From Plows to Horizontal Fracking:

Anti-commons and Unintended Consequences of Land Privatization[1]

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Abstract: Land contains multiple natural resources that are efficiently managed at different spatial scales, either concurrently or over time. We model the use of two such resources under common land ownership, individually owned parcels, and hybrid regimes. The model shows how enclosing the commons for one resource can create anticommons problems for another. We provide empirical tests in the context of American Indian reservations, which are mosaics of private, tribal, and fragmented ownership interests due to U.S. government allotment policies during the late 19th and early 20th centuries. Using spatial data of historical and modern resource endowments, we show how the policies intentionally enclosed commons to agricultural land but inadvertently fragmented land interests over oil and gas shale deposits that are efficiently extracted by horizontal drilling spanning two miles. Based on a detailed case study of Fort Berthold reservation – which sits atop the highly productive Bakken oil field – we find evidence that deposits under parcels surrounded by neighboring tribal lands are more fully exploited than are deposits under parcels surrounded by neighboring allotted and privatized parcels. The results show how subdividing land can inadvertently raise the transaction costs of spatially coordinated resource use and impair resource utilization.

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I. 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 property rights are too insecure and lack the necessary transferability 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 2010).

Land-titling and 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). Through subdivision and codification of land rights, privatization programs seek to enclose the "commons", which are areas or resources for which individual users lack fully defensible exclusion rights (Gordon 1954, Hardin 1968, Barzel 1997). In theory, having title over a specific parcel lowers the costs of enforcing exclusion rights and hence makes future claims on prior investments more secure (Alston et al. 1996). The empirical evidence suggests that individual land rights do tend to raise agricultural productivity.[2]

In this paper, we study a potential unintended consequence of top-down privatization. Even when subdividing and privatizing land successfully encloses the commons for one type of land use (e.g., agriculture), the subdivision process can create anticommons problems for other valuable types of resource use. Anticommons problems arise when too many exclusion rights are granted, raising the transaction costs of resource use and leading to underutilization (Heller 1998, Buchanan and Yoon 2000). The concern here is that subdividing and codifying land rights may raise the transaction costs of managing larger-scale resources such as oil shales, wind energy, and wildlife herds that are best managed at spatial scales exceeding those required for agriculture (see Lueck 1989, Fennell 2011). Moreover, in some areas of the world with large indigenous populations the potential 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 typically 160 acre parcels and allotted to

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[2] Galiani and Shcargrodsky (2012) provide a review of empirical studies. Most recent studies find that private land ownership rights have generally stimulated productivity-enhancing investments in land and agriculture (see, e.g., Banerjee et al. 2002, Field 2005, Do and Lakshmi 2008, Galiani and Schargrodsky 2010, Libecap and Lueck 2011). Other studies, however, fail to find significant improvements in agricultural investment after titling (see Brasselle et al. 2002 and Jacoby and Minten 2007).

individual Native American families with the stated goal of encouraging productive farming (Carlson 1981).[3] Some of the allotted lands were fully privatized and others remain held in trust by the U.S. government with multiple owners retaining exclusion rights as we explain in more detail in section 3. Other tribal lands were never allotted and remain governed by informal use rights determined by tribal members and their governments. The upshot is that modern Indian reservations are a patchwork of commonly owned land, individually owned parcels, and minute inherited subdivisions of allotted lands (see Trosper 1978, Anderson 1995, Banner 2005). This patchwork enables comparisons of long-run investments in land under different tenure arrangements. Empirical research suggests that trusteeship on Indian lands has limited housing investments (Akee 2009) and lowered agricultural productivity, especially on tribal lands that were never allotted (Anderson and Lueck 1992). [4]

We contribute to the literatures on land privatization, anticommons, and Native American land allotment by examining how land tenure affects the timing and density of modern oil extraction under reservation lands. Our focus on oil is important for four reasons. First, modern extraction is executed by drilling a set of wells along a horizontal line extending up to three miles from the main well pad. Hence, an oil company wanting to drill horizontally will need to get consent from owners of adjacent parcels (e.g., there would be 24 separate square 40-acre parcels along a three-mile line). This drilling technology generates land assembly transaction costs that are not relevant with agriculture, or even with the drilling of a conventional vertical oil well, especially because state-level forced pooling and oil unitization laws do not generally apply on Indian reservations (Slade 1996). As our theoretical framework in section 2 elaborates upon, the land assembly transaction costs are plausibly lower under tribally governed, common lands.

Second, these land assembly transaction costs create a unique opportunity to identify how the economic use of a natural resource by one landowner is affected by the property rights systems governing neighboring parcels. When exploitation of a resource requires coordination across parcels with varying bundles of property rights, even those parcels with well-specified rights may underutilize the resource due to the composition of land tenure on neighboring parcels. The ability to directly observe within parcel investment in oil wells in

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[3] A less charitable interpretation is that land allotment policies were devised to transfer land from Native Americans to white settlers (see Carlson 1981, Banner 2005).

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

conjunction with cross-parcel development of horizontal wells provides a rich setting for identifying parcel-level spillover effects associated with systems of property rights.

The third reason for focusing on oil is that shale endowments were exogenous to the land allotment process whereas agricultural potential was not. As we describe in section 3, high quality agricultural lands were the main targets of allotment and this explains why arid Indian reservations remain largely intact, in tribal common ownership. Oil reserves in general, and certainly shale deposits in particular, were largely undiscovered at the height of allotment and are either weakly related to or uncorrelated with agricultural potential. For this reason, shale deposits are largely uncorrelated with modern land tenure patterns.

The fourth reason for focusing on oil and gas is that its value dwarfs that of other natural resources on reservations, and royalties from drilling could significantly mitigate poverty on some reservations. For context, consider that income per capita for American Indians living on reservations over 2006-2010 was only $11,454 compared to $27,344 for the total U.S. population. As shown in Anderson and Parker (forthcoming), the drilling of an additional well per capita on Indian reservations is associated with increases of about $2,670 per capita based on regression analysis of panel data spanning 1915-2010.[5] This striking relationship between incomes and oil development highlights the importance of identifying transaction cost barriers to consensual drilling.

Unfortunately for tribes with allotted and privatized land, we find evidence of substantial contracting barriers due to those forms of land tenure. Our findings are based on a detailed case study of drilling on North Dakota’s Fort Berthold reservation, which combines GIS shape files of land tenure on and off the reservation with proprietary oil and gas drilling data from a private company called iHS and publicly available data on horizontal wells from the North Dakota Oil and Gas Commission. The Fort Berthold reservation sits atop the highly productive Bakken oil field and contains a mosaic of tribal land, allotted land, and fully privatized parcels. The history of land and mineral tenure on this reservation, as described in section IV, almost guarantees that tenure is exogenous to shale access and quality and we provide evidence that this is true within oil field units.

We compare parcel-specific oil fracking investment, measured as the number of horizontal well bores drilled, across over 40,000 parcels off and on the reservation. We find evidence that the number of well bores drilled is negatively impacted by having more allotted

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[5] Several factors beyond oil and gas drilling and casino gaming help explain differences in per capita income across reservations (see Cornell and Kalt 2000, Anderson and Parker 2008, Dippel 2013, Cookson 2009).

and private parcels in a surrounding two mile-radius. In contrast, we do not find a negative neighbor effect for neighboring tribal parcels, which share a common owner, or for vertical wells, which do not require spatial coordination. Moreover, regression analysis shows that a measure of contracting and delay costs—the average number of days elapsed between the permitting of well and its spudding (i.e., when drilling commences)—increases with the number of allotted parcels that the horizontal line cuts, but it does not increase as the horizontal line extends further into tribal land. These detailed results support our theoretical claim that subdividing land too finely has raised land assembly transaction costs and frustrated oil development.

II. Theoretical Framework

The starting point for our analysis is recognizing two challenging facts about land, natural resources, and property rights. First, a swath of land harbors multiple resources that are efficiently managed at different spatial scales, either concurrently or over time. Second, 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 different natural resources (Lueck 1989, Barzel 1997). We model a fully bundled regime but we also discuss the unbundled case below. In the fully bundled regime, an owner of a tract of land also has rights to the subsurface (e.g., oil and gas) and the super-surface (e.g., wind).[6]

A. Model Basics

We imagine a swath of land of area L acres that could be held in common by N users or privatized and subdivided in N parcels of size L/N. The land is of homogenous quality for agriculture and it sits atop a subsurface resource—an oil shale—of homogenous quality and depth that is extracted using horizontal drilling technology that spans the entire length of L.

The income generated from the land is the sum of agricultural and oil income, because we assume that these resource uses do not compete.[7] Abstracting from the dynamics of agricultural investment and oil extraction, we have:

(1) $\pi_A = p_A F(K, L) - rK$ and
(2) $\pi_O = T \cdot W(T, P_O)$.

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[6] The owner may also have rights to resources that migrate through the land (e.g., wildlife, stream water, etc.).

[7] In our view, this assumption of non-competing uses is approximately realistic for agriculture and oil drilling, and for agriculture and wind turbines, but less realistic for agriculture and wildlife management as we discuss below.

Equation (1) indicates that collective agricultural profit, π_A, is equal to agricultural revenue minus costs, where p_A 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.

Equation (2) indicates that aggregate oil income is the revenue earned from charging oil companies a fee of T for each oil well, W. The fee is itself a function of the price of oil (p_O), land area, and the number of individuals with exclusion rights (N). The number of wells chosen by the oil company is also a function of the fee it will be charged. The key assumption about oil drilling, however, is that consent of all landowners is necessary before a horizontal line can be drilled.

B. Agricultural Income

To keep things simple, and to highlight our key points expeditiously, we assume that the production function for agriculture exhibits constant returns to scale in L so that we can write per-acre investment as:

$$(3)\ f(k) = F\left(\frac{K}{L}, 1\right)$$

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:

$$(4)\ \max_{k_i}\ \ \pi_i = \left(\frac{L}{N}\right)[p_A f(k_i) - r k_i]$$

Optimizing with respect to k_i and solving, we have:

$$(5)\ k_i^{SD} = f'^{-1}\left(\frac{r}{p_A}\right) \text{ and } K_i^{SD} = \left(\frac{L}{N}\right) f'^{-1}\left(\frac{r}{p_A}\right)$$

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

$$(6)\ K^{SD} = \left(\frac{L}{N}\right) N f'^{-1}\left(\frac{r}{p_A}\right) = L f'^{-1}\left(\frac{r}{p_A}\right)$$

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

$$(7)\ \max_{k_i}\ \ \pi_i = \left(\frac{L}{N}\right) p_A f\left(\sum k_i\right) - rLk_i$$

The individual users optimize by choosing k_i, taking as given the investment choices of all other users. If we assume symmetric behaviour in a Cournot-Nash equilibrium, the solutions for k_i are:[8]

$$(8)\ k^{CP}{}_i = \frac{f'^{-1}\left(\frac{Nr}{p_A}\right)}{N} \text{ and } K^{CP} = Lf'^{-1}\left(\frac{Nr}{p_A}\right)$$

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

$$(9)\ f'^{-1}\left(\frac{r}{p_A}\right) \geq f'^{-1}\left(\frac{Nr}{p_A}\right)$$

The second-order condition for profit maximization requires $f''(\cdot) < 0$, which implies that (9) holds for all positive prices and rental rates.[9] The equality holds only if $N = 1$. This is the well-known prediction that investment in agriculture will be lower when other users cannot be excluded from the returns on investments. We show in the mathematical appendix 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. Hence, it must also be that $\pi_A^{SD} \geq \pi_A^{CP}$, where the inequality is strict for $N>1$.

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[8] See Mathematical Appendix for proof.

[9] The second-order condition for profit maximization requires $f'(\cdot)$ to be a decreasing function, which implies that it's inverse, $f'^{-1}\left(\frac{r}{p_A}\right)$, is also decreasing.

C. Oil Extraction

We assume that income earned from oil development comes from charging a fee on each well that is drilled, like a per-unit tax.[10] This system means that an outside oil company bears the risk of fluctuations in the world price of oil. The revenue earned from fees on oil wells is given by equation (2) above, which is $\pi_O = T \cdot W(T, P_O)$ and T is the fee determined by land owners.

The oil company's demand for oil-producing wells is derived from their profit equation. We assume the oil company, denoted D, solves the following profit maximization problem:

$$(10) \qquad \max\nolimits_W \pi_D = P_O g(W) - TW$$

We assume a concave production function such that $g'(W) \geq 0$ and $g''(W) \leq 0$, which is required for a unique maximum to the oil company's profit maximization problem. Additionally, we assume that $g'''(W) \leq 0$, indicating that the *marginal* productivity of additional wells is concave for any given L, due to congestion costs of crowding oil wells next to one another.[11] Optimizing with respect to W yields the following demand function for wells:

$$(11) \qquad W^*(T, P_O) = g'^{-1}\left(\frac{T}{P_O}\right)$$

This demand curve is decreasing in T, the fee charged per oil well.

In the case of common property, there are N users but no one individual has exclusion rights and hence cannot holdup oil extraction. In the common property regime, the collective seeking to maximize their income from mineral development solves the following problem

$$(12) \qquad \max\nolimits_T \pi_O = TW^*(T, P_O)$$

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[10] Alternatively, we could assume there is a royalty payment based on the amount of oil extracted. In either case, we would arrive at the same conclusion with respect to the effect of the number of exclusion rights on extraction levels.

[11] We make use of this condition in the mathematical appendix.

