PRIVATE VS. GOVERNMENT OWNERSHIP OF NATURAL RESOURCES: EVIDENCE FROM THE BAKKEN[*]

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Abstract:

Land ownership in the United States extends below ground, whereas most governments retain subsurface ownership. Which system generates greater resource use? We use an anticommons model to show the answer with respect to shale oil depends on land fragmentation. Our empirical analysis exploits a mosaic of government, private, and co-owned parcels created by historical policies on the Ft. Berthold Indian reservation above the Bakken shale long before its value was known. Studying the 2005-2015 fracking boom, we find that private ownership generated more oil production than government ownership unless parcels were smaller than 5 acres (private) or 63 acres (co-owned). Scattered government holdings within private areas further reduced production. We estimate the implied gains from consolidation and find that either fully private or fully public ownership of resources yields greater resource use than a fragmented mix of the two.

Key words: transaction costs, anticommons, land fragmentation, property rights, subsurface ownership, oil, resource booms

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1. Introduction

Under the ancient *ad coelum* doctrine, ownership of land extends downward to the center of the Earth. No ownership regime fully adheres to this principle in modern times, but there is a notable dichotomy across countries. In the United States, subsurface mineral rights are bundled with surface ownership whether private or public. In most other countries, governments retain subsurface ownership even when the surface is privately owned.

Which ownership regime generates greater resource utilization and rents? Existing research has not answered this question in a quantitatively detailed manner, but points to tradeoffs. Libecap (2018), for example, suggests that private ownership of conventional oil has encouraged discovery, but suboptimal levels of output conditional on discovery due to uncoordinated competitive extraction.

We highlight two factors that affect subsurface utilization under each regime: the fragmentation of surface ownership relative to the scale of mineral extraction, and the bureaucratic structure of government. We hypothesize these factors affect resource utilization by influencing the costs of mineral access and use. This framing follows Coase (1960, 1988), who emphasizes the importance of transaction costs when assessing the relative efficiency of private contracting versus governmental control.

This paper studies ownership trade-offs in the context of shale oil endowments that are accessible via horizontal drilling and hydraulic fracturing. Shale is a valuable resource—global endowments may contain at least three times as much oil as conventional reserves (World Energy Council 2016). The degree of ownership fragmentation is important because extraction techniques involve drilling a "lateral" that extends about two miles from a vertical well pad deep beneath the surface.[1] Oil leasing units in our study area and elsewhere are configured as 1 x 2 mile rectangles that span 1280 acres, which is roughly the technologically optimal scale of extraction under existing technology.

We model shale extraction as an anticommons problem under either ownership regime. When minerals are privately owned, the cost to a developer depends on N, the number of individuals who hold exclusion rights within the spatial scale of a project. Theory predicts the total costs will rise with N, reducing utilization relative to rent-maximization by a sole private owner. When government owns shale, the cost of access and use includes the expenditure of time and effort to navigate bureaucratic red tape and permitting processes and, potentially, bribes to government officials. Theory predicts these costs will rise with the number of excluders—politicians, officials, and agencies—that must consent to a project before it can commence (see Heller 2008, Buchanan and Yoon 2000, Shleifer and Vishny 1993).

Which ownership regime will entail higher costs of shale use? This is an empirical question that requires context specific comparative analysis. On one hand, shale use may be stymied if the U.S. system

[1] Shale extraction techniques were developed in the United States but many countries have commercial shale development or the potential for it (Harleman and Weber 2017).

of private subsurface ownership were applied to countries where small landholdings and fragmented ownership are prevalent.[2] On the other hand, shale use will be limited under contiguous government ownership when exclusion rights are extended broadly to administrative agencies and political agents. Shale use will be especially limited under bundled ownership if projects must span government *and* fragmented private land.

We exploit plausibly exogenous variation in ownership of the Bakken shale in North Dakota to compare production under varying conditions of land fragmentation. The Bakken—one of the world's most valuable oil endowments—sits beneath the Fort Berthold Indian reservation, which was subdivided into parcels of various sizes as part of the U.S. government's program for "allotting" Native American land to promote agriculture over 1887-1934 (Carlson 1981). In 1947 some parcels were consolidated into tribal ownership as part of a federal water reclamation project, inadvertently conveying valuable shale rights to a government with sovereign power to permit or exclude shale development.

