other comparisons of government versus subdivided private land. Evidence that it does is found in Table D3 of the appendix, which shows that patterns of drilling on and around federal BLM and North Dakota state land resemble patterns on and around tribal land. We do speculate, however, that the potential scale advantages of government ownership, whether tribal, state, or federal, is conditioned by the quality and transparency of governance.

2.7 Conclusion

Land privatization programs are appealing to economists because most agree there are stronger incentives to invest in individually owned land when compared to communal land. Where programs have been implemented, they have generally induced investment on privatized parcels, particularly with respect to agricultural production and household quality (see Galiani and Schargrodsky 2012). In the specific case of North American indigenous lands, there is also evidence that movement towards privatization has improved parcel-specific surface investments (Anderson and Lueck, 1992; Akee, 2009) and improved overall measures of Native population incomes (Aragón, 2015).

We examine an important qualification to the benefits of privatization. Creating more exclusion rights through the subdivision of communal land can frustrate the efficient use of natural resources that cannot be profitably exploited without the consent of all (or most) owners. The problem is that subdivision raises contracting and coordination costs and may lead to the underutilization of large-scale resources, such as wind and shale oil, which is the focus of our study.

We study shale oil extraction from the Bakken, through the Fort Berthold Indian reservation and surrounding lands.[43] In that setting, we find that having more subdivided and private neighboring parcels reduces and delays oil drilling on a parcel, thereby reducing the expected compensation or rents from ownership. In general, we find that well drilling on a parcel is encouraged if the surrounding land is owned by a single entity, namely the tribe.

Our findings provide another angle from which to view the allotment of Native American lands that complements other research on the legacy of this era. Accounts written by sociologists, historians, and legal scholars characterize the injustices of allotment by documenting the large transfers of land wealth from Native Americans to non-Indians that resulted (see, e.g., Banner (2009)). We join other economists by emphasizing that allotment did much more than transfer land wealth; it also fundamentally affected land productivity, both positively and negatively, by creating new systems and mixtures of land tenure. Our contribution is to emphasize, with specific detail, how the subdivision

[43]Our arguments and study are similar to a working paper by Holmes et al. (2015) who study agglomeration economies of density, also in the context of the Bakken. One key difference is that our study focuses to a greater extent on property rights and tenure, exploiting the different systems that exist on Forth Berthold.

of tribal tenure has derailed the coordinated development of a valuable natural resource. Back-of-the envelop estimates suggest the subdivision of tribal land reduced Fort Berthold per-capita earnings from the fracking boom by an amount exceeding annual per capita incomes from other sources. Moreover, we expect that subdivided tenure has reduced rents on other Native Americans lands that harbor large stocks of oil and natural gas shale, and hold other spatially expansive resources with value such as wind.

Beyond the context of Native American reservations, our finding that land subdivision has delayed horizontal drilling on the Bakken is relevant to a burgeoning literature on the local economic benefits from the fracking boom (e.g., Maniloff and Mastromonaco (2014)). Our study may help explain why some locales boomed earlier than others, and it suggests that local benefits may have been even larger if delays due to contracting could be avoided. The findings here also provide context to research suggesting that conventional oil and gas drilling is more costly and subject to more delays on U.S. government land (Kunce et al., 2002). The evidence here suggests that government ownership may be relatively more beneficial for shale oil, due to the horizontal nature of drilling.

We recognize there are attractive alternatives to managing shale oil besides communal ownership of land. One alternative used extensively in the United States is the regulation of horizontal fracturing by state oil and gas commissions, including forced pooling rules that limit contracting costs and the power of individual landowners to holdup development. The findings here suggest that significant contracting delays persist in spite of these rules, at least on the Bakken. Another alternative is split estates and government ownership of minerals (Fitzgerald, 2010). Subsurface ownership by government is common throughout the world, and it could in principle solve the coordination problem we have highlighted, but it does so at a large cost of creating principal-agent problems. We are interested in the costs and benefits of government mineral ownership but the issue is beyond the scope of our study. Our study does raise questions about how new fracking and horizontal drilling technologies have changed the optimal ownership of oil, however, and we hope to see future research on that topic.

2.8 Permissions and Attributions

The content of Chapter 2 is the result of a collaboration with Dominic Parker.[44]

[44]For helpful comments on earlier drafts, we thank Jane Friesen, Terry Anderson, Shawn Regan, Tim Fitzgerald, Dan Benjamin, and participants at seminars and workshops hosted by Simon Fraser University, the Society for Organizational and Institutional Economics, the University of Wisconsin, the UC Santa Barbara Occasional Conference on Environmental Economics, and the Property and Environment Research Center. We are grateful to Matt Kelly, an attorney of Tarlow and Stonecipher PLLC for helpful discussions about oil and gas leasing on the Bakken.

Chapter 3

Endogenous First-Possession Property Rights in Open-Access Resources

3.1 Introduction

Losses of competitive entry and production in open-access resources have long been recognized.[1] In the absence of formal property rights, there are no restrictions on entry, and agents do not bear the full costs of their production decisions. Classic externalities arise with the use of excessive capital, other inputs, short-time horizons, races to produce, congestion, reduced investment in the resource stock, and lower output value. To mitigate these externalities, governments implement various regulatory and rights-based

[1]See Gordon (1954) for an outline of the situation in fisheries and Hardin (1968) for a more general description.

instruments to constrain entry, limit output, and internalize external costs. We are interested in a particular set of institutions that establish a total resource extraction cap and then distribute shares of the resource or resource rents to individual users. These institutions are termed rationalization, which is how we will refer to them in this Essay. The potential for open-access exists for many natural resources. Here, we examine attempted rationalization of fisheries and U.S. hydrocarbon deposits in the presence of informal property rights to streams of rents under open-access resource use.

Rationalization can create large gains by internalizing externalities in use decisions and instituting extraction levels consistent with maximizing long-term rents from the resource stock. The existence of net surplus from mitigating aggregate open-access losses suggests beneficiaries of rationalization ought to be willing and able to pay opposing parties for their consent whenever rationalizing creates a surplus. In such settings, willingness to pay for transfers exceeds the willingness to accept transfers, and institutional responses to address open-access dissipation should be observed. Empirically, the process is far more complex, with certain parties systematically holding out.

The existence of heterogeneity, both in users' costs and in the resource itself, has important implications for the emergence of informal institutions to protect inframarginal rents. Informal institutions are locally devised and may not be recognized in formal statutes, regulatory actions, or court rulings. These institutions emerge due to low-cost users' ability to discover and invest in more productive resource deposits and those users' desire to protect their claims. In settings where individuals interact with the resource in particular locations with differential information about the overall stock and invest in protecting their rent-generating skills, rationalization imposed by governments at the behest of less-productive users may strand investments in the resource made by more productive agents, their claims to it, and any associated human capital. In this case, rationalization effectively expropriates the informal property rights of low-cost users. Unless compensated, this expropriation is a basis for opposing otherwise socially beneficial institutional change.

The view that inframarginal rents—positive economic profits earned by low-cost producers in competitive setting—exist in open-access settings has been explored in the fishery-economics literature.[2] Johnson and Libecap (1982) show how differential production costs generate inframarginal rents captured by highly skilled agents that are vulnerable to redistribution or loss if uniform quotas or shares in a total allowable output are installed. Anderson et al. (2011) and Johnson (1995) argue that Pigouvian taxes or the auctioning of production shares transfer rents from low-cost agents. Despite the recognition that inframarginal rents exist in open-access resources, the economics literature has not explored the connection between sustained open-access and the establishment of endogenous, informal institutions to protect these rents.[3]

Long-term expectations regarding the profits to be earned from resource exploitation under open-access are different for inframarginal-rent earners. If users with low expected rents view the resource stock as at risk, they may organize for new institutional arrangements implemented by the state that undermine the practices of those who have adapted to open-access, earn inframarginal rents, and view the stock's condition more favorably. This differential assessment creates a bargaining situation whereby some par-

[2]See generally Clark (1980); Heaps (2003)

[3]See generally Lueck (1995) (exploring open-access resources in the limited context of first possession establishment of property rights).

ties seek to implement new access and production rules whereas others seek to defend their incumbent advantages. If the former anticipate sufficient net gains from institutional change, they ought to be able to compensate the latter for any individual losses. Bargaining involves agreeing on the value of inframarginal rental streams—willingness to accept—and matching it with the value of the net benefits gained—willingness to pay. If these do not coincide, then there is no voluntary agreement and open-access persists; distributional conflicts can have efficiency implications. We examine and discuss empirically observed opposition to theoretically Pareto-improving rationalization attempts. We present a framework of search and exploitation and formation of informal claims to stochastic and heterogeneous resource rents by users who are heterogeneous in search and production cost.