Solving this problem yields the following implicit function for the optimal per-well fee:

(13) $$T^{CP} = -\frac{W^*(T,P_O)}{\frac{\partial W^*(T,P_O)}{\partial T}} = -\frac{g\prime^{-1}(T,P_O)}{\frac{\partial g\prime^{-1}(T,P_O)}{\partial T}}$$

If the land is subdivided into *N* parcels, then the solution is complicated by the fact that *N* landowners have *N* exclusion rights. We follow Buchanan and Yoon (2000) and assume that an exclusion right entitles each landowner the right to charge his own fee, t_i, such that the total per well fee paid by the oil company is $T = \sum_{i=1}^{N} t_i$.

Under subdivided land, each owner solves the following optimization problem

(14) $$\max_{t_i} \pi_{i,O} = t_i W^*(\sum t_i, P_O)$$

Each individual takes as given the fees charged by others. If we assume symmetric behavior, the subdivided regime solutions are:

(15) $$t_i^{SD} = -\frac{W^*(\sum t_i,P_O)}{\frac{\partial W^*(\sum t_i,P_O)}{\partial T}} \text{ and } T^{SD} = N t_i^{SD} = -N\frac{W^*(\sum t_i{}^{SD},P_O)}{\frac{\partial W^*(\sum t_i{}^{SD},P_O)}{\partial T}} = -N\frac{g\prime^{-1}(\sum t_i{}^{SD},P_O)}{\frac{\partial g\prime^{-1}(\sum t_i{}^{SD},P_O)}{\partial T}}$$

We prove in the Mathematical Appendix that $T^{SD} \geq T^{CP}$ which implies directly that $W^*(T^{SD}, P_O) \leq W^*(T^{CP}, P_O)$, where the equality is strict for *N>1*.

D. Implications and Extensions

The main implications from the model are that $K^{SD} \geq K^{CP}$ and $W^{CP} \geq W^{SD}$. That is, the framework predicts there will be underinvestment in agriculture under common property, but underutilization of oil under subdivided privatization. Holding constant the land area, an increase in *N* will exacerbate the differences in these outcomes. Whether or not aggregate income—agricultural plus oil income—is higher under subdivided privatization depends on the relative prices of oil and agricultural output. Privatization makes more sense when agricultural output is relatively valuable and less sense when oil is relatively valuable.

The key mechanism at work in our model is the marginal cost to firms of drilling a well. For $N > 1$ the marginal contracting costs of drilling a well are higher on a divided parcel.

This difference grows as the spatial scale of the resource (and hence the total number of users) grows. The intuition is clear. Creating exclusion rights at a scale finer than the spatial extent of the resource creates a coordination failure because, in setting her fee, each user affects the total number of wells drilled, which affects the profits of all users. Each user sets a higher fee than is optimal because each user fails to consider the effect of an increase in her own fee on the profits of other users. This failure to coordinate reduces income for all users.

The empirical analysis considers an extension of the model that we do not formalize here. We imagine a situation in which a subset of the land mass L is subdivided and privatized with the remainder staying in common ownership. If there is a fixed cost of contracting within each regime, private or common ownership, then there would be a disincentive to contract across regimes. Although we have not formalized this idea, we find evidence that contracting for oil shale use across regimes is costly in our empirical application.

III. Background on Land Allotment

To test the theoretical framework, we study the U.S. Allotment Act of 1887. By 1887, nearly all tribes had signed treaties with the U.S. government relegating them to reservations located primarily in the Western United States (see figure 1). The main wave of western migration had yet to occur, and most reservations were remote from non-Indian populations.

The Allotment Act authorized the U.S. government to sequentially survey and subdivide communal reservations and allot individual parcels to families. It was promoted as a way to encourage agricultural investment[12] and, consistent with this claim, research indicates the scale and timing of allotment across reservations was determined primarily by agricultural land endowments. Importantly for our purposes, the allotment of subsurface rights was largely exogenous to the quantity and quality of underground shale oil and gas deposits that are now valuable for fracking. We argue that this was true in general, and we provide statistical evidence for the Fort Berthold Indian reservation, which is the subject of our empirical analysis.

The Act allotted land to individual Indians with the intention of granting private ownership including the right to alienate after 25 years or once the allottee was declared "competent" (the words in the act) by the secretary of the interior. The Indian head of a household was to receive 160 acres for arable agricultural land or 320 acres for grazing land.

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

On reservations for which total acreage exceeded that necessary to make the allotments, the excess could be ceded to the federal government and opened for white settlers with the proceeds deposited in a trust fund managed by the Department of Interior through the Bureau of Indian affairs. A 1903 U.S. Supreme Court ruling, however, allowed surplus land to be opened to non-Indian settlement without tribal consent.

Through a combination of land sales once allotment owners were declared competent and title was alienable, and through the declaration of surplus land, millions of reservation acres were transferred from Indians to non-Indians.[13] The Indian Reorganization Act (IRA) of 1934 halted such transfers, declaring those acres not already alienated to be held in trust by the Bureau of Indian Affairs, either as individual trust land or as tribal lands. Table 1 reports that the number of reservation acres was cut from 136 million in 1887 to 69 million in 1934. This implies that 66 million acres of surplus lands were sold to white settlers or retained by the federal government. Of the land that was retained within Indian reservations, 22 million acres was fully privatized and out of trust status by 1934; most of these non-trust acres were owned by non-Indians in 1934 (U.S. Dept. of Interior 1935).

Figure 1 illustrates the distribution and timing of allotted reservations, which is an important determinant of whether land on reservations today is fully privatized with one owner or held in individual trust with multiple owners. In general, reservations today have more private land if a) the reservation was opened to settlement, and b) the reservation was allotted at an early date. Land on reservations that were allotted early had a greater likelihood of being privatized because there was more time for allottees to be declared "competent" (see Anderson 1995). Allotted lands that were 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 at the time of the IRA. Hence, the "individual trust" plots of land on reservations today have multiple owners, sometimes more than 100 (Russ and Stratmann 2014).

Figure 1 shows that many reservations that were allotted or opened for settlement overlap shale deposits, but agricultural land endowments, rather than shale deposits, were the main determinants of cross-reservation patterns in allotment. Carlson (1981) uses regression analysis to show that reservations with better agricultural land tended to be allotted earlier, and more completely. Carlson (1981) measured agricultural potential of a reservation with coarse state-level rainfall data, but we verify his findings using more precise GIS data (see

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

Appendix A).[14] We are not aware of systematic empirical research on the determinants of tenure patterns within allotted reservations, but anecdotes and case studies suggest that lands with the best agricultural potential were more likely to be allotted and privatized (Cite).

Most accounts point to agricultural land quality as the main determinant of allotment patterns, but subsurface minerals, particularly coal, also played a role. The general Allotment Act of 1887 gave the allottee full rights to minerals (Ambler 1990). Later legislation, however, sometimes gave mineral rights to either the tribe or to the federal government when the surface was allotted or settled by non-Indians. As Ambler (1990, p. 42-43) notes:

> The complicated land and mineral pattern of energy reservations today results from such decisions made over the years about whether a tribe, an allottee, a non-Indian settler, or the U.S. government should get the minerals under a parcel of land. Those decisions seemed to depend upon four factors: the national sentiment about leasing versus selling public land minerals; the national sentiment about whether tribal governments should continue to exist; demand for land; and what was then known about mineral potential.

In general, allottees and settlers who acquired surplus lands on reservations before 1910 also acquired subsurface rights even if minerals were yet undiscovered. After 1910, the Coal Lands Act split mineral ownership from surface ownership on homesteaded land in the West reserving coal rights to the federal government.[15] This law affected ownership of coal (but not minerals in general) on parcels within surplus reservation lands that were opened for settlement but not yet settled. Reservation lands that were not yet opened for settlement were inventoried for subsurface endowments and, in 1917, Congress opened reservation coal lands for surplus settlement with the federal government retaining coal ownership (Ambler 1990).

Similar split estate policies began to be adopted for reservations with recently inventoried minerals. For some reservations, coal rights under allotments were reserved for tribes by specific laws: for example, Blackfeet in 1919; Crow in 1920; Fort Peck in 1920 and 1927; Fort Belknap in 1921; Northern Cheyenne ain 1926; and Wind River in 1928.[16]

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[14] Carlson (1981) also finds – and we verify – that reservations closer to non-Indian populations and railroad lines were more likely to be allotted earlier and more completely. A political economy interpretation of these findings is that allotment was organized in a way that intentionally gave white settlers access to high quality lands. This interpretation is consistent with various account of allotment (see, e.g., Banner 2005).

[15] The Coal Lands Act of 1909 was push forth by president Theodore Roosevelt who was concerned about coal companies gaining monopolies over coal supplies throughout the U.S. West. This law was passed at the time when homestead entries were reaching a peak, and lands that were thought to potentially have minerals were withdrew from homestead entry until the federal government classified the land (Ambler 1990).

[16] Why did the federal government permit tribes to retain their mineral ownership? One reason is that federal agencies exerted considerable control over the use and revenues from tribally owned minerals through leasing laws and hence apt to prefer tribal to allottee ownership (Ambler 1990).

Importantly, however, some of these reservations had already been allotted and the split estates applied only to new allotments. As a result, only a few mineral-endowed reservations have their communal mineral interests fully intact today and most reservations are mosaics of subsurface tenure due to the allotment era and related policies.

In summary, the variation in mineral tenure induced by the allotment era has exogenous determinants. Although some *cross-reservation* variation in tenure may be endogenous to the political strength of tribes or to the quality of mineral endowments known at the time, the history of allotment suggests that *within-reservation* variation is exogenous to the quality and accessibility of oil and gas shale deposits today. We study this claim in the context of North Dakota's Fort Berthold reservation.

IV. Tenure and Shale Endowments on Fort Berthold

To study the effects of tenure on oil development, we focus on the Fort Berthold Indian reservation in North Dakota. The reservation was established in 1851 by the Fort Laramie Treaty. Though that treaty established a reservation of over 12 million acres for three tribes – the Arikara, Mandan, and Hidatsa – subsequent Executive Orders and allotments reduced the reservation to its contemporary size of 988,000 acres (see figure 2).

Congress approved the reservation for allotment in 1894, but the northeastern section was opened for surplus homesteading settlement in 1910 and the surface and subsurface rights were immediately converted to fee simple (see figure 3). In appendix B, we show that land in this surplus zone was of higher agricultural quality than the rest of the reservation; this is not surprising given that allotment targeted high quality agricultural lands for privatization as describe above. The majority of the allotted Fort Berthold land was not released from trust, but some allotted parcels did convert to fee simple (figure 3).

Fort Berthold was essentially completely allotted during the allotment era, but over 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.[17] This Garrison Dam project was controversial and it forced the relocation of families off of allotted land near the Missouri River and into other areas of the reservation. Accounts of the Dam episode characterize the flooded area as having the best agricultural land within the allotted portion of the reservation (cite). The Garrison Dam episode explains why so much of the tribal land today is by the river (see figure 3); most of the land is dry now but it was in the original flood basin.

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[17] See http://library.ndsu.edu/exhibits/text/fortberthold.html.

With this background, we claim the Fort Berthold reservation is a good case-study for our study of contracting costs and natural resource use for four key reasons. First, and most obviously, the reservation sits atop the Bakken Shale Oil Formation—one of the largest in the world.[18] Oil from the Bakken is technologically accessible through horizontal fracturing, which typically requires horizontal lines spanning 1.5 to 3 miles. Because the oil formation is so productive, the consequences that tenure has on oil drilling is economically important.

Second, the reservation contains each type of tenure system - fee simple, allotted, and tribal – enabling comparisons of drilling patterns under the different tenure systems (see figure 3). 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.[19] Moreover, as figure 3 makes clear, the reservation contains clusters of homogenous tenure in some areas but, in other areas, different tenure types are interspersed. The occurrence of both clusters and interspersed tenure patterns will allow us to test separately for the effect of tenure mixtures, and tenure types, on oil drilling patterns.

The third reason why Fort Berthold is a good case study is because it borders non-reservation land that shares common oil fields. This fact allows us to compare oil drilling patterns on and off the reservation in areas that differ in terms of tenure and governance, but that share common geological endowments.

A fourth reason to focus on Fort Berthold is that the reservation boundaries, and the variation in tenure within the boundaries, are plausibly exogenous to the quality of shale oil and gas. One reason why is because the reservation was established, allotted, and opened for surplus settlement long before oil and gas was discovered.[20] In fact, the reservation was allotted and opened for settlement even before the reservation's full coal potential was known. As Ambler (1990, 42-43) notes:

> When it surveyed [Fort Berthold] in the 1910s, the U.S. Geological Survey discovered only about half of the actual coal potential. It found no oil and gas potential, which is not surprising because oil and gas was not discovered in the state until 1951. As was true on other reservations, [Department of Interior] attorneys later determined that the early mineral classifications were final, and the tribes had no claims on minerals

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[18] 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).

[19] Across the entire reservation, the tenure breakdown is approximately 35% in fee simple, 39% in allotted, and 26% in tribal ownership.

[20] The reservation was established in 1870 and the northeastern section was opened for surplus settlement in 1910.

> under allotments or homesteads that were not recognized during that classification. That early ignorance had lasting financial and political impacts at Fort Berthold. Instead of the tribes' owning all minerals on the reservation, non-Indian descendants of the settlers owned the coal and oil and gas in the homesteaded area and allottees owned most of the oil and gas on the rest of the reservation.

The fact that the Garrison Dam project was approved in 1947 also means that it was planned before the discovery of oil and gas.