The upshot is that shale ownership now occurs in four categories: contiguous blocks owned by the tribal government; small and large privatized parcels (fee simple); small and large allotted trust parcels co-owned by multiple heirs of the original allottee; and parcels of government land scattered within mostly privatized areas. We use this variation to identify the effects of ownership patterns on drilling outcomes during the fracking boom of 2005-2015. Ownership was solidified long before the value of shale was known, unlike many settings where property rights are endogenous to resource quality (Demsetz 1967, Besley 1995, Alston et al. 1996, Kaffine 2009, Galiani and Schargrodsky 2012).

We model the tradeoff of contiguous government vs. fragmented private ownership in the context of shale oil leasing and test implications by comparing production from horizontal drilling across 12,000 parcels on the reservation during the fracking boom. We find that both the type (private vs. government) and the acreage of parcels affects production *per acre*. Holding constant shale endowments and neighborhood fragmentation, fee simple parcels yield greater production compared to tribally owned areas of equivalent size. However, when an area is subdivided into smaller private parcels, production from private ownership decreases.

The results suggest a threshold level of private subdivision beyond which oil production under contiguous government ownership exceeds production under private fee simple ownership. In our study area, tribal ownership dominates if private parcels are smaller than five acres. The private vs. tribal trade-off is sharper for allotted trust lands, which have an average of fifteen owners per parcel. In this case, the

[2] Globally, 84% of farms are smaller than 5 acres whereas over 90% of farms in the United States exceed 10 acres (Foster and Rosenzweig 2017, Lowder et al. 2016). Moreover, in many regions, multiple owners own fractional interests in land because inheritance laws or customs allocate equal shares to descendants (see Baker and Miceli 2005, Palsson 2018, Hartvigsen 2014).

threshold parcel size is 63 acres.[3] We also find that scattered government holdings are especially influential in reducing output. Adding a single government (tribal) parcel within a neighborhood of private parcels reduces expected oil production by 42%. This indicates the productivity advantages of bundled ownership are diminished when private land borders tribal land.

In addition to providing a variety of robustness checks, we demonstrate that our core results are externally valid by comparing private versus federal ownership off of Fort Berthold. Despite the different institutional context and potential measurement error concerns off the reservation, we find a similar size-contingent tradeoff between private and government ownership: there is a threshold parcel size below which contiguous government ownership of shale yields greater production.

We provide evidence that the tradeoff in oil production is driven, at least in part, by royalty rates facing the developer. Holding constant neighborhood fragmentation, the royalty rates in allotted or fee simple leases are less than the royalty rates in tribal leases, consistent with an anticommons model in which contracting with the tribe entails satisfying a larger number of excluders relative to a single lease on a non-tribal parcel. Royalty rates increase with the number of fee and allotted parcels in a neighborhood, which is also consistent with theory.

This study adds to a growing body of empirical evidence on the anticommons including Mitchell and Stratmann (2015), who find that cell phone use is decreasing in the number of agents with power to exclude access, and Olken and Barron (2009), who find that truckers in Africa pay higher tolls for road passage with increases in the number of officials who can exclude passage.[4] Our study differs in that it considers how variation in the number of private excluders affects resource use and pricing.

We also contribute to the empirical literature on institutional aspects of oil extraction, which has focused primarily on conventional reservoirs. Early work by Libecap and Wiggins (1984) and Wiggins and Libecap (1985) demonstrates how small farm sizes caused large common pool losses. More recent contributions include Boomhower (2019), who provides evidence of the sensitivity of oil driller behavior to direct and indirect costs, and Fitzgerald (2010), who studies split estates to minerals in the Western United States. Our study also complements Vissing (2017), who studies contracting problems in the context of shale.