3.2 Analytical Framework

3.2.1 Sources of Inframarginal Rents in Open-Access

Understanding how informal institutions can emerge within open-access regimes requires studying the factors that allow users to earn rents in the absence of formal, legal property rights to resources. The most common explanation of inframarginal rents assumes some users have lower costs than others and are able to earn rents even when individuals on the margin earn zero profit (Johnson and Libecap, 1982). Although this way of thinking about heterogeneity is analytically tractable, it is problematic because it does not account for how cost advantages persist over time. Open-access settings are characterized by a lack of formal rules or restrictions, so all users are free to adopt similar technologies and production practices as they become aware of them. Rent-generating cost advantages can persist only through differences in knowledge either about the resource or about production techniques. If that knowledge were common or costless to obtain, costs would converge and inframarginal-rent earners would cease to exist. Differences in search and production knowledge that are difficult to copy or convey to others must drive users' ability to sustain inframarginal rents over time.

Differences in knowledge about a resource will arise in settings where the resource is spatially heterogeneous and large and where extraction is site-specific. If search is costly and users are heterogeneous, those with lower search costs will find more productive locations and potentially earn inframarginal rents because they can access the most valuable part of the resource sooner than those who ultimately extract from less-productive locations. If these users also invest in specialized knowledge about how to produce the resource from particular locations, their production costs are also lower, further increasing their rents. Rents derive from asymmetric information—over the resource and over techniques—so settings where information is less stratified will be more subject to rent dissipation. Acquiring site-specific production knowledge increases the expected gains from searching for a productive location if site-specific resource abundance and user productivity are complements.

Where the resource is small and homogeneous in quality and users are also similar in search and production costs, the full-dissipation competitive setting described by Gordon (1954) occurs. Resource homogeneity reduces the incentive to search because all locations are equally abundant and, if coupled with user homogeneity, prevents users from exploiting asymmetric information to earn rents. In this setting, users keep entering the resource as long as positive rents exist. Since all users are homogeneous, the equilibrium level of resource extraction corresponds to zero rents for all users. Resource and user homogeneity is also, paradoxically, the setting outlined by Ostrom (1990) for successful communal management of a local common-pool resource ("CPR"). It cannot be the case that homogeneity in the resource and agents leads to both success and failure. Accordingly, we seek a more general characterization of open-access that reflects the asymmetric information problems that cause collective action for mitigation of rent dissipation to break down.

Table 3.1 shows how our setting compares to those considered by Gordon and Ostrom. We argue that the homogeneity and information assumptions of Gordon and Ostrom, as shown in the upper left quadrant, are not representative of resources where sustained open-access is observed. Our focus is on exploring the implications of relaxing these assumptions. We argue that most of the world's sustained open-access settings are located where inframarginal rents are earned by some agents, but low or zero rents are earned by new entrants, and there are no local communal arrangements to manage relatively small resource stocks. These conditions arise in the bottom right quadrant of the Table.

Table 3.1: Open-Access Conditions and Collective Action

	Resource Characteristics	
User Characteristics	Small, Homogeneous	Large, Heterogeneous
Homogeneous	Ostrom (1990) /Gordon(1954). No Search or Production Advantages; Willingness to Pay = Willingness to Accept; Collective Action Agreement	No Search or Production Advantages; Willingness to Pay = Willingness to Accept; Collective Action Agreement
Heterogeneous	No Search Advantages; Production Differences Observed; Willingness to Pay = Willingness to Accept; Collective Action Agreement	Our Framework: Search and Production Advantages; Willingness to Pay Willingness to Accept; No Collective Action Agreement

3.2.2 Strategies to Defend Inframarginal Rents—The Spontaneous Emergence of de facto Property Arrangements

Productive locations and specialized search and extraction techniques can be thought of as rent-generating factors of production. Low-cost users are able to sustain their rents to the extent that they can maintain exclusive use of these factors of production. Despite their advantages, low-cost users' rents may be dissipated by high-cost users' actions in two ways. First, if high-cost users attempt to directly access specialized factors of production by imitating low-cost users (either following them to productive locations or adopting what they are able to observe about extraction techniques), they may reduce inframarginal rents.[4] Second, entry by high-cost users—though it generates little to no rents—may deplete the aggregate stock in a way that reduces rents for inframarginal users.[5]

Rent earners stand to lose if others are able to dissipate their rents through entry

[4]This scenario assumes that it is less costly for high-cost users to imitate low-cost users than for low-cost users to initially discover the rent-generating factors of production.

[5]See Levhari and Mirman (1980) (providing an example of a resource harvesting problem with a Nash Equilibrium in harvest strategies that may correspond to a declining resource stock).

or imitation. The benefits of establishing informal claims under open-access derive from streams of inframarginal rents that users seek to protect. There are a variety of ways in which rent earners might defend rental streams, and the method chosen depends on the characteristics of the resource, characteristics of the rent earners, informal norms, and broad underlying political institutions. Where users can profitably invest to defend rents, informal property rights spontaneously emerge. We define an informal property right as the de facto ability to earn a stream of rents over time—to the exclusion of others—due to search and production advantages or actions taken to exclude other individuals from one's stream of rents. These informal rights may cause open-access to persist longer than would otherwise be expected if the spontaneously emerged rights do not easily convert to de jure property rights. In this case, low-cost users would resist institutional change. Hence, the type of informal property rights that emerges has important implications for whether users will be willing to transition to a formal rights regime or some other joint-management institution.

Depending on inframarginal-rent sources and other users' attempts to compete those rents away, inframarginal-rent earners may pursue numerous strategies to defend their claims. Spatial exclusion may effectively block competition in some settings. Threatened or actual force, fencing, and continued occupation are possible strategies for establishing exclusive access of a location. Spatially excluding other users produces greater returns when rents derive primarily from knowledge of productive locations and when the spatial distribution of the resource is stable over time. For example, informal spatial claims within a fishery for a stationary species like lobster have higher expected returns than spatial claims in the fishery for tuna, which migrate globally. If spatial exclusion and private information are costly or not effective, or if competitive entry continues, inframarginal users will capture more of the resource rents in the short-term, but in the long-term, Gordon's (1954) prediction of full rent dissipation prevails. Accordingly, we expect rent earners to invest in natural capital—to save some of the resource stock for later—only if they successfully establish an informal, spontaneous property right.

Users may also use the existing legal framework to exert spatial claims. Many spatially heterogeneous resources are relatively fixed and so correspond closely with the location of land. Grazing lands, surface water flow, stationary marine species, and (to some extent) oil reservoirs are a few examples. In these settings staking de jure claims to land coinciding with productive resource locations allows de facto exclusion of outsiders from the resource. Such de jure provisions quickly transform open-access resources into limited-access resources because users must have a land right prior to occupation and production. Like informal exclusion, this approach is much less effective if the spatial distribution of the resource is highly variable. For example, Lueck (1989) documents the challenges associated with managing highly migratory wild game with private property rights to land alone. Users of a resource will prefer formal, de jure claims over informal spatial claims in settings where there is a low-cost and low-risk existing legal framework for asserting title to land. In this case, users rely on the state to keep outsiders from trespassing on land and extracting the resource in their valuable location.

Faced with the prospect of resource dissipation through knowledge dissemination, users invest in knowledge and processes that are inherently difficult to communicate or copy.[6] As with search, users with lower costs of investment in knowledge and greater ca-

[6]This up-front investment in highly specialized, private, and tacit knowledge reduces the costs of

pacity to pay up-front costs will earn differential rents from their investments. Therefore, choosing whether to invest in "cheap" or "costly" knowledge has important implications for users' ability to agree on compensation when faced with the prospect of joint management or rationalization by the state. The upshot is that asymmetric information is endogenous in spatially heterogeneous resources with heterogeneous users. This same asymmetric information, however, creates barriers in negotiations for rationalization because the claims of low-cost users will be difficult for others to verify. Hence, willingness to pay and willingness to accept will diverge.

Spontaneous property rights to open-access resources tend to emerge in settings where users and resources are both heterogeneous (large potential gains), the spatial distribution of the resource is relatively stable over time, production is not fully transparent, and there is potential for learning by experience (lowering costs of developing rights). The greater the gains from asymmetric information, the more users will invest in keeping their advantages private. As in any competitive setting, rents accrue from the exclusive use of a factor of production. In our case, that factor may be an especially productive location or a production technique. Either way, rents will dissipate if knowledge of the factor is not kept private.

For those users who earn positive rents, information is valuable precisely because it is asymmetric. Developing and protecting information advantages is costly, but incurring these costs can allow users to assert an informal, de facto right to more of the resource than others who do not possess these advantages. The value, strength, and extent of these informal rights will shape users' expectations about the future of the resource stock and

maintaining privacy later.

their willingness to participate in any attempt at formal management of the resource.

3.2.3 Challenges in Transitioning to de jure Property Rights

The extent and character of spontaneously evolved, informal property rights in open-access resources determines whether collective action to create formal property rights will confront bargaining problems over rent distribution. Informal property rights emerge after costly investments in search, knowledge, and exclusion. Creating formal property rights may strand some of these investments by changing the way in which all users interact with the resource. A user's willingness to accept rationalization will depend on their expected stream of rents both under open-access and under the new regime. If the investments made to secure rents under open-access are not as productive after rationalization, then the value of formal rights is reduced and inframarginal-rent earners will demand compensation. Those investments, however, are likely difficult to value because of endogenous information asymmetries.