Although history indicates that tenure patterns on Fort Berthold were not intentionally selected based on oil shale endowments, it is possible that the process unintentionally biased one form of tenure towards higher quality shale. We investigate this possibility empirically by examining how shale thickness and depth correspond to tenure. 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 other studies, including Weber et al. (2014), by measuring the economic quality of shale with its thickness-to-depth ratio.

Panel A of figure 4 shows the depth of the Bakken formation underneath our study area. Darker areas indicated deeper shale formations. Panel B illustrates the thickness of the formation. Lighter areas indicate thicker shale. The visual evidence in figure 4 indicates there is variation in the quality of shale resources within and across land tenures, and on versus off the reservation. 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 quality of shale under different tenure regimes, we run parcel-level regressions with thickness-to-depth as the dependent variable.[21] The full data set consists of the 51,083 parcels. For the reservation, we obtained parcel-level GIS data on mineral tenure for allotted and tribal parcels from the Bureau of Indian Affairs in addition to GIS data on which areas of the reservation have fee simple mineral rights. We augmented these data with GIS data on parcels for Dunn, McKenzie, and Mountrail counties, which overlap the portion of the reservation with oil development. Where possible, we update missing fee parcels on the reservation using the county files and fill in the remaining fee area with 640-acres PLSS Sections.[22]

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[21] 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.

[22] Figure 1 shows the universe of our parcel data and Appendix C provides maps of the raw and augmented reservation file.

We estimate (16) using OLS, where *i* indicates the parcel and *j* is one of the 210 oil fields. Data on the location of oil fields, which we consider to be relatively homogenous spatial endowments of oil over which extraction of shale is technologically feasible, come from the North Dakota Oil and Gas Commission and are shown in figures 2 and 3.

$$\text{(16)} \qquad \textit{thick-to-depth}_{ij} = \alpha_j + \beta_F \textit{Fee}_{ij} + \beta_A \textit{Allotted}_{ij} + \beta_T \textit{Tribal}_{ij} + \varepsilon_{ij}$$

Column 1 of table 2 shows a raw comparison across tenure for all 51,083 parcels. Column 2 shows a comparison across tenure for the 42,500 parcels that are on an oil field. Column 3 includes oil field fixed effects to assess the degree of within-field variation in shale quality by tenure. Off-reservation parcels form the omitted category in models 1 and 2, and the omitted category in column 3 is an off reservation parcel in oil field 1. Column 1 suggests that shale quality on the reservation exceeds average quality off the reservation, and that fee parcels tend to be endowed with the highest quality shale. We fail to reject the null hypothesis that allotted and tribal parcels have equally desirable shale at the one-percent confidence level. Column 2 echoes the finding of column 1 after restricting the data to parcels on existing oil fields—this is unsurprising given that areas that lack oil fields have less desirable shale. Column 3 demonstrates there is no statistically significant variation in shale quality within oil fields. This is an important consideration when we attempt to identify the effects of tenure on shale development in the next section. Because oil quality is more plausibly exogenous to tenure *within oil fields*, we will control for oil field fixed effects in all of our estimates of the effects of tenure on oil drilling patterns.

V. Effects of Tenure on Oil Development

In this section, we assess the effects of spatial tenure patterns on the density and of horizontal drilling. We begin by describing the data, and then we proceed with the empirical analysis.

A. Data

We have created two separate data sets from various sources (see table 3, panels A and B). The first is a parcel-level data set, and the second is a well-level data set, conditional on a well having been drilled. The main source for data on drilling is the North Dakota's Oil and Gas Commission website. It contains GIS data for every vertical and horizontal well bore, and every horizontal well line, that has been drilled in the state. Figure 5 illustrates the location of well bores, and figure 6 illustrates the location of horizontal fracking lines. We downloaded these data in May 2015, so they closely represent the present accumulation of wells. At the parcel level, the average number of horizontal well bores is 0.279, ranging from 0 to 37. This amounts to a total of 14,976 horizontal well bores in our study area, of which 2,708 are located on the reservation. The average number of vertical well bores is 0.136, ranging from 0 to 29. This amounts to 6,001 vertical wells in our study area, of which 863 are on the reservation. Although we do not explicitly consider the year in which the well was drilled in this draft, we note that most of the horizontal wells were drilled since 2006, and most of the vertical wells were drilled earlier in time.

Some of our empirical analysis is conducted at the well level, conditional on a well having been drilled. In particular, we analyze the number of directional lines extending from each well pad. The average number of directional lines is 1.65, ranging from 1 to 9 (see table 3). Note there are 13,137 observations for the number of directional lines, which is less than the full number of 14,976. This discrepancy exists because, in some cases, we were unable to match the well bore with the fracking lines associated with a bore.

To measure the spatial effects of tenure, we have calculated variables that measure the tenure mix of parcels within a 2-mile radius of each parcel. We chose the 2-mile radius because lines from horizontal well bores typically extend 1 to 2 miles but we plan to explore other measures and radius limits in future drafts. Our first spatial variable measures the number of tenure regimes within the 2-mile radius. It ranges from 1 to 4, with the maximum indicating that the radius contains fee, allotted, tribal, and off reservation tenure. The second set of spatial variables measure the number of neighboring parcels from each type of tenure. For example, the variable Allotted Neighbors indicates the number of allotted parcels within the 2-mile radius, ranging from 0 to 308 with a mean of 21.9.

Finally, we have collected data to measure a variety of parcel-level factors that may influence the net value of extracting oil from a given parcel. First, we created a “topographical roughness” variable from the average and standard deviation of a parcel’s surface slope. Second, we calculated the distance from each parcel’s centroid to the nearest natural gas processing plant, the reservation boundary, the railroad, and the nearest river. Third, we calculated the miles of surface roads in a 2 mile radius around a parcel to account for infrastructure differences. Table 3 gives summary statistics.

B. Empirical Model and Hypotheses

We begin the empirical tests by estimating the following regression model.

$$\begin{aligned}(17)\quad Horizontal\ Wells_{ij} &= \alpha_j + \beta_O OffNeigh_{ij} + \beta_F FeeNeigh_{ij} + \beta_A AltNeigh_{ij} + \beta_T TrNeigh_{ij} \\ &\delta regimes_{ij} + \lambda_F Fee_{ij} + \lambda_A Allotted_{ij} + \lambda_T Tribal_{ij} + \gamma X_{ij} + \varepsilon_{ij}\end{aligned}$$

Here *i* = parcels, *j* = oil fields, the notation α_j represents the 210 oil-field fixed effects, and the notation X_{ij} indicates the vector of covariates. We include oil field fixed effects to control for unobserved differences in the net value of oil drilling across locales, and because our analysis above suggests that shale quality is more plausibly exogenous to tenure within rather than across oil fields.

The coefficient estimates of β_O, β_F, β_A, β_T, and δ provide the key tests of the theoretical framework. The β coefficients measure how the number of horizontal well bores in parcel *i* responds to the addition of more “neighbors” of different tenure types. Modifying our theory to the empirical setting of Fort Berthold implies a prediction of $\beta_T > \beta_O \geq \beta_F > \beta_A$. Our theory also implies that $\beta_T = 0$ and $\beta_{-T} < 0$ for each of the non-tribal tenure types.

To understand why we predict $\beta_T = 0$ and $\beta_T > \beta_F > \beta_A$, recall that our main theoretical argument is that divided ownership over shale will repress oil extraction by raising the costs of contracting to drill horizontal wells. The allotment of Fort Berthold resulted in three types of tenure with different numbers of exclusion rights per parcel. Fee simple parcels are basic private property and typically have a sole owner. Allotted parcels are subject to fractionation over time (Russ and Stratmann 2014), so that each time an owner dies the parcel is divided among living heirs resulting in subdivided ownership among claimants who have land use veto rights. Tribal land is communally owned with individuals having use rights but the tribal government ultimately holds exclusion rights.

Hence, in this empirical setting the rate of increase in the number of exclusion rights differs across tenure types as the horizontal fracking line expands into multiple parcels. As fee simple parcels are added, the number of contracting parties increase by one owner for each parcel added. Assuming there are on average *z* owners per allotted parcel, each additional allotted 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.

Our theory does not contrast the costs of contracting with additional fee owners off versus on reservations, but there is a contracting rationale behind the prediction $\beta_O > \beta_F$. The rationale is that off reservation parcels are subject to North Dakota forced pooling laws but on-reservation parcels are not. Forced pooling laws force holdout landowners into fracking projects if a majority of neighbors desire the project. With forced pooling laws, the contracting costs of extending through additional parcels should be relatively low (see Slade 1996, Libecap and Wiggins 1984, Wiggins and Libecap 1985).

Our theoretical reasoning also implies that $\delta < 0$. This coefficient measures the effect of adding additional tenure regimes into the neighborhood surrounding parcel *i*. Contracting across tenure types – e.g., fee owners on the reservation with fee owners off the reservation or fee owners on the reservation with allotted owners on the reservation – 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 Anderson 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 importance of tenure on parcel *i*, conditional on the tenure compositions of neighbors. Because our theoretical framework focuses on spatial dimensions of contracting costs, these λ coefficients are of secondary interest. If contracting with the owner parcel *i* is not an important economic cost, conditional on the composition of neighbors, then we expect λ =0 for all tenure types. If contracting with the owner of parcel *i* is an important economic cost, we expect $\lambda_O = \lambda_F > \lambda_A > \lambda_T$. These are the predictions our model would imply if the outcome variable measured agricultural investment. [23] The key reason why is that number of owners of parcel *i* is one with fee land, greater than one for most allotted lands, and it is equal to the number of tribal members for tribal land.[24]

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[23] The prediction that $\lambda_F > \lambda_A > \lambda_T$ if Y = agricultural investment is consistent with the empirical findings of Anderson and Lueck (1992). Their study ranks agricultural productivity on reservation land based on tenure, finding that it was highest on fee land and lowest on tribal land.

[24] Despite fractionalization of allotted lands, on Fort Berthold the number of tribal members exceeds the highest number of allotted land claimants (Cite).

C. *Empirical Estimates of Horizontal Well Counts*

Although the well outcome variable is count data, we estimate the empirical model with an OLS estimator. We justify this choice on technical and practical grounds. On the technical side, some recent econometric theory research questions the use of poisson or negative binomial estimators in models like ours with a large number of fixed effects (cite). On the practical side, we have found that our main inferences are not sensitive to estimator choice, and the findings are similar if we use a poisson estimator. In all estimates, we cluster standard errors at the oil field level to account for possible spatial correlations of errors within oil fields. In future drafts, we plan to account more explicitly for spatial correlation in the errors.

Table 4 shows the coefficient estimates. In columns 1-4 the sample includes all parcels on oil fields. In columns 5-8, the sample is restricted in ways that we describe below. Columns 1 and 2 omit the ‘Neighbor Tenure Regimes’ variable, thereby restricting $\delta=0$. The odd numbered columns report results that control only for the thickness-to-depth and parcel acres variables. The even numbered columns include the full set of controls. All columns control for oil field fixed effects.

We focus first on the ‘Neighbors in 2m Radius’ coefficients in columns 1-2. In column 1, the point estimates indicate that $\hat{\beta}_O = -0.00019 > \hat{\beta}_F = -0.00049 > \hat{\beta}_A = -0.0018$. This rank ordering is consistent with our predictions. Moreover, the coefficient on $\hat{\beta}_T$ is not statistically different than zero, so we fail to reject our hypothesis that $\beta_T=0$. The rank ordering of coefficients is the same in column 2. In column 2, however, we cannot reject the null hypothesis that $\hat{\beta}_F = \hat{\beta}_A$. In terms of magnitude, the $\hat{\beta}_A$ coefficient of -0.00187 means that an additional 50 allotted neighbors lowers the predicted number of horizontal well bores by 0.094. For perspective, the mean number of horizontal wells on a reservation parcel is 0.26 and the standard deviation of allotted neighbors is 51.19. Hence, an increase of one standard deviation in the number of allotted neighbors is associated with a decrease in the number of horizontal wells on a parcel by 36 percent.

Columns 3 and 4 of table 4 add the ‘Neighbor Tenure Regimes’ variable. In both columns, we find that $\hat{\delta} < 0$ indicating that an increase in the number of tenure regimes in a parcel’s neighborhood is associated with fewer horizontal well bores. For perspective on the magnitude, the column 4 coefficient of -0.0716 implies that increase from 1 to 3 tenure regimes reduces the number of horizontal well bores by 0.213. This is an 82.6 percentage reduction, relative to the mean number of 0.26 horizontal well bores per reservation parcel.

To examine how the effects of having more neighbors interacts with the number of tenure regimes in a neighborhood, columns 5-8 present estimates of the model that impose different tenure regime restrictions on the estimating sample. In columns 5 and 6, we restrict the sample to the 31,766 parcels that are surrounded by neighbors of the same land tenure (within the 2 mile radius). Of these 31,766 parcels, only 622 are on the reservation. Of these parcels, 589 are on fee land, 24 are on allotted land, and 9 are on tribal land. In columns 3 and 4, we restrict the sample to the 10,635 parcels that are surrounded by neighbors with at least one different type of land tenure. Of these 10,635 parcels, 8,828 are on the reservation, 3,450 are allotted parcels, 3,299 are fee, and 2,079 are tribal parcels. In columns 5 and 6, the identification of the $\hat{\beta}$ coefficients comes only from variation in the number of neighbors across different homogenous tenure neighborhoods. In columns 7 and 8, the identification of the $\hat{\beta}$ coefficients comes also from variation in the number of different neighbors within heterogeneous neighborhoods.