On the theme of government vs. private ownership of conventional oil, Edwards et al. (2018) and Kunce et. al (2002) exploit random assignment of U.S. federal ownership in 1x1 square-mile sections of

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[3] In Heller's (1998) terminology, there are 'legal anticommons' on even large heirship parcels that fully contain a horizontal well because of multiple owners. Most heirship parcels are small, however, implying the spatial anticommons problems are combined with legal anticommons. This is one distinction between anticommons and land assembly problems studied by economists (see Brooks and Lutz 2016 and Isaac et. al 2016).

[4] Heller (2008) suggests that empirical assessments of anticommons are less abundant than assessments of common property because anticommons problems are more difficult to code. In the latter case, a resource becomes visibly wasted or congested, but with anticommons, the predicted outcome of underutilization is difficult to observe.

railroad checkerboards in Wyoming to make side-by-side comparisons of drilling through government versus private land, finding that conventional drilling was costlier and slower on federal land due to bureaucratic red tape and environmental regulations. While useful for conventional oil, the Wyoming checkerboard is not ideally suited for studying shale extraction because it would miss the broader effect of the checkerboard itself on horizontal wells that typically exceed 1x1 square miles. In this way, our study complements Lewis (2019) who also emphasizes how neighborhood heterogeneity in ownership can cause spillover effects on oil discovery. He finds that conventional oil drilling through state owned land declines with proximity to federally owned land.

Finally, this study adds to a literature comparing group versus individual ownership of land and natural resources for indigenous people. This is an important topic in North America where there is evidence that agricultural productivity on Indian reservations is higher on fee simple when compared to tribal land (Gee et al. 2018) and follows the rank ordering of fee simple, then allotted trust, then tribal land (Anderson and Lueck 1992). There is evidence that land-based income is declining in the number of fractionated ownership interests (Russ and Stratmann 2015, 2016), and that movement towards land privatization may increase land values (Akee 2009), housing investment (Aragón and Kessler 2018), and measures of Native population incomes (Aragón 2015). This paper provides the first rigorous measurement of the negative effects of the checkerboard of fee simple, allotted trust, and tribal ownership found on many reservations today. Though checkerboarded jurisdiction likely also frustrates other forms of development not studied here, our findings suggest that contiguous tribal ownership of subsurface resources may be an effective remedy to one important aspect of the problem.

In a policy thought-experiment motivated by recent federal efforts at land reform on reservations, we estimate the effects of a pre-boom consolidation of all allotted trust mineral ownership into tribal ownership.[5] By reducing fragmentation, the consolidation would have increased expected royalty earnings during the boom by over $132 million. This amounts to roughly $26,702 for each fractional interest owner or $10,819 for each tribal member.

The paper proceeds with discussion commons and anticommons wherein we highlight the importance of scale when comparing ownership regimes. We then apply anticommons logic to shale drilling before describing the history behind the modern variation in shale ownership on Fort Berthold. Next we describe the data and the empirical model, present empirical results, and discuss policy relevance and external validity. Though our findings suggest that highly fragmented land rights help explain why an estimated $1.5 trillion worth of coal, oil, and gas remain untapped below Indian reservations (U.S. Senate

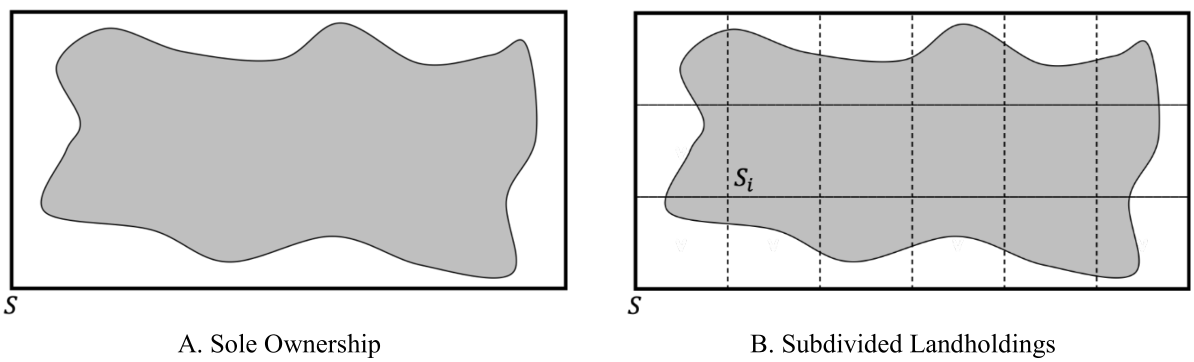
[5] A 2010 settlement of federal litigation (*Cobell vs. Salazar*) created a $1.9 billion "land consolidation fund" for Native American tribes to buy fractionated allotted trust interests and convert them into tribal ownership. This settlement explicitly recognizes the potential drag that fractionated ownership has on productive resource use, and implicitly assumes that consolidated tribal ownership will be an improvement.