While recognizing informal rights is important in any transition from informal to formal property rights, rationalization of open-access resources presents unique challenges. Users' ability to earn rents in open-access derives from their ability to translate some particular realization of the stochastic resource stock into output more effectively than others. Because official rationalization by the state involves formally open-access natural resources with no legally recognized owners, it is understandable that offered shares are uniform. Uniform shares are, by definition, a direct translation of the aggregate resource stock into individual output that works in the same way for every user. Rationalization puts all users on equal footing with respect to aggregate resource variability in a given period, be it stream flow, fish stock, or rangeland. Rationalization harms low-cost users of the resource by reducing their competitive advantage. Whereas, previously, users could assert an informal right to more of the stock, rationalization makes that right conditional on the structure of formal property rights. Though low-cost users will still translate an open-access resource into output at an above-average rate, rationalization tends to reduce low-cost users' competitive advantage and artificially advantage high-cost users.

If low-cost users' informal rights to the resource exceed their formal rights assigned under rationalization, those users must formally acquire rights to the additional units of output that they previously achieved informally. This acquisition reduces the value of the information that generated rents under open-access. Users can no longer profit directly from their specialized knowledge and cannot easily convey this tacit, private knowledge to others to secure offsetting shares. The corollary to this loss is that users with higher search costs that face low probabilities of discovering productive spatial claims stand to gain from being granted the right to a given amount of output. High-cost users gain the right to the return on natural capital investments made by low-cost users, forcing these parties to buy back their own returns through additional shares. Thus, rationalization in certain settings may represent expropriation of informal property rights and redistribution of the rents from investment in informal property rights. That expropriation requires side payments—made feasible by the aggregate gains from formal controls—to informal-property-rights holders to secure agreement over rationalization.

The aggregate gains from rationalizing open-access resources may be quite large, even in settings where inframarginal users are made worse off. Costs associated with declining stocks and externalities from overproduction in both renewable and nonrenewable resources can be substantial from competition on the margin. The benefits—both immediate and long run—of instituting sustainable resource management accrue especially to high-cost, marginal users of the resource because they are most affected by variation in the stock and have the least specialized knowledge. Therefore, high-cost users ought to be willing to pay low-cost users to agree to rationalize. This willingness to pay for transfers should exceed the low-cost users' minimum willingness to accept in any setting where aggregate net gains from rationalization exist, provided that users agree about the net gains from rationalization. Agreement will nonetheless fail in the presence of what appear to be large aggregate gains if users' knowledge about the resource and the source of differential returns from exploitation systematically differ.

Individuals form their beliefs about the aggregate resource stock based on observations from particular locations in the spatial distribution of the resource. If low-cost users defend the most productive claims, then the claims available for extraction by high-cost users will be systematically less productive and lead to a more pessimistic view of the resource. Holders of informal property rights learn more about the location-specific dynamics of the resource in their location than do other users, giving them a different estimate of the stream of rents associated with holding that informal right. Alternatively, high-cost users develop a different sense of the potential rents from resource use. Each type of user learns about the resource and responds to that knowledge in sometimes fundamentally different ways. This can lead to different views about the benefits of rationalization because, in spatially connected resources such as fisheries and oil reservoirs, the productivity of each location affects the productivity of the resource as a whole.

The key insight of our framework is that inframarginal rents in open-access resources ultimately derive from differences in highly specific knowledge. Users who develop spontaneous claims to the resource develop knowledge of the stock in their private location. That knowledge generates inframarginal rents, shapes expectations of future rents, and molds investment and production choices. High-cost users learn about the resource in a different way because they observe less productive and more vulnerable parts of the stock. Low-cost users invest to protect their rents by keeping their differential knowledge private. Through this process, informal de facto property rights emerge spontaneously with no central organization or demarcation. Accordingly, these informal rights are inherently difficult to value because their basis is in asymmetric information, private, tacit knowledge and related production and investment decisions. Users seeking to negotiate over rationalization will find it difficult to credibly communicate their profitability under either regime because their differences in knowledge are the source of their differences in profitability.

Table 3.2 lists some hypotheses that structure our examination of the natural-resource cases. We use two cases, fisheries and oil and gas, to explore these hypotheses. However, we do not test these hypotheses because of limited data.

Table 3.2: Hypotheses

Differences in knowledge of specialized sites and/or production processes drive sustained inframarginal rents.
Settings where users earn inframarginal rents will be characterized by asymmetric information about the resource.
Inframarginal-rent earners are motivated to invest in strategies that generate private knowledge of the resource and/or techniques and block others from imitating.
Informal rights spontaneously emerge as spatial exclusion when the spatial distribution of the resource is not subject to high variation over time, generating durable productive locations.
Informal rights spontaneously emerge as spatial exclusion to adjacent land when bounding costs are lower than for the resource itself.
Informal spatial rights may complement valuable specialized knowledge when the spatial claim limits observation.
Informal spatial claims may be marked and defended by foregone inframarginal through under- or overexploitation.
Inframarginal-rent earners have an incentive to support rationalization if it recognizes their informal claims.
Rationalization may not be Pareto improving even when there are aggregate benefits. Distributional disputes result in delayed or blocked rationalization.

3.3 The Framework Applied

3.3.1 Oil and Gas

Nature of the Resource and Potential for Open Access

The size of oil and gas reservoirs generally is given in production potential.[7] In the United States, access to subterranean deposits is granted by surface landowners, thus surface acreage is a more useful measure for this Essay. Sizes for some prominent oil fields range from 213,543 acres for Prudhoe Bay in Alaska to 140,000 acres for East Texas to 26,400 acres for Yates in West Texas to 13,770 acres for Oklahoma City.[8] Larger fields

[7]See, for example, the list of the worlds largest oil fields in The List: Taking Oil Fields Offline, Foreign Pol'y (Aug. 14, 2006), http://www.foreignpolicy.com/articles/2006/08/13/the_list_taking_oil_fields_offline.

[8]See Gatewood (Gatewood); BP plc, Fact Sheet: Prudhoe Bay 12 (2006), available at https://dec.alaska.gov/spar/perp/response/sum_fy06/060302301/factsheets/060302301_

with more fragmented surface ownership raise the potential for open-access as greater opportunity exists for firms drilling from each parcel to compete to capture the resource. Hydrocarbon reservoirs are heterogeneous in terms of the production potential, amounts of oil versus natural gas, subsurface flows, porosity, and rock formations. Accordingly, there are more productive areas in the reservoir, often above the deepest portion, and less productive areas, often on the deposits periphery. Moreover, natural gas tends to congregate in certain areas (the gas cap), whereas oil settles in other areas (the oil rim). This heterogeneity affects the value and productivity of those firms that hold productive leases to the reservoir.

The problem of open-access losses in oil and gas production has been recognized since they were first discovered in the United States in 1859 (Libecap and Smith, 2002). Entry is limited based on the number of leases from surface landowners, but hydrocarbons migrate, thus creating the potential for competitive drilling and draining of the reservoir. Oil and natural gas deposits are under great pressure. When any part of the surrounding geologic formation is punctured by a well bore, a low-pressure area is created and natural gas and oil migrate toward the opening. Movement depends upon subsurface pressures, oil viscosity, amount of natural gas, and the porosity of the surrounding rock. In the United States, surface-land owners generally grant search and production leases to specialized firms. Both surface property owners and leaseholders have an incentive to produce rapidly, and most leases contain production timelines. Oil and natural gas cannot be left in the ground because property rights to the resource are secured only via

factsheet_PB.pdf; Julia Cauble Smith, East Texas Oil Field, Tex. State Historical Assn (June 12, 2010), http://www.tshaonline.org/handbook/online/articles/doe01; Julia Cauble Smith, Yates Oilfield,Tex. State Historical Assn (June 15, 2010), http://www.tshaonline.org/handbook/online/articles/doy01.

the rule of capture. This, combined with the spatial connectivity of reservoirs, makes hydrocarbons a classic common-pool resource.

With fragmented surface ownership, multiple firms extract from the same reservoir. Firms are motivated to drill and drain competitively to increase their shares of oil field rents, even though these individual actions lead to aggregate losses. The rule of capture results in various forms of rent dissipation. First, capital costs increase by drilling wells beyond what geologic conditions or price and interest rate projections warrant. Additionally, firms invest in surface storage to protect against drainage by other firms, and storage can lead to fire and other losses. Rents also dissipate by venting natural gas too rapidly. Natural gas is lighter than oil and is necessary to push oil across subsurface formations to the surface, necessitating early use of costly injection wells and reducing total recovery because heavy oil becomes trapped in formations as gas passes by. Finally, aggregate, long-term rent decreases because production patterns deviate from those that would maximize the value of output over time.