The contrast in the $\hat{\beta}_O$ and $\hat{\beta}_F$ coefficients in columns 5-6 versus columns 7-8 are informative. The columns 5-6 coefficients evaluate the contracting costs of adding an additional neighbor that is homogenous in tenure to parcel i . The columns 5-6 coefficients provide a sharper test of our theoretical reasoning, which ignores the effects of land tenure mixtures on oil drilling decisions. The columns 5-6 finding that $\hat{\beta}_O > \hat{\beta}_F$ indicates that further subdividing private parcels in a neighborhood around parcel *i* has a relatively larger effect on deterring oil well drilling on the reservation. This result is consistent with the presence of forced pooling laws off but not on the reservation. The columns 7-8 coefficients evaluate the contracting costs of adding an additional neighbor that is different than parcel *i*. The finding that $\hat{\beta}_O < \hat{\beta}_F$ in columns 7-8 probably indicates that adding more off-reservation neighbors into the neighborhood of fee parcel *i* deters horizontal well drilling on fee parcel *i* because the drilling would require contracting with private landowners on both sides of a jurisdictional border.

The column 5-6 coefficients on the tribal and allotted parcel variables are probably not reliable given the small number of observations from which those coefficients are estimated. The coefficients follow the predicted ranking of $\hat{\beta}_F > \hat{\beta}_A$, however. The negative column 7-8 coefficients of $\hat{\lambda}_T$ suggest that drilling a horizontal well bore on tribal land is not preferred when the tribal parcel is surrounded by non-tribal land. The $\hat{\beta}_T = 0 > \hat{\beta}_F > \hat{\beta}_A$ estimates in column 7-8, however, suggest that drilling near tribal neighbors is more attractive than drilling near fee and allotted parcels.

The coefficients on the parcel tenure variables, $\hat{\lambda}$, are often not statistically different from zero in across columns 1-4 or in columns 7-8. All of the point estimates, however, follow the ranking $\hat{\lambda}_F > \hat{\lambda}_A > \hat{\lambda}_T$ as we would expect. In general, the findings that $\hat{\lambda}$ are insignificant might indicate that contracting costs of drilling on a single parcel can be overcome, regardless of tenure, but the spatial contracting problems are more onerous.

Turning to the coefficients on the controls in table 4, which are not our focus, we note the following patterns. First, thickness-to-depth of the shale positively relates to horizontal drilling as expected. Second, parcel size is positively related to the number of wells drilled as expected. Third, wells are more prevalent on parcels closer to fossil fuel processing plants, although the location of plants is likely endogenous to drilling. Fourth, horizontal wells are more prevalent as distance to the reservation border declines. This variable may imply that off-reservation oil operators are trying to capture oil that is trapped in shale on the reservation. Fifth, the prevalence of horizontal wells increases with the density of roads in the neighborhood of the parcel. This finding makes sense because road infrastructure likely lowers the cost of accessing drilling sites and transporting output.

D. Empirical Estimates of the Number of Lines from a Single Well Pad

The regression estimates in table 4 focus attention on one margin in which spatial contracting costs can influence drilling, which is by decreasing the number of horizontal well bores on a parcel. In this section, we examine another margin. Here we estimate how the number of fracking lines emanating from a single well pad is affected by neighbour tenure patterns. The estimating equation is the same as in (16), but now the unit of analysis is a well pad instead of a parcel and the dependent variable is the Number of Lines, conditional on a well having been drilled. The Number of Lines dependent variable ranges from 1 to 9 (see table 3).

Table 5 shows the estimated coefficients. In columns 1-4, we find that $\hat{\beta}_T > 0$, which indicates that the number of lines increases with the number of tribal parcels in the neighborhood of parcel *i*. This result is consistent with our theoretical reasoning that having tribal neighbors will lower the contracting costs of radiating multiple lines out from a single well pad. Columns 7 and 8 show that this positive effect of having tribal neighbors is identified off of variation in the number of neighboring parcels in neighborhoods containing at least two tenure regimes. There we find that wells on tribal parcels tend to have fewer lines (because $\hat{\lambda}_T < 0$) but tribal neighbors encourage more lines per well (because $\hat{\beta}_T > 0$).

VI. Alternative Mechanisms and Evidence of Contracting Cost Channel

We hypothesize that the empirical patterns in horizontal drilling uncovered in tables 4 and 5 are best explained by tenure-induced spatial contracting costs but there are other possible explanations. First, there may be omitted variables that correlate with spatial tenure patterns such as infrastructure and cultural differences in preferences towards drilling. Second, we have learned that tribally imposed fees pertain to well bores drilled on tribal land but not to horizontal lines under tribal land. This tax policy might explain why the number of horizontal well bores is lower on tribal land, but it does not obviously explain why having tribal neighbors positively relates to oil drilling.

To further probe the role of contracting costs, we conduct two additional tests in this section. First, we estimate ‘placebo’ effects that spatial neighbors have on the number of vertical wells. The decision to drill a vertical well on a parcel should not be directly affected by the tenure mix of neighbors, but it may be affected by infrastructure and cultural preferences. Second, we estimate the length of horizontal well drilling delays – measured as days between permitting of a well and the commencement of drilling – as a function of the tenure mix of parcels through which the horizontal line intersects. We interpret delays, conditional on drilling, to be a direct measure of contracting costs.

A. Vertical Wells

Table 6 reports results from our ‘placebo’ estimates of the spatial tenure effects on vertical wells. The estimating equation is identical to the equation in (16). In Table 6, we see that none of the coefficients on the “neighbor” variables are significantly different than zero. We view this null finding as evidence in support of our theory. If tenure affects horizontal fracking patterns primarily through the channel of spatial contracting costs, as we hypothesize, then we should not expect the tenure of neighbors to affect vertical well drilling decisions. There are two caveats. First, the empirical model may be ill-suited for identifying determinants of vertical drilling because we lack controls for conventional oil deposits. Second, our current measure of vertical wells simply aggregates the number of wells ever drilled up to the present and ignore differences in the year of drilling. This approach is reasonable for horizontal wells but less so for vertical wells, because many of the vertical wells in our sample were drilled during the 1960s, 1970s, and 1980s.

B. Drilling Delays

In an attempt to isolate the impact of landowner contracting costs from other factors that may influence the density of well drilling, we test for the effects of tenure on the number of days between the permitting of a well (by state oil and gas commissions) and the spudding of that well. Although some of the landowner contracting costs must be incurred by the drilling company prior to obtaining a permit, we argue that the permit-to-spud variable still captures some of the landowner contracting costs based on our reading of the legal literature. After a permit has been obtained but before drilling has commenced, individual landowners along the proposed drilling line still have opportunities to holdup drilling. For example, the oil company must still obtain agreement on specific drilling plans and non-participating landowners can still refuse to allow surface access to stages of a multi-staged fracking plan.[25] For these reasons, we predict longer durations for horizontal wells than for vertical wells because more parties are necessarily involved raising the possibility of holdups.[26]

To create the permit-to-spud variable, we employ data on oil drilling and permitting from the private company iHS because the North Dakota Oil and Gas Commission well data do not provide permitting dates. The iHS data indicate when each well was permitted (by the state of North Dakota), the date that drilling began (referred to as the spud date), and the date the well was completed. Each well has a unique API number that we use to match wells from the iHS data set to the GIS lines that are provided in the North Dakota Oil and Gas Commission data. This allows us to generate a count of the total number of parcels of each type—fee simple, allotted, tribal, and off-reservation—that each horizontal fracking line passes through and associate these counts with the permit-to-spud duration of the well. We also create a variable called “Tenure Regimes” that counts the number of different types of property a line passes through, including the parcel where the well originates.

There are two features of the permit-to-spud variable that bear clarification. First, the variable covers only those wells that were spudded by the end of 2012, because we do not

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[25] In the case of allotted Indian reservation parcels with multiple owners, the oil company will have to notify the surface landowners before drilling but some may be difficult to locate.

[26] Moreover, because drilling a horizontal well requires first drilling a vertical well, it is unlikely that differences in permit-to-spud duration between vertical and horizontal wells are driven by technical constraints or costs of moving equipment.

have access to more recent iHS data. Second, the permit-to-spud variable covers only those horizontal wells that we could be reliably match with horizontal lines in the North Dakota Oil and Gas Commission GIS files—a number of the iHS wells lack API numbers and are excluded. Given these two limitations, we have spud-to-permit measures for 6,124 wells in our sample area.

Panel B of table 3 gives summary statistics. The average time from permit to spud is 72.6 days for all wells. The average time is 129 days for horizontal wells and 19 days for vertical wells. We note that the longer average permit-to-spud time for horizontal wells is consistent with the argument that this window measures contracting costs because verticals wells involve fewer contracts than horizontal wells. The "Tenure Regimes" variable measures the number of tenure regimes a horizontal line cuts, ranging from 1 to 4 (and taking a value of 1 for vertical wells). The second set of variables measure the number of parcels from each tenure type that a horizontal line cuts. For example, the variable "Fee Line Parcels" ranges from 0 to 28, indicating that one horizontal line intersected 28 separate fee parcels.

We estimate the regression in (18), which is similar to the model for (17) except that here the data indicate the tenure of the parcels that a well line actually intersects. Another differences is that here we include in the vector *X* controls for Lines from Well and whether the well is horizontal or vertical. We also include year-of-month fixed effects (π_m) to account for seasonal delays in getting wells spudded.

$$\begin{aligned}(18)\quad & Spud - Permit\ Date_{ij} = \alpha_j + \pi_m + \eta_O OffParcels_{ij} + \eta_F FeeParcels_{ij} + \eta_A AltParcels_{ij} \\ & + \eta_T TrParcel_{ij} + \mu regimes_{ij} + \phi_F Fee_{ij} + \phi_A Allotted_{ij} + \phi_T Tribal_{ij} + \gamma X_{ij} + \varepsilon_{ij}\end{aligned}$$

If spatial contracting costs are a key driver of the regression results in tables 4 and 5 above, we should expect the following coefficient relationships. First, $\eta_A > \eta_F \geq \eta_O > \eta_T$ would indicate that delays in drilling rise to a greater degree when the line intersects an additional allotted parcel, and to the smallest degree when the line intersects an additional tribal parcel. Second, μ>0 would indicate that drilling delays increase with the number of different tenure types that the line intersects.

Table 7 presents the estimates. In all columns we find that $\hat{\eta}_A > \hat{\eta}_O > \hat{\eta}_F > \hat{\eta}_T$, although these point estimates are not all statistically different from zero nor are they all statistically distinct from each other. For interpretation, the $\hat{\eta}_A$ estimate of 6.12 indicates that a line intersecting an additional allotted parcel increases drilling delays by 6.12 days. The estimates of $\hat{\mu}$ are positive, and large, indicating a horizontal line that intersects an additional tenure regime is subjected to 50.01 day delay in drilling. Finally, the coefficients $\hat{\phi}_T > \hat{\phi}_A > \hat{\phi}_F$ indicate that delays tend to be longest when the well bore is on tribal land, and shortest when the well pad is on fee land as we would expect, based simply on the fact that tribal land has the most owners, allotted has second most, and fee has the fewest.

Although tribal land tenure over the well bore location is associated with longer delays in drilling, the extension of the line into adjacent tribal lands (relative to other tenures) actually reduces delays. Due to this spatial pattern, our estimates imply that overall delays will be shorter for a line that is drilled under tribal tenure, when compared to a line that is drilled under multiple private parcels. These permit to spud duration results are complementary evidence – albeit preliminary - that contracting costs, rather than confounding factors, explain our main set of empirical patterns.

VII. Conclusions

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 investments (Anderson and Lueck 1992, Akee 2009, Akee and Jorgensen 2015) and improved overall measures of Native population incomes (Aragon 2015).

We examine an important qualification to the benefits of privatization. We theorize that the subdivision of communal land into individual parcels can frustrate the efficient use of natural resources that span large spatial scales. The problem is that subdivision raises coordination costs for resource users, especially if the privatization process is incomplete and therefore creates discrete boundaries of private and communal land that are spanned by the natural resource.

We believe our arguments are relevant for many natural resources including wind, groundwater, wildlife, and rivers, but we demonstrate the unintended effects of privatization in the context of oil shale extraction on the Fort Berthold Indian reservation. In that setting, we find that having more subdivided and private neighboring parcels reduces the amount of oil drilling on a parcel. We also find that a greater mixture of land tenure types around a parcel discourages the drilling of a horizontal well on that particular parcel. In general, we find that well drilling on a parcel is best encouraged if the surrounding land is owned by a single entity, namely the tribe. This finding highlights a potential silver lining of the 1951 Garrison Dam project for tribal residents on Fort Berthold. Although the flood relocated families and damaged agricultural land, it also was a catalyst for a sweeping transfer of land from allotted tenure to tribal tenure. We tentatively claim that the tribal tenure has enabled a fuller exploitation of the valuable oil shale endowment under Fort Berthold.

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 2005). 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 (cite). Our contribution is to emphasize, with specific detail, how the checkerboarding of reservation tenure has derailed the coordinated development of a valuable natural resource. More surprisingly, our results also suggest that relatively successful cases of allotment – i.e., those reservations that were fully privatized and not checkerboarded – may have also reduced the net value of spatially expansive natural resources by eliminating communal ownership.

We recognize there are attractive alternatives to managing spatial natural resources such as oil shale 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 the power of individual landowners to holdup development. Another alternative is split estates and government ownership of minerals (cite Fitzgerald, others). 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 technologies have changed the optimal ownership of oil, however, and we hope to see future research on that topic.