2009), our study does not address some important aspects of the ownership tradeoff. We do not study distributional issues (i.e., how government royalties are distributed to tribal citizens)[6] or the relative extent to which governmental decisions account for environmental concerns about drilling.[7]

2. Spatial Scale, Commons and Anticommons

Figure 1 depicts two scenarios of surface ownership above an oil deposit. The large rectangle represents a landscape of size S containing the deposit. Panel A depicts a case in which the deposit is fully contained within a single private landholding. Panel B depicts subdivided private ownership with parcels of size S_i.

Figure 1: Surface Ownership over a Mineral Deposit



Notes: S represents the size (area) of the rectangle demarcated by the solid line. The dark shape represents an oil deposit, either a conventional oil reservoir or shale containing oil. Si represents an individual parcel of a particular size.

If the deposit in Figure 1 represents a conventional oil reservoir, then surface subdivision into private parcels of size S_i creates $N = S/S_i$ use rights to the reservoir under the U.S. regime of bundled surface and subsurface ownership. Individual exclusion rights are difficult to enforce because conventional oil can migrate across property lines from high to low pressure areas, implying that an oil developer could suck oil from beneath surrounding land from a single vertical well. Libecap and Wiggins (1984) and Wiggins and Libecap (1985) quantify the common property loss resulting from subdivision under private ownership.[8] We extend the traditional analysis by i) considering how rents from a different

[6] Corruption could reduce earnings to tribal citizens under government ownership, even if government ownership increases overall earnings (see Caselli and Michaels 2013). We discuss this issue in Section 7.
[7] The potential silver lining of fragmented ownership is that reduced drilling may have averted local environmental harms (e.g., Olmstead et al. 2013, Boomhower 2019). We discuss this issue in greater detail in Sections 7 and 9.
[8] One solution, discussed by Libecap and Wiggins (1984) and Wiggins and Libecap (1985), is to require coordination through oil field unitization. Regulatory agencies determine unit sizes, and a single oil developer is granted an access right when landowners within the unit consent to leasing terms. Royalty earnings from the drilled unit are apportioned based on oil owner lease terms and parcel sizes. This kind of forced coordination can mitigate

subsurface resource (shale oil) are dissipated with surface subdivision and ii) comparing private to government ownership.

A. Fragmentation of Private Shale Ownership as an Anticommons

To illustrate the important difference between shale and conventional oil, now imagine the deposit in Figure 1 is shale oil and S represents the economically profitable scale of a horizontal drilling project. Shale oil is tightly trapped within the rock so—unlike conventional oil—physical access is required for extraction. This implies that surface subdivision into parcels of size S_i creates N exclusion rights because a developer must gain permission from each owner before penetrating their shale with a horizontal well bore, or "lateral."

Whereas surface subdivision has caused common-property rent dissipation in the race for conventional oil, anticommons theory implies that subdivision can also cause rent dissipation in the extraction of shale oil. Allocating exclusion rights to too many people creates contracting barriers to fuller resource use through two mechanisms (Heller 1998, 2008). First, it can be costly to identify and contract with everyone with exclusion rights. Second, rational individuals do not consider their impact on other owners when setting prices for resource use, leading to an aggregate price that exceeds the income-maximizing price and lowers resource use and rents relative to sole private ownership (Buchanan and Yoon 2000).[9]

The upshot is that conventional and shale oil pose symmetric coordination problems—commons and anticommons—with the same conceptual solution: sole ownership. In practice, sole private ownership of large deposits is rare, but government ownership is not.[10] The anticommons framework also applies to government decision-making, allowing us to compare fragmented private ownership with government ownership in a single model.