Characteristics of Claimants and the Existence of Inframarginal Rents

Claimants invest in specialized search and production methods and have an incentive to drain neighboring properties secretly. Though surface-land rights are secure, because migratory hydrocarbons can be extracted from many parts of the field, and because of the uncertainty as to location and size of deposits, there is an important benefit from search. Certain small firms termed "wildcatters" specialize in search and risk taking, while larger firms with multiple leases across many fields are termed "majors." Majors may also have integrated refining and retail operations along the supply chain and are more likely to agree to constraints on production to reduce open-access losses because they capture more of the in situ rents, whereas smaller lease owners depend more on drainage or hold rights to particularly valuable locations less vulnerable to overall field conditions and hence, are more likely to resist those controls. For example, unconstrained output from the East Texas field in the early 1930s led the Governor of Texas to place the field under martial law, enforced by the National Guard. The production constraints' main problem was rampant violation by small firms (Steven N Wiggins, 1987).

What is important for our purposes is that leaseholders all rely on private information to develop their understanding of the resource and that small and large leaseholders get different information about the reservoir based on the size and location of their claims. Some leases are far more productive than others, and holders of leases to small, very valuable portions of a reservoir are often favorably positioned to capture subterranean hydrocarbon flows and earn rents, even in the presence of competitive open-access drilling and production. These leaseholders have different assessments of the hydrocarbon stock's long-term viability and resist unitization or buyout as solutions.

Nature of Spontaneous Property Rights

Informal claims to hydrocarbons correspond to de jure property rights to surface land. In competitive oil and gas production, firms secure rights to search and produce through leases from land owners and property rights to oil via the rule of capture. Information on lease output from individual wells is public, but it is descriptive only of the immediate vicinity of a well and does not necessarily reflect subterranean conditions (Wiggins and Libecap, 1985). This creates incentives for competitive waste. Through drilling individual leases, firms gain knowledge of their portion of the reservoir, though the full extent of the deposit and the other areas' production potential are revealed only through other firms' drilling activities. A lease's production potential and commercial value are a function of objective variables—such as the number of wells, current and past production, and lease acreage—as well as subjectively evaluated geological variables—including the amount of oil below lease lines, net oil migration, oil viscosity, permeability of the surrounding medium, bottom hole pressure, net-acre feet of pay (nonporous and non-oil-bearing rock are subtracted for estimates of gross acre feet of pay, which is the estimated size of the producing formation), and assessments of remaining reserves below lease lines and location of the lease above subsurface flows (some leases are well situated to capture hydrocarbon movement across the formation). Interpreting data gathered from well bores suggests the thickness of the formation, oil and gas migration, and surrounding medium conditions and allows for estimating how production techniques might fracture the formation and release more hydrocarbons. Company engineers translate these interpretations into long-term projections for production, revenues, and costs through subjective assessments. Those assessments are private information and may differ importantly among engineers from different firms, but they are the basis for lease owners' individual value estimates.[9]

[9]The likelihood that there will be differing, and difficult to reconcile, valuations of particular leases increases with the complexity and depth of a formation as well as with the amount of oil and natural gas lodged within.

Formal and Informal Attempts to Rationalize

Local common-oil pool management occurs through unitization or by lease consolidation through buyout. In either case, the rule of capture is replaced by single-firm extraction or ownership of the subsurface hydrocarbon stock. But leases are not uniform in production potential or value and this heterogeneity blocks agreement on those options. When competitive extraction is eliminated, output timelines can maximize return, capital investment in wells and storage occurs only if it is profit enhancing; and overall recovery increases.

By the early 20th century, oil was valuable enough to raise concerns about open-access losses and engineering information developed sufficiently to understand potential remedies. Despite this, neither the option for joint management through unitization or lease buyout was widespread through the 20th century. Even where the numbers of lease owners are relatively small, a local complete solution generally did not occur (Libecap and Wiggins, 1984). As late as 1975, neither Oklahoma nor Texas had as much as 40% of production from fully-unitized fields, and even the huge Prudhoe Bay field, discovered in 1968, suffered from competitive production until buyout was completed in 1999 (Libecap, 2008). In their analysis, Wiggins and Libecap (1985) and Libecap and Smith (2001) show that opposition has not merely been held up by lease owners to extract more of field rents, with lease owners defecting sequentially as purchase agreements are completed or as unit agreements are finalized. Rather, certain lease owners systematically resist because they believe their leases are more valuable than do those seeking to purchase or unitize with them.

Wiggins and Libecap (1985) identify small leaseholders above the deepest and potentially longest-lived portion of the reservoir as the firms most likely to resist buyout or unitization. Estimating long-term production patterns in these areas involves more subjective private information and more uncertainty than for leases located in shallower areas on the field periphery, where value assessments based on private and public information often converge. Firms with large leases covering more of the reservoir, or with many leases on the field, are also more likely to have value assessments agreed upon by others because differing value assessments across leases offset one another. Libecap and Smith (2001) also emphasize the bargaining problems raised when lease owners specialize in oil or natural gas due to the difficulty in valuing the two different hydrocarbons and in developing an agreeable conversion factor to translate natural gas into oil or vice versa. This is a significant issue because 63% of the largest U.S. oil fields have significant volumes of natural gas along with oil; oil lease owners prefer to re-inject gas into the formation to expel the oil, whereas gas lease owners prefer to sell the gas.

Another related asymmetric information problem that is not stressed by Wiggins and Libecap or Libecap and Smith is valuing locational advantages and investments that provide value under open-access but not under rationalization. Unitization changes field and production dynamics such that lease locations above past reservoir flows and related investment in resources knowledge and production may no longer have value. This is, in effect, stranded capital that affected firm owners would seek to recover in voluntary transactions as part of their willingness-to-accept calculations. At the same time, other parties may disagree on the value claims made by those lease owners. Hence, willingness-to-pay calculations may be too low to support side payments.

In a detailed analysis of unitization efforts for seven reservoirs in Texas and New Mexico, Wiggins and Libecap (1985) found that negotiations took from four to nine years to complete. Negotiations for one of the fields, Empire Abo in New Mexico, took six years and required 58 different votes on the distribution of shares. The division of net revenue via shares is specified at unit agreement, and these are permanent; updates are not possible because once the unit is formed, production dynamics change and the lease loses its production role. Some wells are plugged and others are converted to natural gas injection to maintain subsurface pressure, changing subterranean hydrocarbon flows. The absence of contingent updates places particular pressure on long-lived leaseholders who have the most asymmetric information and uncertainty associated with calculating lease values. Moreover, in five of the seven cases, the final unit's acreage was far less than that involved in the early negotiations because not all parties would agree. Subunits, however, are less complete solutions because they involve only part of the formation and because they require drilling costly boundary wells to block the migration of hydrocarbons to non-cooperating leases. Libecap and Smith (1999) examine 60 unit agreements and find that those with distinct oil and gas deposits are most apt to be incomplete. They detail the case of Prudhoe Bay where 31 years from discovery passed with competitive subunits until lease owners on the gas area (gas cap) and the oil area (oil rim) agreed to consolidate. In the meantime, there was substantial waste in lost oil production and excessive, competitive capital.

Large firms, often majors, with multiple leases across many non-unitized oil fields bear disproportionate costs from the failure to cooperate to control rent dissipation. These leaseholders lobby state legislatures to impose field-wide unitization. This, however, produced opposition from the same small lease owners that resist voluntary private agreements (Libecap and Wiggins, 1985). Lease owners do not believe they would receive sufficient returns under the new arrangement, even with open-access, and forced unitization or rationalization does not offer compensation to align willingness to accept with willingness to pay. Similarly, the State of Alaska could not force complete unitization of Prudhoe Bay, and other states' forced-unitization statutes implement assigned net production shares to complete units only once a designated percent of the field acreage agrees to unitize. In Oklahoma, compulsory unitization legislation was adopted in 1945, which required unitization once 85% of the leased acreage supported unitization. This percentage was gradually reduced to 63% by 1951 as production declined and information asymmetries dissipated. In Texas, however, opposition by small-lease owners continues to block a compulsory unitization law forcing lease owners to accept a share that they believed undervalued their leases (Libecap and Wiggins, 1985).

Oil and gas search and production under open-access has not led to smooth and quick responses to close the potential for rent dissipation. Rather, opposition of particular lease owners that do well under open-access delayed or limited possible institutional responses. Despite a general belief that gains are possible from defining more precise formal property rights, the parties cannot agree upon the sharing of those rents. As described in the framework above, distributional factors impede agreement on what otherwise would be efficiency-enhancing institutional change.