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Appendix A: Theory Proofs

1. Sketch of a proof that $k^{CP}{}_i = \frac{f'^{-1}\left(\frac{Nr}{p_A}\right)}{N}$

   The first-order condition of the agricultural profit maximization problem for each individual *i* under the common property regime is

$$\frac{\partial \pi_i}{\partial k_i} = \left(\frac{L}{N}\right) p_A f'\left(\sum k_i\right) - rL = 0$$

   We assume a Counot-Nash equilibrium; taking the investment of other users as given, each user chooses k_i such that

$$f'\left(\sum k_i\right) = \frac{Nr}{p_A}$$

   If $f'(\cdot)$ is invertible then there is a unique $\bar{k}$ that satisfies this expression, which we can write as

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

   Each user, taking other users investment as given, chooses their own investment such that $k_{-i} + k_i = \bar{k}$. We've assumed homogeneous agents and thus focus on the symmetric case where each individual chooses the same level of investment. This implies that

$$k^c{}_i = \frac{f'^{-1}\left(\frac{Nr}{p_A}\right)}{N}$$

   QED

2. Equivalence between sole-owner problem and sub-divided problem for agricultural investment.

   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:

$$\frac{\partial \pi_i}{\partial k_i} = L[Pf'(k) - r] = 0$$

$$\Rightarrow$$

$$f'(k) = \frac{r}{p}$$

$$\Longrightarrow$$

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

$$\Longrightarrow$$

$$K^{SO} = Lf'^{-1}\left(\frac{r}{p}\right) = K^{SD}$$

QED.

3. Sketch of a proof that $T^{SD} \geq T^{CP}$.

Recall $T^{SD} = Nt_i^{SD} = -N\frac{g'^{-1}(\sum t_i{}^{SD}, P_O)}{\frac{\partial g'^{-1}(\sum t_i{}^{SD}, P_O)}{\partial T}}$ and $T^{CP} = -\frac{g'^{-1}(T, P_O)}{\frac{\partial g'^{-1}(T, P_O)}{\partial T}}$ where T^{SD} is the solution to the Cournot-Nash equilibrium where each owner set's their fee, taking the other owners' fees as given. We proceed with a proof by contradiction.

Assume *N>1*

Assume T^{SD}=T^{CP}.

$$\Rightarrow \sum t_i{}^{SD} = T^{SD} = T^{CP}$$

$$\Rightarrow -N\frac{g'^{-1}(T^{CP}, P_O)}{\frac{\partial g'^{-1}(T^{CP}, P_O)}{\partial T}} = -\frac{g'^{-1}(T^{CP}, P_O)}{\frac{\partial g'^{-1}(T^{CP}, P_O)}{\partial T}}$$

$\Rightarrow N = 1$, a contradiction.

$$\therefore, T^{SD} \neq T^{CP} \quad if\ N > 1$$

Now, assume *N>1*

Assume $T^{SD} < T^{CP}$

$$\Rightarrow -N\frac{g'^{-1}(T^{SD}, P_O)}{\frac{\partial g'^{-1}(T^{SD}, P_O)}{\partial T}} < -\frac{g'^{-1}(T^{CP}, P_O)}{\frac{\partial g'^{-1}(T^{CP}, P_O)}{\partial T}}$$

$$\Rightarrow N < \underbrace{\frac{g'^{-1}(T^{CP}, P_O)}{g'^{-1}(T^{SD}, P_O)}}_{A}\left[\underbrace{\frac{\frac{\partial g'^{-1}(T^{SD}, P_O)}{\partial T}}{\frac{\partial g'^{-1}(T^{CP}, P_O)}{\partial T}}}_{B}\right]$$

$$g''(W) \leq 0 \Rightarrow g'^{-1}(T^{CP}, P_O) < g'^{-1}(T^{SD}, P_O) \quad for\ \ T^{SD} < T^{CP}$$

$$g'''(W) \leq 0 \Rightarrow \frac{\partial g'^{-1}(T^{SD}, P_O)}{\partial T} < \frac{\partial g'^{-1}(T^{CP}, P_O)}{\partial T} \quad for \quad T^{SD} < T^{CP}$$[27]

$$\Longrightarrow N < \underbrace{\frac{g'^{-1}\left(T^{CP}, P_O\right)}{g'^{-1}\left(T^{SD}, P_O\right)}}_{A<1} \left[\underbrace{\frac{\frac{\partial g'^{-1}\left(T^{SD}, P_O\right)}{\partial T}}{\frac{\partial g'^{-1}\left(T^{CP}, P_O\right)}{\partial T}}}_{B<1}\right] < 1, \text{ a contradiction.}$$

$$\neg\{T^{SD} = T^{CP}\} \wedge \neg\{T^{SD} < T^{CP}\} \Longrightarrow T^{SD} > T^{CP}$$

QED.

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[27] We need for the derivative of the inverse of the marginal productivity of a well to be an increasing function. This requires the inverse itself to be convex (so that it’s second derivative is positive). In order for the inverse function to be convex, it must be that original function—the marginal productivity of a well—is concave.

Appendix B: Cross Reservation Determinants of Allotment

To demonstrate how the demand for agricultural land during 1887 to 1934 is a dominant determinant of land tenure patterns on reservations today, we created a historical cross-reservation data set. We first digitized reservation shapefiles from an 1890 Office of Indian Affairs map, tracing the boundaries of all 97 reservations west of the state of Michigan and visible on the original map.[28] To measure endowments of agricultural land, we calculate average annual precipitation across the 1890 reservation acreage. We divide the 1890 reservation acreage into four categories which are "arid" (less than 10 inches of annual precipitation), "semi-arid" (10-25 inches), "moderate" (25-50 inches), and "wet" (greater than 50 inches).[29] To measure population pressures near reservations, we calculated the proximity (in kilometers) of a reservation's boundary to a major railroad line, based on 1893 rail lines and the population density of the state. We also digitized historical maps of inventoried coal deposits in 1919 and overlaid that map with reservation boundaries. Figure A1 displays rainfall, coal deposits, and rail lines with the 1890 reservation boundaries.

Table A1 shows relationships between resource endowments and the current percentage of reservation acreage that is privately owned ("fee-simple"), allotted but not fully privatized ("allotted"), and remaining in tribal ownership. The results complement Carlson (1981) who finds that reservations in states with faster population growth and more rainfall were more likely to be allotted first. In columns 1 and 4, we find that having more arable acres, being closer to 1893 railroads, and being in a densely populated state in 1890 are all associated with more fee-simple land today.[30] Fee simple lands include those opened for surplus settlement and lands that were allotted and alienated after "competence" was declared. In columns 2 and 5, we find that larger endowments of semi-arid acres and shorter distances to railroad lines correlate with higher percentages of allotted (but not fully privatized) acres today. In columns 4 and 6, we see the determinants of tribal land tenure are opposite to those of fee simple. Having more arid acres, being further to 1893 railroads, and being in a sparsely populated state in 1890 are all associated with more tribal land today. Although these findings do not rule out the possibility that the pattern of allotment was intended to benefit Native Americans, they are consistent with the view that allotment was

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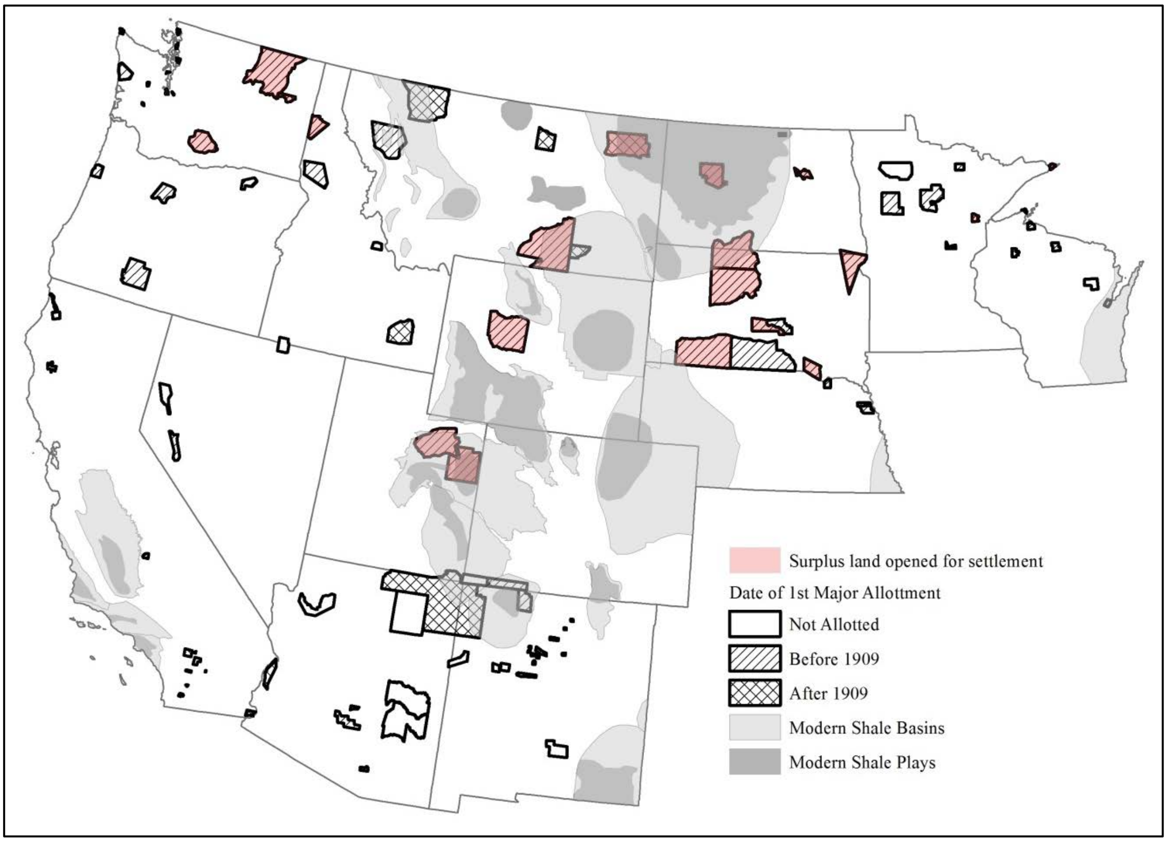
[28] The year 1890 is the closest to 1887 for which we could find a high-quality map of reservations.

[29] Like Haber (2012), we assume that growing conditions increase with rainfall as we move from arid to moderate categories, but the relationship is less clear as rainfall increases from moderate to plentiful.

[30] The coefficients have the following interpretations. In column 1, for example, an increase of 100,000 acres of arable land is associated with a 4.1 increase in the percent of fee simple land today. Similar, an increase in the distance of a reservation boundary to an 1893 rail line of 100 kilometers is associated with a decrease the percent fee simple today of 24.2 percent.

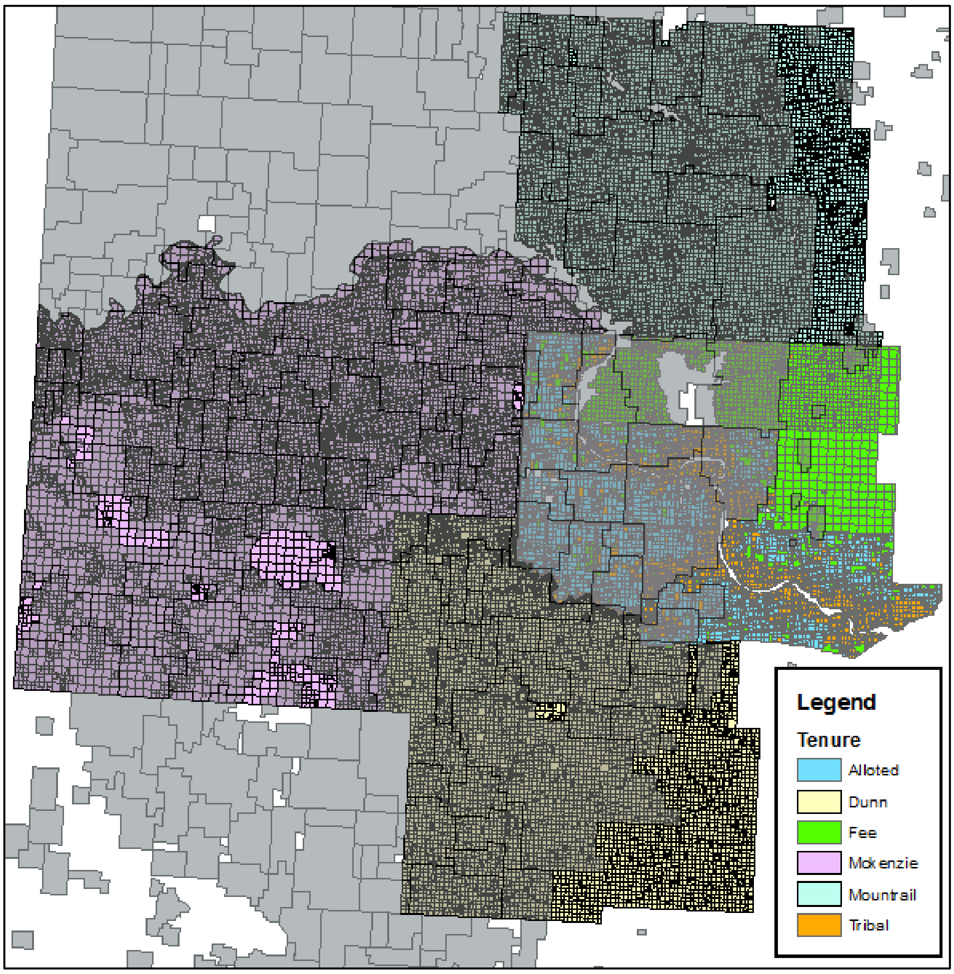
administered in a way that let non-Indians acquire quality and accessible agricultural lands that were otherwise unattainable.