B. Government Ownership as an Anticommons

Contiguous government ownership of shale mimics sole private ownership as in Panel A of Figure 1 if a single public decision maker "holds the core bundle of property rights relatively intact"

common property problem caused by fragmented ownership but at the potential cost of creating an anticommons problem.

[9] This second mechanism is sometimes confused with holdup problems but it is actually a price-setting externality that is akin to the resource-use externality in common property. Rent dissipation under anticommons is due to a failure to coordinate, rather than a strategic attempt to extract surplus by exploiting bargaining power. See footnote 15 for a discussion of how forced pooling laws reduce the potential for strategic hold-up in the context of oil and gas leasing.

[10] Sole private ownership is rare for two reasons. First, surface parcels are typically demarcated before the location, scale, and technology of resource extraction is known. Second, there is often political opposition to concentrating resource ownership in large estates, which has affected the size of parcels created by land titling globally (see, e.g., Hibbard 1939, Mwangi 2007, Ali et al. 2016, Hartvigsen 2014).

(Heller 1998, 682). A prospective oil developer, for example, can negotiate with the decision maker rather than with multiple parcel owners, thereby circumventing coordination problems. However, governments typically require approval of several agencies and officials who are unable to make decisions unilaterally (Weingast and Marshall 1988; Calvert et al. 1989).

Following Heller (1998, 2008), Buchanan and Yoon (2000), and Schleifer and Vishny (1993) we assume that resource use declines with the number of excluders (*N*), whether they are government agents (e.g., bureaucrats, interest group lobbyists, local politicians), or individual private shale owners. Whereas Schliefer and Vishny model inefficient (uncoordinated) government corruption in a way that could be characterized as an anticommons, Buchanan and Yoon argue that bureaucratic red tape reduces resource use when the "price" for each agent's approval is driven by transactions costs of getting approval rather than an aggregation of bribes as in Schliefer and Vishny (1993).[11]

The anticommons model implies that the aggregate price charged to an oil company to develop a shale deposit will increase, and production of shale will decrease, as N increases. In what follows we argue that surface ownership fragmentation is a key determinant of whether anticommons problem more or less severe under private or contiguous government ownership.

3. Testable Implications for Shale Use under Private vs. Government Ownership

A. Threshold Degree of Subdivision

Panel A of Figure 2 illustrates the tradeoffs in the number of excluders associated with private vs. government ownership of subsurfaces. The figure holds constant the scale of profitable extraction, as in area S of Figure 1. Moving left to right from the origin corresponds to further surface subdivision, or smaller parcels above the shale. Decreases in parcel size increase the number of excluders under private subsurface ownership, which is why the N_P line is positively sloped.[12]

The horizontal line N_G in Panel A represents the number of exclusion rights implicit in contiguous government ownership, which does not vary with the degree of surface subdivision. We assume the height of the government line lies above one because administrative decision making in most governments is vetted through multiple agencies, agents, and constituent groups that must each be