3.3.2 Fisheries

Nature of the Resource and Potential for Open Access

Depending on the species, fish stocks may be large and variable as to location in the sea and migration patterns. Shellfish, such as oysters, lobsters, mussels, crabs, and clams, tend to be located in specific sites with little movement, whereas demersal and pelagic fish move more broadly. Distribution is often imperfectly known, and uncertainty increases with range of movement and variation in currents and sea floor terrain. Accordingly, the sea is heterogeneous in the probability of harvest, and this condition creates returns to search and a race to locate the richest fishing areas. The potential areas involved are very large, even within U.S. waters.[10]

In 2013, the largest fisheries by landings in the United States were Pollock, Menhaden, Pacific Cod, Pink Salmon, and Pacific Hake (NOAA, 2013). Historical catch rates grew rapidly beginning in 1940 before slowing dramatically by 1970, drawing attention from the scientific community and from policymakers. That slowdown resulted in the passage of the Magnusson-Stevens Act—the United States' first national fishery legislation—which established the extent of U.S. territorial waters and outlined fisheries management goals (Magnuson, 1976).

The Magnusson-Stevens Act sets few restrictions on entry, either because of the migratory nature of the species or due to legal requirements in the United States for open-access by the general population. For this reason, wild ocean fisheries are classic open-access

[10]The length of U.S. coasts is 12,383 miles with tidal shorelines comprising 88,633 miles. The exclusive economic zones (EEZs) of the U.S., in turn, extend out 200 miles into the open sea except where constrained by the international boundaries of adjacent coastal states.

resources. Fishers from many different ports can intercept migratory stocks, and rising fish prices encourages entry. But competitive access also means that fish stocks are depleted from over-harvest; firms over-capitalize and invest excessive labor inputs; catch-per-unit-of-effort and incomes decline; and product value decreases by the rush to harvest. Therefore, output is comprised of small or juvenile fish or frozen fish products rather than more valuable larger and fresher products, which are possible only with moderated fishing effort. Indeed, fish stocks are the focus of the most complete discussion of the theory and empirical evidence of the losses of open-access.[11]

Characteristics of Claimants and the Existence of Inframarginal Rents

Fishers invest in specialized search and production skills and capital, and in concealment through limited information sharing. As a result, they are heterogeneous in their search and production skills, and differential harvests and incomes persist. In fishing communities, there is a hierarchy of fishers exploiting the resource, and more skilled fishers—termed "highliners"—consistently outperform others (Johnson and Libecap, 1982). Scott notes: "Fisheries experts repeatedly speak of durable groupings of skippers, vessels, and crews according to the size of their catch or earnings, year in and year out" (Scott, 1979, p. 733). These returns are primarily attributed to knowledge of how to set nets and regulate their spread, where to set lines and their depth, correct trawling speed, and identifying where to find fish.[12] Skills develop over time and are not easily duplicated. They cannot be readily conveyed or valued from fisher to fisher or from skipper to skip-

[11] See generally Gordon (1954); Devine et al. (2006); Grafton et al. (2000a); Myers and Worm (2003); Scott (1955); Smith (1969)

[12] See generally Hilborn (1985); Kirkley et al. (1998) (discussing the relationship between sea captains' experience and education and fishing productivity).

per. Long-lasting, higher-than-average catches translate into inframarginal rents that exist even when average fishers may earn no rents. Johnson and Libecap (1982) provide evidence of persistent differential harvest returns among fishers using data from the fall 1978 bay shrimp season on the Texas Gulf Coast. Fishers with catches one standard deviation above the sample mean were termed "good," those at the mean, "average," and those one standard deviation below the mean, "poor." These differences across fishers persist through the fishing season.

Similar to oil and gas lease valuation, public information on differential success includes past and current harvests, vessel size, equipment, crew size, and departure and arrival times at port. Private information includes the subjective interpretation of tides, water temperatures, ocean currents, floor terrain, historical migratory patterns of the stock, as well as the art of fishing itself.

Nature of Spontaneous Property Rights

Enforcing claims to fish stocks via land or other spatial claims is not feasible for highly migratory fish species. Instead, control arises from investment in specialized search and production skills and keeping information private or asymmetric. Because fishers for migratory fin fish cannot easily establish spontaneous, informal first-possession claims, they rely upon secrecy and limited information sharing about productive fishing locations and useful fishing techniques among vessels from their own community or fleet. There are complex, quid-pro-quo information sharing practices that favor long-term, local knowledge of the stock and of fishers. Other less-skilled, higher search-and-production-cost fishers have incentives to free ride as much as possible, so highliners limit information sharing (Wilson, 1990). As with hydrocarbons, secure property rights to open-access fish are granted only by the rule of capture. Hence, first arrival at a spot and secrecy (as well as superior skills and lower costs) form a type of spontaneous property right when more formal ownership rights, such as those called for by Scott (1955), are not feasible.

Formal and Informal Attempts to Rationalize

Widespread open-access losses in fisheries since the 1970s prompted state and federal governments in the U.S. to implement various regulations to constrain entry and harvest. These constraints include limited entry, limited fishing seasons, vessel, and equipment controls (Homans and Wilen, 1997). Fishers adapted around these regulations such that stock and rent depletion continued. Grafton et al. (2000a) detail vessels and other capital increases in the Pacific Northwest halibut fishery as seasons tightened to protect the stock. Between 1980 and 1989, the number of vessels rose by 31% and as stock levels fell, regulators progressively reduced the fishing season from 65 days to six days a year by 1990. The shortened season increased investment by fishers in larger and more powerful vessels and created a competitive fishing derby to harvest as many fish as possible in the limited time available.

Recent rationalization efforts involve assigning individual transferable quotas ("ITQs") and these arrangements increased fishery rents (Cosetllo et al., 2008). ITQs involve setting an annual total allowable catch ("TAC") and shares of that total allowable. Rationalization via ITQs was first proposed as a solution to open-access conditions in fisheries in 1972, but the United States has been slow to adopt individual transferrable rights in fisheries (Libecap, 2008). Our framework sheds light on why this might be the case, given the characteristics of the resource outlined above and the claimants themselves, which we describe below.

Johnson and Libecap (1982) describe how spontaneous property rights and inframarginal rents based on those rights, earned by highliners, are at risk from rationalization that imposes uniform quotas or in other ways undermine their skill and knowledge advantages and investments. These advantages and related human and physical capital investments allow highliners to out-compete others under regulated open-access. Unless they are compensated, rationalization is not Pareto-improving for highliners, even though the overall fishery stock is better-conserved and total rents increase. Similarly, Abbott and Wilen (2011) discuss how catch limits to reduce bycatch result in races to harvest commercially valuable stocks before reaching the total allowable bycatch. These regulatory-imposed races change optimal fishing strategies, potentially reducing returns and inframarginal rents.

There are few documented cases of highliner-opposed rationalization. Deacon et al. (2013) provide such a study of the short-lived Chignik Salmon Fishery Cooperative in Alaska. In 2002, the Alaska Board of Fisheries approved a request from a group of fishers to create a voluntary cooperative to coordinate harvests and limit effort and vessels. Eighteen highliners, whose catch histories exceeded those of members, chose not to join. The Alaska Board of Fisheries increased the share of the total annual allowable catch assigned to the cooperative as the number of cooperative members grew from 77 to 87. The cooperative retired the proportion of permits and vessels that otherwise would be used by its higher-cost members by 31%, reducing capital and labor costs per unit of harvest. It also increased the fishing time or season for its members by about 48% by reducing the race to intercept fish in the open ocean.

Highliners and members generally agreed that the cooperative improved overall rents by around 33%, but disagreed as to the division of the rents. The cooperative was granted a growing share of the TAC as its membership expanded. Hence, allowable harvests were not distributed according to historical catch shares, and the share granted by the regulators to independents declined in 2004 by 40%. Independents' share of the total allowable catch threatened their inframarginal advantages, which were most valuable under competitive conditions and entry controls. In the face of this, two of the most successful highliners successfully sued to block the Alaska Board of Fisheries' allocations to the cooperative in 2005, and the cooperative was dismantled by court order.[13]

One might ask why allocation did not use historical harvest. The cooperative changed fishing practices and location so that past practices reflecting fish interception in the open ocean and uncoordinated harvest were no longer relevant. Highliners who invested in those techniques demanded compensation or allocations based those techniques. Cooperative members, however, were earning rents based on new coordinated fishing practices, not historical ones, and apparently did not have willingness-to-pay commensurate with the willingness-to-accept demands of highliners. Although there is no information as to the source of any bargaining breakdown, such a breakdown is consistent with difficulties in valuing stranded capital and skills appropriate for open-access and a race to capture stock, but not relevant or valuable under rationalization. This bargaining breakdown in the presence of aggregate benefits is similar to outcomes observed in oil field unitization

[13]The Alaska Supreme Court ruled that the co-op was inconsistent with Alaska's Limited Entry Act of 1973, which requires "present active participation" of any permit-holder in a fishery (Deacon et al., 2008).

efforts, and likely undermines other efforts to rationalize.

3.4 Conclusion

This Essay outlines a framework for understanding how informal property rights emerge in open-access resource settings traditionally characterized as lacking any sort of property right. Our approach elucidates why sustained open-access is observed, even in the presence of apparently large aggregate benefits from transitioning to joint management of the resource. Heterogeneous users of spatially heterogeneous resources will invest in differential levels of search and learning, accumulating knowledge that generates inframarginal rents. In response to threats of continued entry, replication, and other forms of rent dissipation, inframarginal-rent earners invest in strategies to protect their expected rental streams. These strategies create and entrench asymmetric information about any particular institution's costs and benefits for managing the resource, making bargaining between parties costly, potentially to the exclusion of side payments for what otherwise appears to be a Pareto-improving transition to formal management of the resource.