Figure 1: The Timing and Distribution of Allotted Reservations



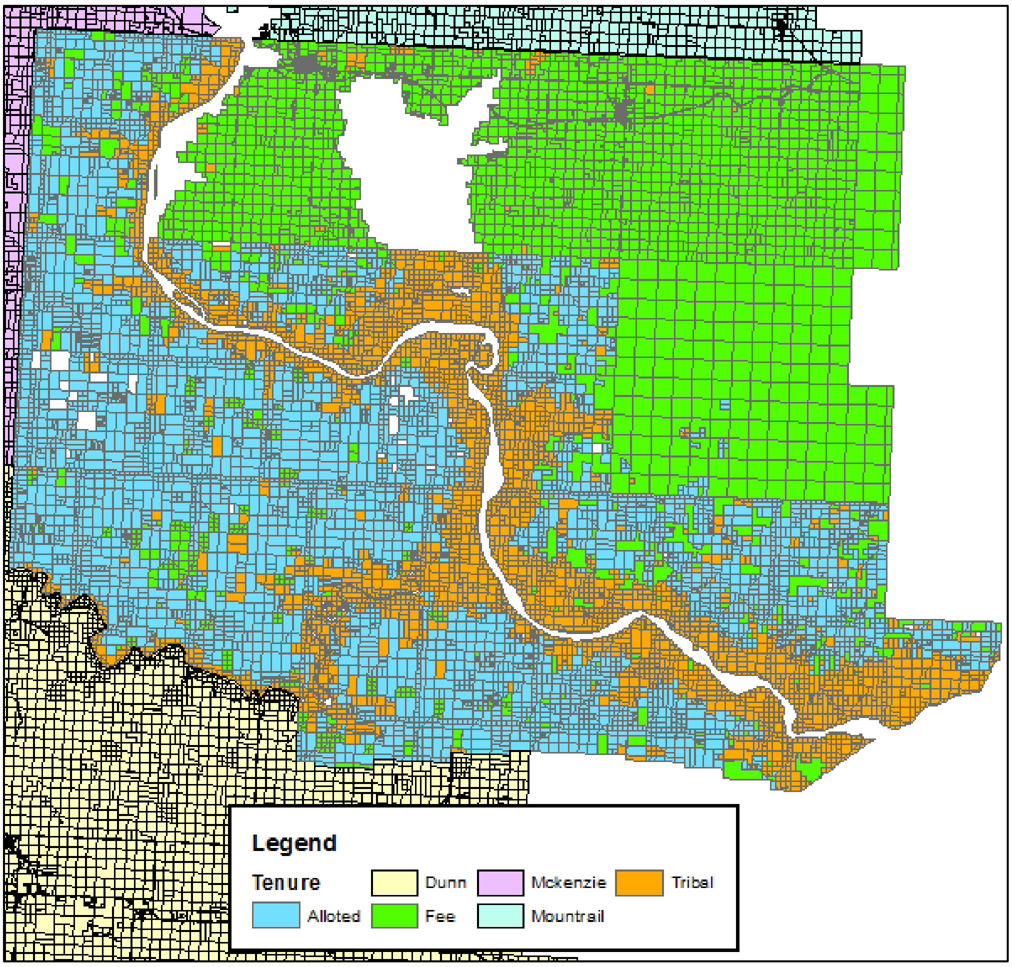
Notes: This map is based on our digitization of an 1890 Office of Indian Affairs map of 97 reservations that were west of the Mississippi River and clearly visible in the original map. With the exception of the Osage Reservation, we exclude Oklahoma because reservations in that state are no longer federally 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.

Figure 2: Oil Fields beneath Fort Berthold Reservation and Surrounding Counties



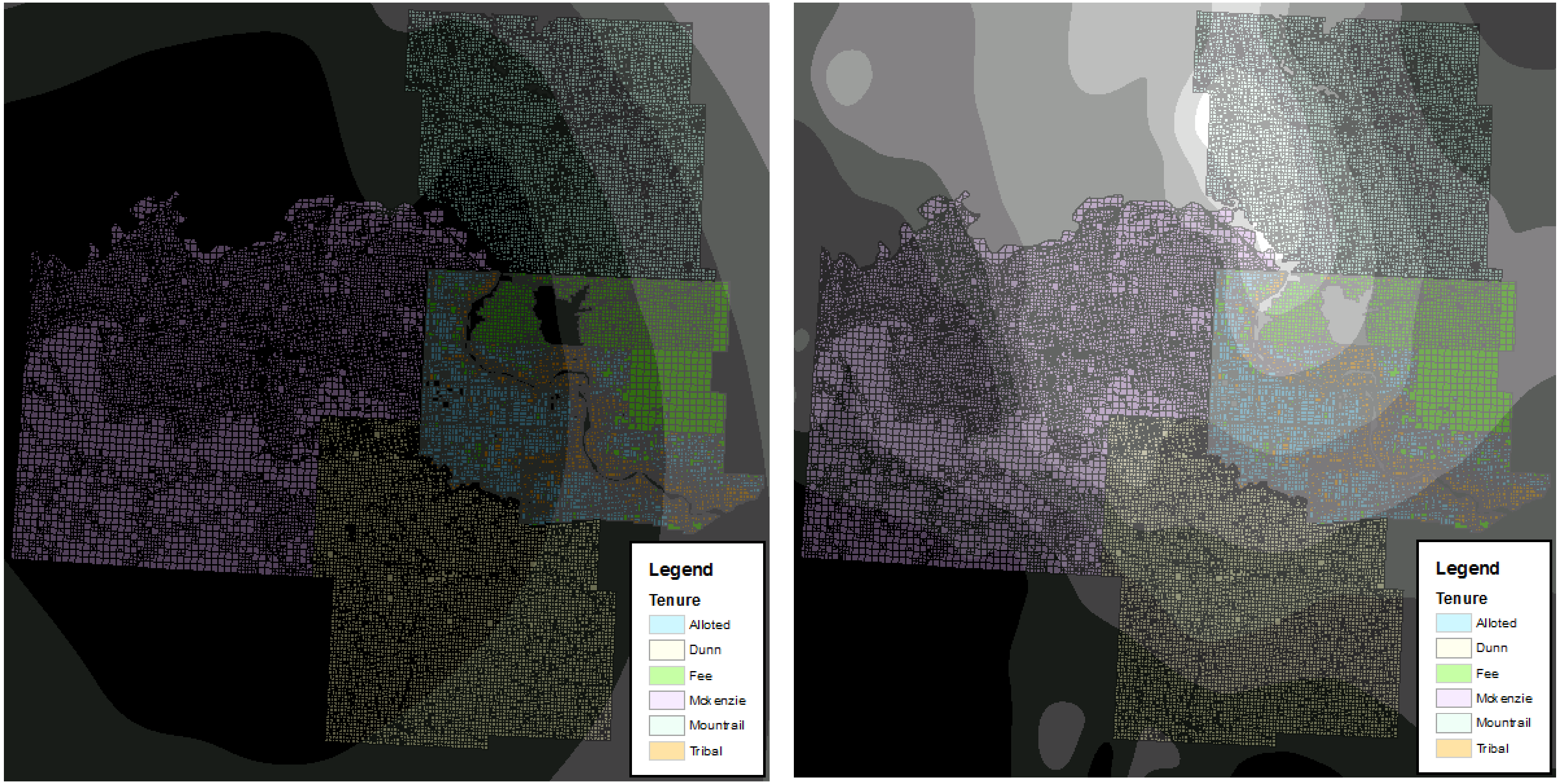
Notes: This map depicts parcel boundaries and oil fields on the Fort Berthold Indian Reservation and surrounding counties. The surrounding counties are Dunn, McKenzie, and Mountrail.

Figure 3: Tenure on Fort Berthold Reservation



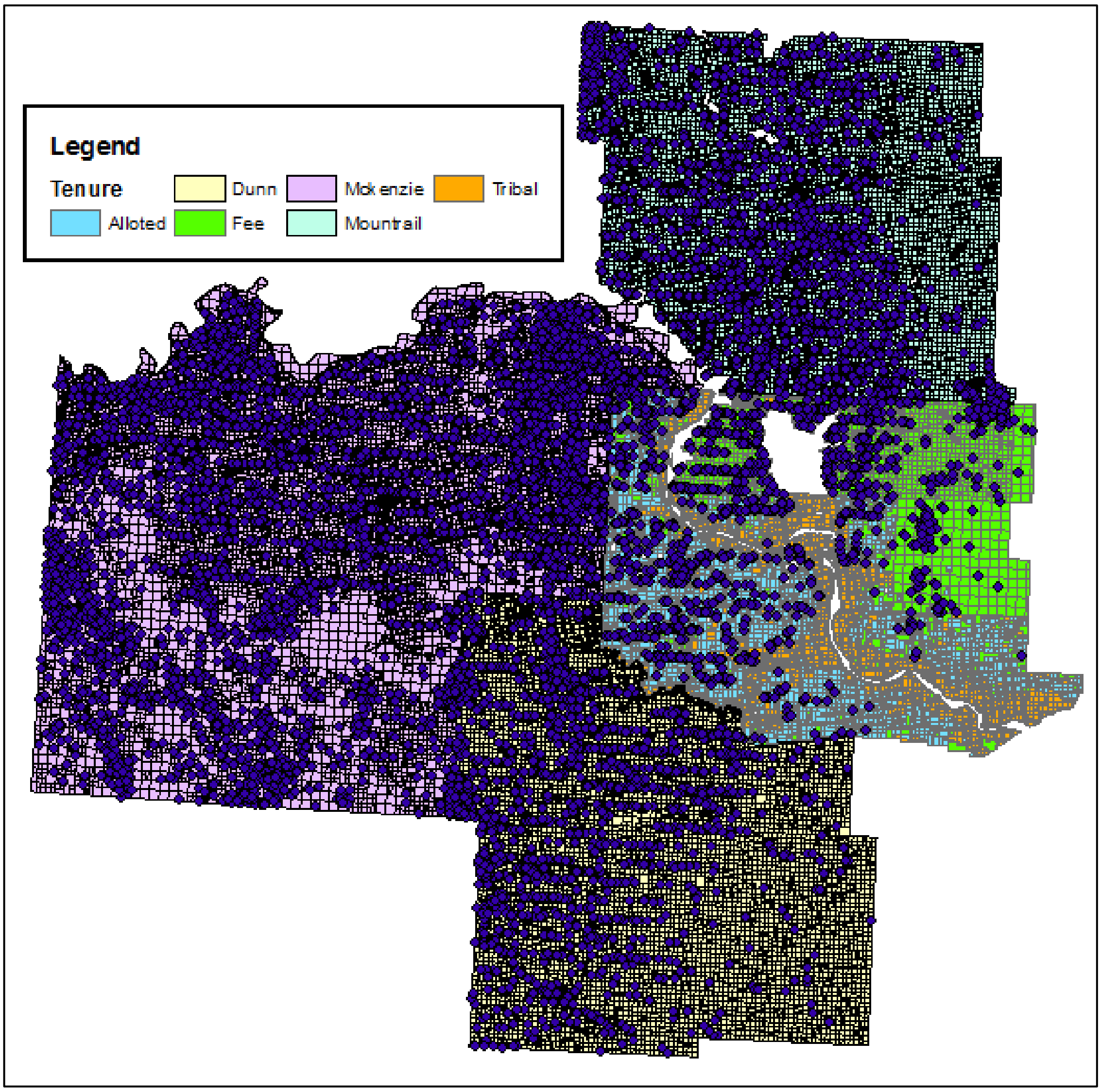
Notes: This map depicts parcel boundaries, oil fields, and mineral tenure types on the Fort Berthold Indian Reservations. The surrounding counties are Dunn, McKenzie, and Mountrail. The parcel sources come from xx. The areas lacking parcel boundaries are areas for which parcel level mineral tenure data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