Our framework describes heterogeneous users' behavior in settings lacking formal property rights, but our predictions are inherently difficult to test. We argue that the source of users' ability to earn and protect positive rents is tacit—private knowledge that is, by design, difficult to communicate. Our framework explains why some resources have proven less amenable to rationalization. We document differential skill in locating hydrocarbons and fishery resources. Differential search and learning in each setting resulted in users with differing knowledge about the resource. This differential knowledge stymies rationalization attempts.

Rationalization is the chosen policy tool for spatially connected resources because each user's behavior affects all other users by changing the aggregate stock available, even when the resource is spatially heterogeneous. Hydrocarbons and fishery resource both fit this pattern. In both cases, we show that users exhibit differing levels of search, investment, and knowledge, resulting in a heterogeneous distribution of rents that is correlated with users' knowledge of the resource itself. Both resources have seen repeated attempts at rationalizing. When unsuccessful, rationalization fails due to users' inability to reconcile their contradictory "knowledge of the particular circumstances of time and place" to form an agreement about characteristics of the aggregate resource (Hayek, 1944). The result is sustained open-access with competitive losses that are larger for high-cost users who tend to know less about the resource.

3.5 Permissions and Attributions

The content of chapter 3 is the result of a collaboration with Gary D. Libecap, and has previously appeared in the Iowa Law Review (Leonard and Libecap, 2015). It is reproduced here in accordance with the reprint policies of the Iowa Law Review.

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Appendices

Appendix A: Theoretical Appendix to Chapter 1

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 claimants' 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 negative 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 $\bar{N}^{PA}$ (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

$$0 = C'(x_i).$$

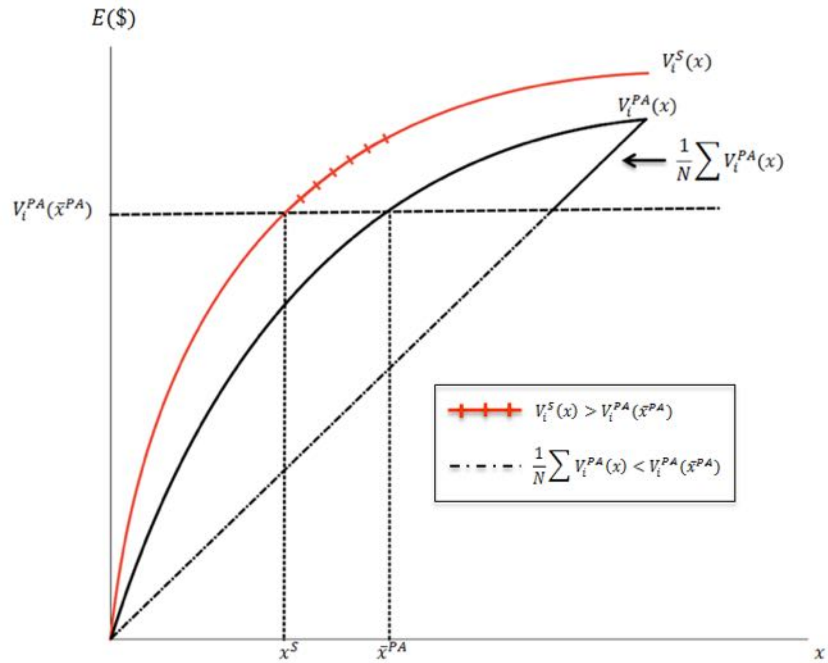
It follows that $x_i^* = 0$, $V^S(0) = 0 < V^{PA}$. For sufficiently large N, the expected share size approaches zero and expected revenues do not exceed expected costs, resulting in zero investment. In this same scenario, the prior appropriation system allows the first $\bar{N}^{PA}$ users to enter 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 size 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 3.1: 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, $V^E > V^S$.*

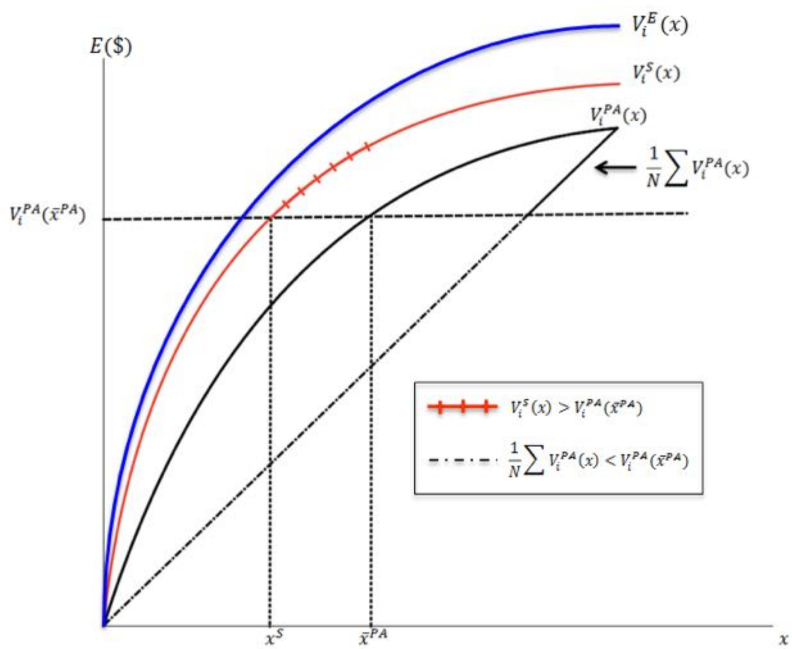
Proof: First, we establish that V^E has a convex region (in N) for sufficiently large γ.

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

If the positive externality is the larger than the ratio of the change in profits to the investment of the 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 $\exists \ \ x_i^S(N) < \bar{x}^{PA}$ 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 3.2: 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 presence of a sufficiently large positive externality. If expected flows are equal across streams, being a junior claimant dominates claiming a new stream, and users follow. QED.

Appendix B: G.I.S. Data Construction for Chapter 1

GIS Hydrologic data on basins, stream names, and network characteristics come from the National Hydrography Data Set (NHD). The NHD 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.[14] Elevation data are measured at 30-meter intervals and

[14]NHDPLUS, provided by the Horizon Systems Corporation, is an augmented version of the National Hydrography dataset that has been combined with the National Elevation Data Set and the PRISM

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.[15] 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 us to use a current GIS measure of soil quality to estimate historical soil quality over the period of our 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 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).[16] The NHDPlus V2 dataset created by Horizon Systems Corporation provides monthly and annual stream flow estimates for each stream on the NHD network. We use this information to create a measure of the

climate dataset to produce a variety of flow-related statistics across the entire stream network.

[15]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.

[16]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.

total flow across May through August.[17] 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.[18] 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 upon request.

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

[18]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 for Chapter 1

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 (cfs)		-0.00000303^{**}	-0.00000302^{**}	0.00000675^{***}
		(0.00000145)	(0.00000144)	(0.00000149)
Lagged Claims* Total Water Claimed		0.000000247	0.000000225	-0.000000351
		(0.000000311)	(0.000000306)	(0.000000258)
Lagged Claims*$\mathbb{1}$(Drought)			0.0584	
			(0.0783)	
Total Homesteaded Acres				-0.0000350^{***}
				(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 (cfs)		−0.00000246	−0.00000235	0.00000797**
		(0.00000417)	(0.00000368)	(0.00000337)
$\mathbb{1}$(Lagged Claims>0)* Total Water Claimed		−0.00000184	−0.00000175	−0.00000238
		(0.00000526)	(0.00000566)	(0.00000793)
$\mathbb{1}$(Lagged Claims>0)*$\mathbb{1}$(Drought)			−0.437*	
			(0.225)	
Total Homesteaded Acres				−0.0000317***
				(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	1,397.6	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	−29,936.76	−29,163.77
	(316.8)	(354.3)
Acres Loamy Soil	60.2	11.1
	(8.1)	(1.7)
Ditch Meters	13,522.2	7,724.0
	(1532.2)	(965.1)
Potential Riparian Claims	50.42	28.43
Per Stream	(72.93)	(47.46)
Actual Appropriative Claims	3.11	2.48
Per Stream	(9.77)	(9.58)
Actual Homestead Claims	84.68	11.1
Per Township	(146.38)	(41.37)
Number of Streams	625	439

Appendix D: Data Appendix to Chapter 2

Table D1: Robustness Checks of Parcel-Level Tobit Estimates of Days Elapsed

	Baseline	Includes Parcel Coordinates	Omits City Parcels	Omits Neighborhoods with >50% City Parcels	Includes Federal & State Govt. Parcels
	(1)	(2)	(3)	(4)	(5)
Parcel acres	-5.808***	-5.733***	-5.687***	-5.683***	-4.732***
Parcel longside	-749.2***	-733.1***	-685.2***	-648.9***	-787.5***
St. dev. of neighbor size	27.70***	26.30***	29.47***	19.47***	26.30***
Fee parcel indicator	131.5	-92.76	80.28	-72.06	352.9
	(245.2)	(290.5)	(247.3)	(244.1)	(229.8)
Allotted trust parcel indicator	15.95	-153.3	7.468	-76.69	164.5
	(213.0)	(226.8)	(221.3)	(232.2)	(189.8)
Tribal parcel indicator	32.94	-132.6	79.73	31.56	144.8
	(228.2)	(232.5)	(240.4)	(260.2)	(218.0)
No. of tenure regimes	106.5**	103.5***	113.1***	108.2***	29.53
	(42.11)	(40.14)	(42.51)	(39.69)	(32.42)
Off reservation neighbors	8.058***	8.276***	7.063***	7.067***	7.451***
	(1.701)	(1.793)	(1.671)	(1.660)	(1.134)
Fee neighbors	7.283***	7.387***	6.211***	9.898***	6.832***
	(1.355)	(1.424)	(1.212)	(1.429)	(1.098)
Allotted trust neighbors	14.92***	14.48***	13.51***	12.89***	12.30***
	(3.113)	(2.779)	(2.846)	(2.778)	(3.122)
Tribal neighbors	0.200	-2.804	-9.864	-12.45	-2.806
	(8.318)	(8.186)	(6.904)	(7.731)	(8.452)
Covariates	All	All	All	All	All
Oil field fixed effects	Yes	Yes	Yes	Yes	Yes
City parcels	Yes	Yes	No	No	Yes
>50% city parcels	Yes	Yes	Yes	No	Yes
Parcel coordinates	No	Yes	No	No	No
Neighborhoods w/gov. land	No	No	No	No	Yes
Pseudo R-squared	0.050	0.051	0.039	0.038	0.048
Observations	27,480	27,480	23,438	22,397	41,452
Censored at 3772 days	16,687	16,687	12,987	12,194	23,764

Notes: We do not show some standard errors in order to save space. Column 1 is the baseline specification from column 4 of table 2. Column 2 includes oil field fixed effects and the x and y coordinates of the parcel's centroid. Column 3 drops all parcels that are within a city. Column 4 drops all parcels that are within a city and also non-city parcels in neighborhoods with greater than 50 percent city parcels. Column 5 includes neighborhoods that have federal and state owned parcels. Column 5 also includes the following controls: (a) indicators for Bureau of Land Management (BLM), U.S. Forest Service (FS), and North Dakota (ND) state-owned parcels and (b) the number of BLM, FS, and ND parcels in each neighborhood. Standard errors are clustered by oil field and shown in parentheses.

Table D2: Parcel-Level Estimates of Days Elapsed with Spatial Error Corrections

	Tobit Estimates Y = Days elapsed between Jan. 1, 2005 and first horizontal line (as of May 1, 2015)				***OLS Estimates*** Y = 1 if at least one horizontal line cuts parcel	
	(1)	(2)	(3)	(4)	(5)	(6)
Parcel acres	-6.226***	-5.418***	-2.876***	-3.051***	0.00159***	0.00163***
	(0.141)	(0.138)	(0.133)	(0.137)	(0.0001)	(0.0001)
Parcel longside	-371.0***	-320.3***	-362.6***	-336.1***	0.217***	0.203***
	(30.15)	(29.42)	(30.39)	(29.16)	(0.0169)	(0.0161)
St. dev. of neighbor size	44.56***	44.61***	10.93***	10.53***	-0.00611***	-0.00609***
	(1.707)	(1.721)	(1.117)	(1.402)	(0.00067)	(0.00082)
Fee parcel indicator	336.6***	419.0***	117.5***	73.16*	0.0203	0.00781
	(31.09)	(29.38)	(27.35)	(38.00)	(0.0142)	(0.0189)
Allotted trust parcel indicator	55.52	154.7***	100.6***	79.83*	0.0601***	0.0286
	(38.64)	(37.52)	(34.48)	(40.91)	(0.0218)	(0.0244)
Tribal parcel indicator	163.6***	273.6***	151.3***	107.7***	0.0146	-0.00777
	(38.67)	(37.58)	(33.77)	(41.08)	(0.0217)	(0.0251)
Neighbor Variables						
No. of tenure regimes	-14.44	-10.53	37.30***	37.03**	-0.0236**	-0.0266***
	(12.24)	(11.29)	(8.597)	(8.513)	(0.00581)	(0.00572)
Off reservation neighbors	1.891*	7.974***	2.284***	3.162***	-0.0236***	-0.0266***
	(0.0265)	(0.214)	(0.171)	(0.219)	(0.000121)	(0.000151)
Fee neighbors	1.113***	6.073***	2.290***	2.818***	-0.00124***	-0.00164***
	(0.0356)	(0.178)	(0.140)	(0.176)	(0.00009)	(0.00012)
Allotted trust neighbors	0.0277	0.723	5.156***	6.995***	-0.00209**	-0.00334***
	(0.743)	(0.763)	(0.716)	(0.920)	(0.00046)	(0.00058)
Tribal neighbors	3.591***	2.719***	0.804	-0.233	0.00117**	0.00165**
	(0.800)	(0.805)	(0.763)	(1.086)	(0.00495)	(0.00067)
Covariates						
Thickness-to-depth ratio	4,833***	52,574***	-56,723***	-51,905***	36.91***	34.61***
Feet to water (000s)	31.28***	29.87***	15.21***	18.33***	-0.00596***	-0.0118***
No. Neighbors underwater	13.95***	13.25***	6.475***	9.034***	-0.00397***	-0.00575***
Topographic roughness	2.597***	2.034***	0.565***	0.314***	-0.000371**	-0.000241***
City indicator		-24.92	-1.458	48.07***	-0.00921	-0.0533***
Feet to railroad (000s)		15.57***	3.248***	8.378***	0.000366	-0.00498***
Road density in radius		-0.0768***	-0.0247***	-0.0351***	0.0000124***	0.0000205***
x coordinate of parcel (000s)			0.293			-0.00255***
y coordinate of parcel (000s)			0.674***			0.00001***
Oil field fixed effects	No	No	No	Yes	No	Yes
Adjusted R-squared	0.937	0.940	0.956	0.959	0.552	0.585
Observations	27,480	27,480	27,480	27,480	27,480	27,480

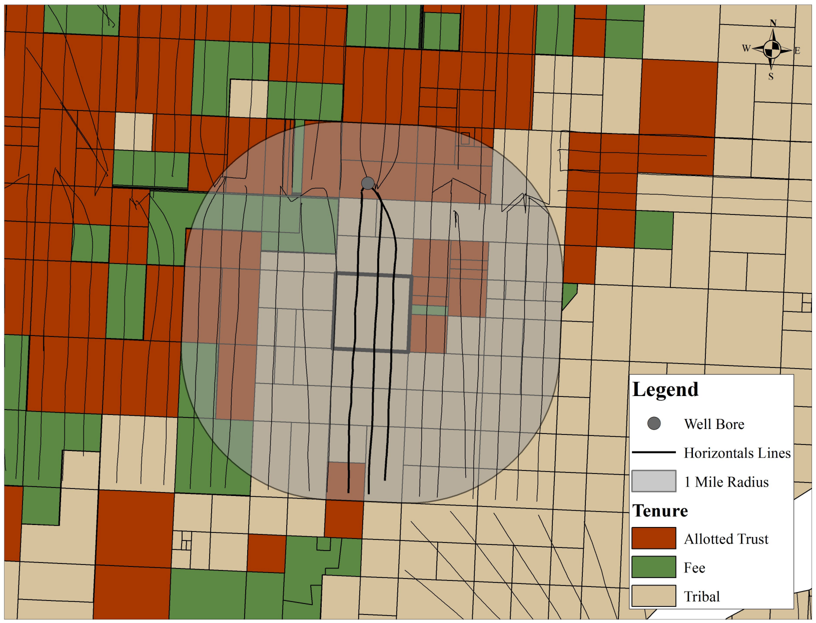
Notes: Spatial HAC standard errors reported in parentheses. Following Hsiang (2010), these models are estimated using a GMM approach that allows for arbitrary forms of spatial correlation in the error term, as described in Conley (2008).