Figure 4: Shale Depth and Thickness



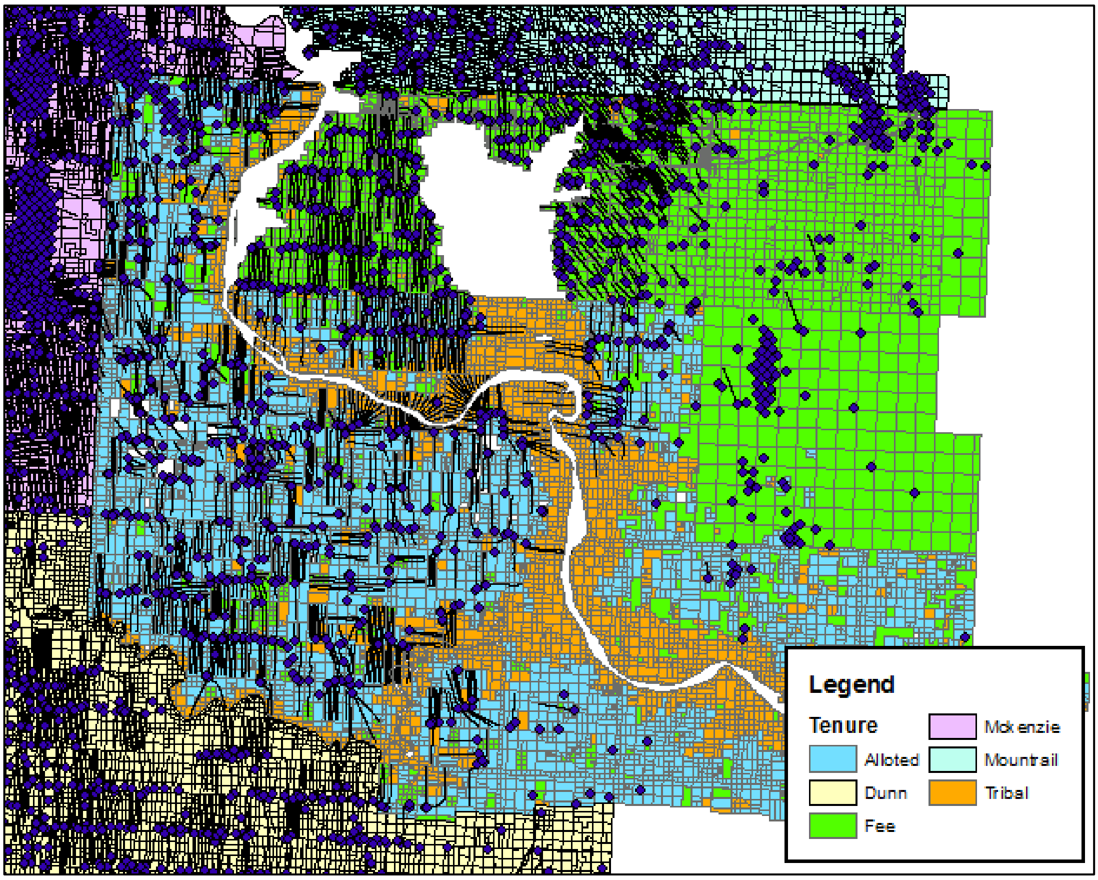
Notes: Panel A (on the left) depicts the depth of shale in the Bakken rock formation, with the darker shades indicating thicker shale. Panel B (on the right) illustrates the thickness of the shale, with lighter shades indicating thicker shale. The data are based on GIS data provided by the U.S. Energy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

Figure 5: The Location of Oil Well Bores in Study Area



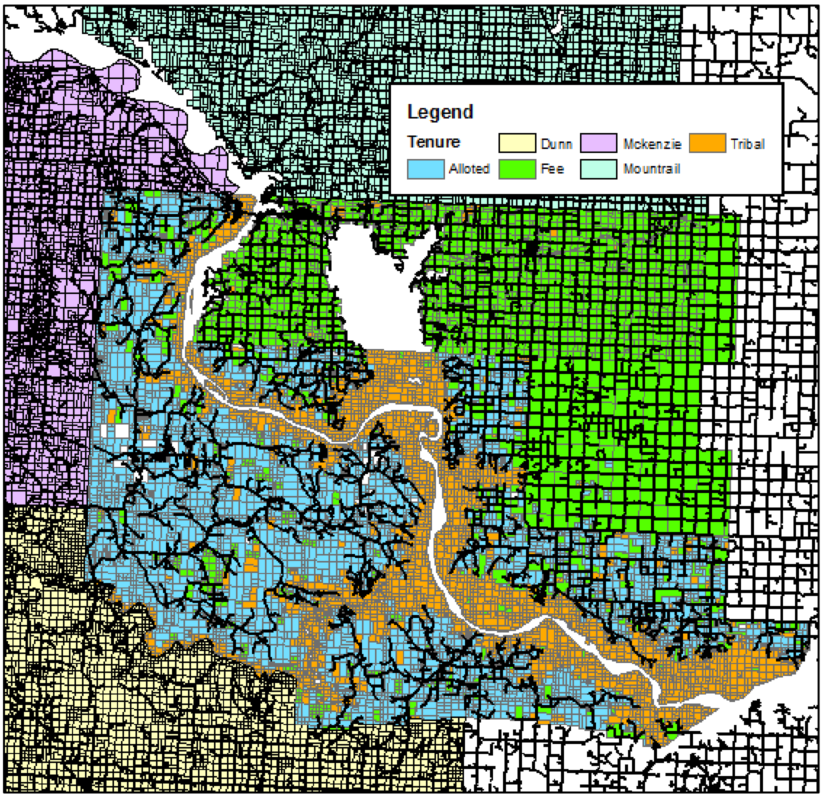
Notes: This map depicts the location oil well bores ever drilled, based on data from the North Dakota Oil and Gas Commission.

Figure 6: Wells and Fracking Lines in and Around Fort Berthold Reservation



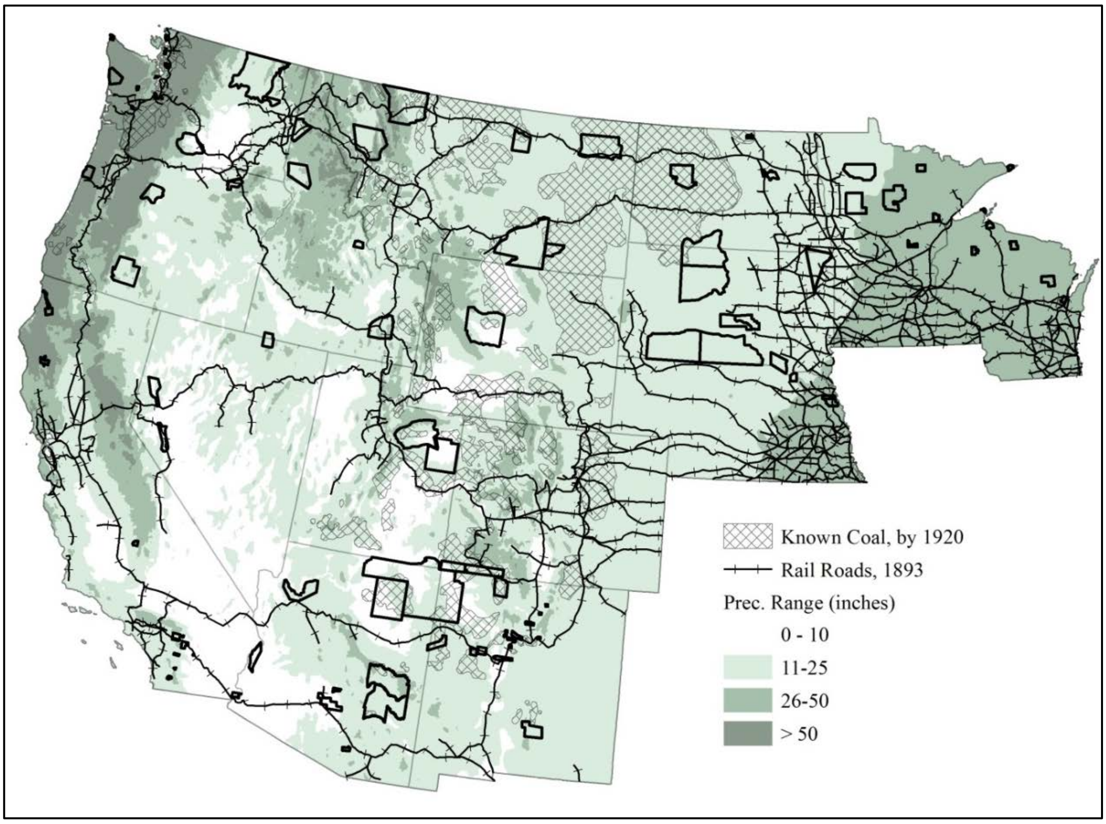
Notes: This map depicts the location of horizontal fracking lines, based on data from the North Dakota Oil and Gas Commission.

Figure 7: Road Infrastructure in and Around Fort Berthold Reservation



Notes: This map depicts the location of paved roads, based on data from xx.

Figure A1: Historical Resource Endowments and 1890 Reservation Boundaries



Notes: This map is based on our digitization of an 1890 Office of Indian Affairs map of 98 reservations that were west of the Mississippi River and clearly visible in the original map. We exclude Oklahoma because reservations in that state are no longer federally recognized, with the exception of the Osage Reservation. [Need to add sources for GIS shapefiles].

Table 1: Reservation Acres in 1887 and 1933

	Acres
1. Reservation Land, 1887	136,394,895
2. Reservation Land, 1933	69,588,411
Tribal trust , 1933	29,481,685
Individual trust, 1933	17,829,414
Allotments no longer in trust (i.e. fee simple)	22,277,342
3. Surplus land surrendered, 1933	66,806,454

Source: U.S. Dept. of Interior (1935).

Table 2: Correlations between Oil Shale Geology and Tenure

	Y = Thickness-to-Depth Ratio		
	(1) All Parcels	(2) On Fields	(3) Within Fields
Allotted	0.00118***	0.00144***	0.000104
	(0.0000260)	(0.000496)	(0.0000973)
Fee	0.00292***	0.00320***	0.000144
	(0.0000314)	(0.000831)	(0.000108)
Tribal	0.00104***	0.00162***	0.0000654
	(0.0000297)	(0.000540)	(0.0000906)
Constant	0.00959***	0.00982***	0.00607***
	(0.0000211)	(0.000484)	(0.0000208)
Oil Field Fixed Effects	No	No	Yes
N	51083	42500	42500
R^2	0.116	0.131	0.972

Robust standard errors in parentheses, clustered by Oil Field for models (2) and (3). * $p < .1$, ** $p < .05$, *** $p < .01$

Table 3: Summary Statistics

Variable	*Mean*	*Std. Dev.*	*Min*	*Max*	*Description*
Panel A: For Analysis of Well Location and Lines from Well (N=53,745)					
Horizontal Wells[a]	0.2790	1.4444	0.0	37.0	# of well pads that drop vertically and extend to a horizontal line
Vertical Wells[a]	0.1143	0.5959	0.0	29.0	# of wells pads that drop vertically and do not extent to a horizontal line
Lines from Well[a]	1.6635	0.7484	1.0	9.0	# of fracking lines radiating from a single horizontal pad, conditional on having well (N = 13,137)
Reservation[b]	0.2925	0.4549	0.0	1.0	=1 if the parcel is on the Fort Berthold Indian reservation, otherwise =0
Fee[b]	0.1027	0.3036	0.0	1.0	=1 if the reservation parcel is fee simple, otherwise =0
Allotted[b]	0.1136	0.3173	0.0	1.0	=1 if the reservation parcel is allotted but not alienated from trust, otherwise =0
Tribal[b]	0.0763	0.2655	0.0	1.0	=1 if the reservation parcel is tribally owned, otherwise =0
Parcel Acres[b, c]	82.360	103.723	0.0	1258.9	Area of the parcel, in acres
Neighbor Tenure Regimes[b, c]	1.6612	1.01756	1.00	4.0	Number of tenure regimes (off res, fee, allotted, tribal) in 2 mile radius around parcel
Off Res. Neighbors[b, c]	153.031	211.703	0.0	993.0	Number of parcels, off the reservation, within a 2 mile radius around parcel
Fee Neighbors[b, c]	44.1529	166.9316	0.0	1000.0	Number of fee parcels within a 2 mile radius around parcel
Allotted Neighbors[b, c]	21.9074	45.2473	0.0	308.0	Number of allotted parcels within a 2 mile radius around parcel
Tribal Neighbors[b, c]	15.9516	38.7954	0.0	250.0	Number of tribal parcels within a 2 mile radius around parcel
Thick-Depth Ratio[d]	0.0096	0.0033	0.0	0.0182	Shale thickness divided by shale depth
Topography Roughness[e]	20.016	36.483	0.0	314.5	The mean slope divided by the standard deviation of slope
Feet to River[f]	27302.7	15434.9	0.0	67993.4	Euclidean distance (in feet) from parcel centroid?? to nearest river bank (name?)
Feet to Gas Plant[f]	27525.8	18289.3	0.0	78011.8	Euclidean distance (in feet) from parcel centroid to nearest gas processing plant
Feet to Res. Border[f]	28075.3	22516.4	0.0	98206.9	Euclidean distance (in feet) from parcel centroid to nearest reservation border
Road Density[g]	2561.7	5689.2	0.0	28523.5	Number of road miles within 2 mile radius of parcel centroid, divided by area
Panel B: For Drilling Delay Analysis (N = 6,124)					
Permit to Spud Days[h]	72.585	117.18	1.0	1437	Number of days elapsed between permitting and spudding of a well
Tenure Regimes	1.5608	0.5767	1.0	4.0	Number of tenure regimes (off res, fee, allotted, tribal) line passes through
Off. Res. Line Parcels	2.8156	4.2150	0.0	45	Number of off reservation parcels line passes through
Fee Line Parcels	0.2413	1.1872	0.0	28	Number of fee parcels line passes through
Allotted Line Parcels	0.2810	1.3285	0.0	15	Number of allotted parcels line passes through
Tribal Line Parcels	0.0808	0.7369	0.0	15	Number of tribal parcels line passes through

Notes: N=53745 for panel A. a) The source is the North Dakota Oil and Gas Commission website. b) The source is the BIA. c) The source is Real Estate Portal. d) The source is the EIA website at xxx. e) Authors calculations from topography data downloaded from the National Elevation Dataset. f) Authors calculations from data downloaded from North Daokta GIS Portal8 g) xxx. h)iHS_database/

Table 4: OLS Estimates of Number of Horizontal Oil Well Bores

	All Parcels on Oil Fields				*Radius with 1 Tenure Regime*		*Radius with >1 Tenure Regime*	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Neighbor Tenure Regimes			-0.06045*	-0.07165***			-0.07967**	-0.05985
			(0.03216)	(0.02601)			(0.03637)	(0.03835)
Neighbors in 2m Radius								
Off Res. Neighbors	-0.00019**	-0.00070**	-0.00019**	-0.00051	-0.00020***	-0.00030	-0.00124*	-0.00224**
	(0.00008)	(0.00035)	(0.00008)	(0.00033)	(0.00006)	(0.00035)	(0.00065)	(0.00095)
Fee Neighbors	-0.00049***	-0.00092***	-0.00047***	-0.00078***	-0.00099***	-0.00193***	-0.00047***	-0.00163**
	(0.00006)	(0.00028)	(0.00009)	(0.00025)	(0.00003)	(0.00039)	(0.00005)	(0.00072)
Allotted Neighbors	-0.00188*	-0.00187*	-0.00106	-0.00083	-0.01143***	-0.01022***	-0.00149	-0.00221*
	(0.00102)	(0.00101)	(0.00115)	(0.00105)	(0.00254)	(0.00177)	(0.00111)	(0.00129)
Tribal Neighbors	-0.00042	-0.00024	0.00020	0.00050	omitted	omitted	0.00005	-0.00022
	(0.00106)	(0.00111)	(0.00097)	(0.00099)			(0.00095)	(0.00098)
Tenure of Parcel								
Fee	0.18481**	0.12335	0.22019**	0.16987	0.20796***	1.31731***	0.01761	0.04825
	(0.09338)	(0.11938)	(0.09560)	(0.11234)	(0.06424)	(0.41387)	(0.13954)	(0.14492)
Allotted	0.16547	0.11101	0.18939	0.14498	0.97525***	1.89443***	0.04394	0.07879
	(0.11943)	(0.13757)	(0.12282)	(0.13506)	(0.27927)	(0.37311)	(0.13829)	(0.14293)
Tribal	-0.18596	-0.24354*	-0.16543	-0.21228	0.34300***	1.66124***	-0.28454*	-0.26338*
	(0.12391)	(0.13415)	(0.12402)	(0.13062)	(0.08188)	(0.47944)	(0.14353)	(0.14082)
Controls								
Thickness to depth of shale	89.03023***	54.71431**	90.22213***	49.73743**	1.1e+02***	77.10112***	31.97948	31.91852
Parcel acres	0.00282***	0.00280***	0.00281***	0.00278***	0.00254***	0.00253***	0.00412***	0.00410***
Topography roughness		-0.00003		-0.00002		0.00011		-0.00057
Feet to river		0.00000		0.00000		0.00001*		-0.00001
Feet to gas plant		-0.00001**		-0.00001**		-0.00001***		-0.00001
Feet to Res. border		-0.00001**		-0.00001**		-0.00001*		0.00002
Feet to Res. border x Res. Indicator		0.00001		0.00002		-0.00011***		-0.00002
Road density in 2m radius		0.00001*		0.00000		0.00000		0.00002
Oil field fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	-0.89317***	-0.77892**	-0.84882***	-0.66443**	-0.12985	0.95378***	-0.12598	0.96813***
Adjusted R-squared	0.059	0.060	0.059	0.060	0.061	0.062	0.080	0.081
Observations	42401	42401	42401	42401	31766	31766	10635	10635

Notes: Standard errors are clustered by oil field and shown in parentheses. * p<0.1, ** p<0.05, ***p<0.01. The data include completed wells in sample areas as of May 2015.

Table 5: OLS Estimates of Number of Directional Lines from a Single Well Pad

	All Horizontal Wells				*Radius with 1 Tenure Regime*		*Radius with >1 Tenure Regime*	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Neighbor Tenure Regimes			0.0041	0.0084			-0.0502*	-0.0322
			(0.0171)	(0.0202)			(0.0268)	(0.0284)
Tenure of Neighbors in 2m Radius								
Off Res. Neighbors	0.0002	0.0003	0.0002	0.0003	0.0003*	0.0003	-0.0008*	-0.0006*
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0004)	(0.0004)
Fee Neighbors	-0.0001*	0.0000	-0.0001*	0.0000	-0.0002***	-0.0001**	-0.0000	0.0002
	(0.0000)	(0.0001)	(0.0000)	(0.0001)	(0.0000)	(0.0001)	(0.0000)	(0.0002)
Allotted Neighbors	0.0003	0.0003	0.0002	0.0002	insufficient	insufficient	-0.0003	-0.0008
	(0.0008)	(0.0008)	(0.0008)	(0.0008)	observations	observations	(0.0007)	(0.0008)
Tribal Neighbors	0.0016***	0.0011*	0.0016***	0.0010*	insufficient	insufficient	0.0015**	0.0014
	(0.0006)	(0.0006)	(0.0006)	(0.0005)	observations	observations	(0.0006)	(0.0009)
Tenure of Parcel								
Fee	-0.0028	-0.0325	-0.0042	-0.0347	-0.0334	-0.1009	-0.0879	-0.0905
	(0.0331)	(0.0598)	(0.0334)	(0.0578)	(0.1084)	(0.1603)	(0.0634)	(0.0776)
Allotted	-0.0068	-0.0319	-0.0075	-0.0329	insufficient	insufficient	-0.0603	-0.0592
	(0.0621)	(0.0680)	(0.0628)	(0.0674	observations	observations	(0.0540)	(0.0765)
Tribal	-0.1191	-0.1666	-0.1207	-0.1696	insufficient	insufficient	-0.1949*	-0.2361**
	(0.1073)	(0.1041)	(0.1086)	(0.1063)	observations	observations	(0.0984)	(0.1166)
Controls								
Thickness to depth of shale	44.5203	48.6093	44.5370	49.4410	35.2732	32.9792	71.1865**	110.1135***
Parcel acres		-0.00030		-0.00030		0.00020		-0.0013*
Topography roughness		0.00000		0.00000		0.00000		-0.0000*
Feet to river		0.00000		0.00000		0.00000		0.00000
Feet to gas plant		0.00000		0.00000		0.00000		0.00000
Feet to Res. border		0.00000		0.00000		0.00000		0.00000
Feet to Res. border x Res. Indicator		0.00000		0.00000		0.00000		0.00000
Road density in 2m radius		-0.0029*		-0.0029*		-0.00230		-0.00300
Oil field fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	0.8641***	1.6596***	0.8682***	1.7145***	0.3297	1.2668***	-0.7976	-0.8166
Adjusted R-squared	0.137	0.138	0.137	0.139	0.146	0.148	0.109	0.122
Observations	12225	12225	12225	12225	9755	9755	2470	2470

Notes: Standard errors are clustered by oil field and shown in parentheses. * $p<0.1$, ** $p<0.05$, *** $p<0.01$. The data include completed wells in sample areas as of May 2015.

Table 6: OLS Estimates of Number of Vertical Oil Wells

	(1)	(2)	(3)	(4)
Neighbor Tenure Regimes			-0.00527	-0.00898
			(0.00803)	(0.00864)
Neighbors in 2m Radius				
Off Res. Neighbors	0.00006	-0.00007	0.00006	-0.00005
	(0.00004)	(0.00014)	(0.00004)	(0.00014)
Fee Neighbors	-0.00001	-0.00014	-0.00001	-0.00012
	(0.00003)	(0.00012)	(0.00003)	(0.00011)
Allotted Neighbors	-0.00047	-0.00041	-0.00040	-0.00028
	(0.00043)	(0.00045)	(0.00049)	(0.00048)
Tribal Neighbors	-0.00020	-0.00004	-0.00015	0.00005
	(0.00022)	(0.00025)	(0.00025)	(0.00024)
Tenure of Parcel				
Fee	0.06061	0.07143	0.06369	0.07727
	(0.05033)	(0.06232)	(0.05124)	(0.06324)
Allotted	0.03879	0.04393	0.04087	0.04819
	(0.05918)	(0.06534)	(0.06056)	(0.06681)
Tribal	-0.01569	-0.01014	-0.01390	-0.00622
	(0.06545)	(0.07165)	(0.06642)	(0.07275)
Controls				
Thickness to depth of shale	-2.86766	-1.5e+01	-2.76383	-1.6e+01
Parcel acres	0.00164***	0.00163***	0.00163***	0.00163***
Topography roughness		0.00005		0.00005
Feet to river		0.00000*		0.00000*
Feet to gas plant		0.00000		0.00000
Feet to Res. border		0.00000		0.00000
Feet to Res. border x Res. Indicator		0.00000		0.00000
Road density in 2m radius		0.00000		0.00000
Oil field fixed effects	Yes	Yes	Yes	Yes
Constant	-0.12985	0.95378***	-0.12598	0.96813***
Adjusted R-squared	0.123	0.124	0.123	0.124
Observations	42401	42401	42401	42401

Notes: Standard errors are clustered by oil field and shown in parentheses. * p<0.1, ** p<0.05, ***p<0.01. The data include completed wells in sample areas as of May 2015.

Table 7: OLS Estimates of Days between Horizontal Well Permit and Spud Date

(for all spudded wells in sample area as of December 2012)

	(1)	(2)	(3)	(4)
No. of Tenure Regimes line cuts			50.0126***	48.8373***
			(6.7985)	(6.9092)
Number of Parcels line crosses				
Off Res Line Parcels	2.2371**	2.3573**	0.9711	1.1026
	(1.0081)	(0.9910)	(1.0332)	(1.0300)
Fee Line Parcels	0.6193	0.5906	-2.4492	-2.4547
	(2.4698)	(2.3565)	(1.8238)	(1.7904)
Allotted Line Parcels	6.1488***	6.1271***	2.6797	2.7387
	(2.0973)	(2.0830)	(1.9924)	(2.0023)
Tribal Line Parcels	-2.2429	-2.5303	-9.2135**	-9.2354**
	(3.8265)	(3.8655)	(4.2862)	(4.3213)
Tenure of Parcel				
Fee	26.0463***	24.1240**	26.2189***	25.8784**
	(9.3111)	(9.9229)	(9.3013)	(10.4772)
Allotted	36.0309***	30.7689**	39.6570***	36.4528**
	(13.3772)	(14.5566)	(14.3206)	(16.1032)
Tribal	67.8357**	66.5388*	96.6362***	96.3197***
	(33.4713)	(33.7890)	(34.5416)	(35.0662)
Controls				
Horizontal well	76.2166***	74.7583***	42.7327***	42.3594***
Lines from well	5.9110	5.4544	2.6556	2.3804
Thickness to depth of shale	1.2e+03	205.9112	432.3729	-2.6e+02
Topography roughness		0.0766	0.0716	0.0766
Feet to river		-0.0008*	-0.0006	-0.0008*
Feet to gas plant		-0.0004	-0.0004	-0.0004
Feet to Res. border		-0.0006	-0.0005	-0.0006
Feet to Res. border x Res. Ind/		-0.0632	-0.0956	-0.0632
Road density in 2m radius		-0.2413	-0.1596	-0.2413
Month fixed effects	Yes	Yes	Yes	Yes
Oil field fixed effects	Yes	Yes	Yes	Yes
Constant	-7.1176	60.1527*	-53.8681***	10.2661
Adjusted R-squared	0.278	0.280	0.287	0.288
Observations	6124	6124	6124	6124

Notes: Standard errors are clustered by oil field and shown in parentheses. * p<0.1, ** p<0.05, ***p<0.01.

Table A1: Cross-Sectional OLS and Tobit Estimates of Land Tenure

	OLS			Tobit		
	Y = Percent Fee Simple (1)	Y = Percent Allotted (2)	Y = Percent Tribal (3)	Y = Percent Fee Simple (4)	Y = Percent Allotted (5)	Y = Percent Tribal (6)
Arid and Wet Acres, in 1000s	-0.008	-0.007^{**}	0.014^{***}	-0.017	-0.007^{***}	0.014^{***}
(< 10 and > 50 inches of precip.)	(0.122)	(0.005)	(0.005)	(0.109)	(0.007)	(0.004)
Semi-Arid Acres, in 1000s	0.005	0.005^{**}	-0.011^{**}	0.006^{*}	0.007^{***}	-0.011^{**}
(10 – 25 inches of precip.)	(0.150)	(0.021)	(0.012)	(0.085)	(0.004)	(0.012)
Arable Acres, in 1000s	0.041^{***}	0.006	-0.047^{***}	0.054^{***}	0.011	-0.047^{***}
(26 – 50 inches of precip.)	(0.006)	(0.438)	(0.001)	(0.001)	(0.151)	(0.001)
Distance from Reservation	-0.242^{***}	-0.090^{**}	0.331^{***}	-0.302^{**}	-0.098^{*}	0.332^{***}
Boundary to RR Line, 1893 (km)	(0.001)	(0.028)	(0.000)	(0.011)	(0.077)	(0.000)
State Pop. Density, 1890	732.5^{**}	-98.73	-638.6^{*}	877.6^{**}	-24.24^{*}	-638.6^{*}
	(0.030)	(0.465)	(0.096)	(0.033)	(0.887)	(0.096)
Δ in State Pop. Density 1890 to	-267.4	186.25	71.67	-591.9^{*}	147.8	71.67
1930	(0.253)	(0.177)	(0.822)	(0.098)	(0.438)	(0.822)
Constant	25.72^{***}	11.09^{**}	63.62^{***}	23.73^{***}	6.27	63.62^{***}
	(0.000)	(0.001)	(0.000)	(0.000)	(0.145)	(0.000)
N	97	97	97	97	97	97
R-squared	0.194	0.099	0.201	--	--	0.201
F-Stat	6.21	2.56	8.65	5.14	2.56	8.65
No. of left censored obs.				25	26	0
No. of uncensored obs.				72	71	97

Notes: Standard errors are robust to heteroskedasticity. P-values are in parentheses. * p<0.1, ** p<0.05, ***p<0.01. The dependent variables come from Anderson and Parker (2008).