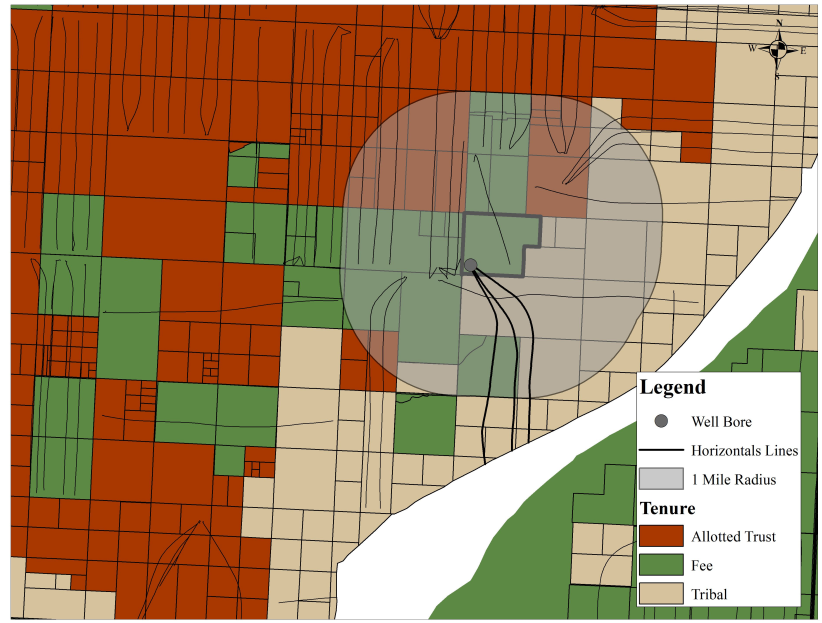
Table D3: Parcel Level Estimates of Days Elapsed for Sample of Off-Reservation Parcels

	Tobit Estimates Y = Days elapsed between Jan. 1, 2005 and first horizontal line (as of May 1, 2015)				*OLS Estimates* Y = 1 if at least one horizontal line cuts parcel	
	(1)	(2)	(3)	(4)	(5)	(6)
Parcel acres	-4.893***	-4.561***	-4.706***	-5.138***	0.00108***	0.00117***
	(0.552)	(0.535)	(0.576)	(0.587)	(0.000127)	(0.000132)
Parcel longside	-922.5***	-869.1***	-880.6***	-764.3***	0.255***	0.230***
	(78.80)	(67.69)	(69.65)	(68.60)	(0.0205)	(0.0202)
St. dev. of neighbor size	27.06***	27.28***	27.79***	12.21**	-0.00649***	-0.00327**
	(5.516)	(5.768)	(5.770)	(5.537)	(0.00127)	(0.00133)
US BLM parcel indicator	401.8***	434.5***	432.6***	406.3**	-0.119***	-0.115***
	(155.7)	(154.3)	(153.7)	(171.9)	(0.0384)	(0.0413)
ND state	190.6	212.4	216.6	217.5	-0.0215	-0.0394
parcel indicator	(146.8)	(139.7)	(140.8)	(138.5)	(0.0499)	(0.0476)
Neighbor Variables						
No. of tenure regimes	66.83	42.92	39.46	-1.970	-0.0134	-0.00298
	(54.71)	(51.74)	(50.61)	(42.44)	(0.0114)	(0.00972)
Off Res. Fee neighbors	1.598***	6.376***	6.726***	6.744***	-0.00149***	-0.00181***
	(0.615)	(1.418)	(1.404)	(1.033)	(0.000323)	(0.000289)
US BLM neighbors	8.953	2.247	1.943	0.907	-0.00117	-0.000645
	(7.087)	(6.427)	(6.499)	(5.794)	(0.00131)	(0.00167)
ND state neighbors	-43.79***	-44.91***	-47.50***	-37.57***	0.0106***	0.00927***
	(16.98)	(14.80)	(13.37)	(8.761)	(0.00393)	(0.00262)
Covariates						
Thickness-to-depth ratio	-101792***	-95842***	-129675***	-109854***	37.58***	31.24***
Feet to water (000s)	33.96***	35.99***	32.06***	32.95*	-0.00809***	-0.0111**
No. Neighbors underwater	28.51*	32.46**	29.99**	41.05***	-0.00757***	-0.00845***
Topographic roughness	0.383	0.0313	0.0475	-0.0936	-0.000107	-0.0000110
City indicator		526.2**	493.2*	394.9**	-0.0842	-0.0710
Feet to railroad (000s)		13.95**	14.76**	20.47**	-0.00129	-0.00230
Road density in radius		-0.0663***	-0.0686***	-0.0718***	0.000016***	0.000021***
x coordinate of parcel (000s)			2.985			-0.00192***
y coordinate of parcel (000s)			2.516			-0.000336
Oil field fixed effects	No	No	No	Yes	No	Yes
Pseudo R-squared	0.033	0.035	0.035	0.048		
Adjusted R-squared					0.237	0.307
Observations	31,556	31,556	31,556	31,556	32,057	32,057
Censored at $\geq$ 3,772 days	17,622	17,622	17,622	17,622	NA	NA

Notes: Standard errors are clustered by oil field and shown in parentheses. * $p < .1$, ** $p < .05$, *** $p < .01$. A parcel's neighborhood includes all parcels touching a one-mile radius extending from the parcel's exterior boundary. All specifications control for the slight variation in the total area of the one mile radius, due to variation in the size of parcels on the exterior of the radius. US BLM indicates parcels owned by U.S. Bureau of Land Management and ND state land denotes parcels owned by the state of North Dakota. The sample excludes all parcels on the Fort Berthold reservation.

Figure D1: Examples of our Mapping from Spatial Data to Empirical Variables





Appendix E: Theoretical Appendix to Chapter 2

Collective agricultural profit, π_A, is equal to agricultural revenue minus costs, where is the output price and $F(K, L)$ is the production function. Agricultural output and costs are a function of aggregate investment, K, which includes digging ditches, planting trees, fertilizing soil, etc. Investment is a function of output price, land area, the price of investment (r), and N, the number of claimants with use rights. Total profit from agriculture is

$$\pi_A = p_A F(K, L) - rK$$

If the land is subdivided into N parcels, then each individual chooses per-acre capital investment to maximize agricultural income across the L/N acres they own. Suppose that constant returns to scale in land dominate for parcels larger than L_A and that $N \leq L/L_A$ so that each user faces constant returns to scale and we can write per-acre investment as

$$f(k) = F\left(\frac{K}{L}, 1\right)$$

Then each individual chooses per-acre capital investment to maximize agricultural income across the L/N acres they own:

$$\max_{k_i} \quad \pi_i = \left(\frac{L}{N}\right)[p_A f(k) - rk]$$

Optimizing with respect to k_I and solving we have:

$$k_i^{SD} = f'^{-1}\left(\frac{r}{p_A}\right) \quad \text{and} \quad K_i^{SD} = \left(\frac{L}{N}\right) f'^{-1}\left(\frac{r}{p_A}\right)$$

The superscript SD denotes the subdivided regime. In aggregate, we have

$$K^{SD} = N\left(\frac{L}{N}\right) f'^{-1}\left(\frac{r}{p_A}\right) = Lf'^{-1}\left(\frac{r}{p_A}\right)$$

When land is subdivided and privatized, we see that aggregate agricultural investment depends on land area and output and input prices. Aggregate agricultural investment, however, does not depend on N.

Next, consider the case when land is not subdivided into private parcels but instead remains held in common. Under this common property regime, each of the N individuals has use rights but lacks exclusion rights. Hence, returns on agricultural investments are not excludable. Each individual user solves

$$\max_{k_i} \quad \pi_i = \left(\frac{L}{N}\right) p_A f(\sum_{i=1}^{N} k_i) - rLk_i$$

The individual users optimize by choosing k_I , taking as given the investment choices of all other users. If we assume symmetric behavior in a Cournot-Nash equilibrium, the solutions for k_I are:

$$k_i^{CP} = \frac{f'^{-1}\left(\frac{Nr}{p_A}\right)}{N} \quad \text{and} \quad K^{CP} = Lf'^{-1}\left(\frac{Nr}{p_A}\right)$$

Comparing the outcomes, we see that $K^{SD} \geq K^{CP}$ if

$$f'^{-1}\left(\frac{r}{p_A}\right) \geq f'^{-1}\left(\frac{Nr}{p_A}\right)$$

The second-order condition for profit maximization requires $f''(\cdot) < 0$, which implies that $f'^{-1}\left(\frac{r}{p_A}\right) \geq f'^{-1}\left(\frac{Nr}{p_A}\right)$ holds for all positive prices and rental rates.

Next, we show that the solution to the subdivided problem is identical to the investment level that a sole owner would choose to maximize the value of the resource from agriculture. Suppose a sole owner chooses per-acre investment to maximize total agricultural income of the land area L. The sole owner's problem is to choose per-acre investment for each of the L acres to maximize total profits.

$$\max_{k} \quad \pi = L[p_A f(k) - rk]$$

The first-order necessary condition for a maximum is:

$$\frac{\partial \pi}{\partial k} = L[p_A f'(k) - r] = 0$$

$$\Rightarrow$$

$$k^* = f'^{-1}\left(\frac{r}{p_A}\right)$$

$$\Rightarrow K^{SO} = L f'^{-1}\left(\frac{r}{p_A}\right) = K^{SD}$$

Hence, it must also be that $\pi^{SD} \geq \pi^{CP}$, where the inequality is strict for $N > 1$.