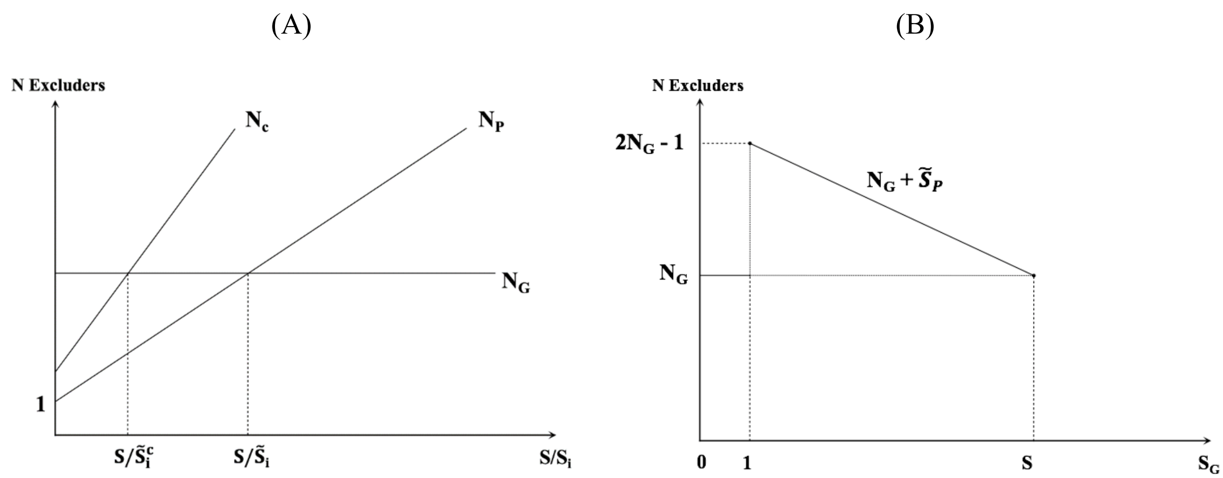
[11] In Shleifer and Vishny's (1993) model, multiple officials "can deny a private agent the passport, access to a road, or an import license" (p. 601). They also note that "an important reason why many of these permits and regulations exist is probably to give officials the power to deny them …" (p. 601). This is similar to Heller's (1998) discussion of a regulatory anticommons, and the motivation for the Buchanan and Yoon (2000) model. Although their model is not about corruption, Buchanan and Yoon emphasize the difficulties of obtaining permits to develop natural resources in the U.S. because many regulatory agencies hold veto rights.

[12] A slope of one implies a requirement of unanimous consent, a requirement of majority consent would correspond to a slope less than one but greater than ½.

satisfied before consenting to a project as articulated in Schleifer and Vishny (1993), Heller (1998), Buchanan and Yoon (2000).

Because the number of private excluders varies with parcel size but the number of government excluders does not, the N_P and N_G lines intersect at some threshold parcel size, $S/\tilde{S}_i$. Hence, there is some level of surface subdivision for which government ownership involves fewer excluders (lower N) than private ownership. While the anticommons framework implies the existence of this threshold, its exact location is an empirical question conditioned on the structure of government and the size of private parcels relative to the scale of resource use.

Figure 2: Exclusion Rights to Mineral Deposit



Notes: Panel A shows how the number of excluders to the shale deposit changes with surface subdivision under bundled private ownership (N_P and N_C) versus government ownership (N_G). The N_P line represents single-owned parcels and the N_C line represents co-owned parcels. S represents the size of landscape containing the deposit. $\tilde{S}i$ denotes the parcel size for which $N_P = N_G$ and $\tilde{S}_i^c$ denotes the parcel size for which $N_C = N_G$. Panel B sets $S_i = \tilde{S}i$ and shows how the number of excluders changes as parcels are converted from private, singular ownership ($\tilde{S}_P$) to government ownership ($\tilde{S}_G$). The number of excluders peaks with $\tilde{S}_G = 1$, and converges to N_G as the number of converted parcels approaches $\sum \tilde{S}_i$.

B. Co-ownership

An additional source of ownership fragmentation is co-ownership by individuals who hold undivided interests in private parcels, typically because of inheritance laws or local customs that prescribe equal shares to descendants (Baker and Miceli 2005).[13] The N_C line in Panel A of Figure 2 depicts how

[13] There is severe co-ownership of parcels in many countries and regions, including Haiti (Palsson 2018), Eastern Europe (Hartvigsen 2014), and former share tenancy lands within the contiguous United States (Deaton 2012). On Native American reservations, millions of acres are jointly owned by descendants of families who received land allotment during 1887-1934 (Shoemaker 2003, Russ and Stratmann 2016).

the number of excluders changes when each parcel is co-owned by C individuals. If each private parcel has C co-owners, then the landscape containing the resource contains $N_c = N_P \times C$ owners. The N_c line has a vertical intercept and a slope greater than 1 because each parcel overlying the shale has multiple owners ($C > 1$) holding undivided exclusion rights. The upshot is that government ownership will entail fewer excluders (lower N) than private ownership at a larger parcel-size threshold when parcels are co-owned.

C. *Non-Contiguous Government Ownership*

In some areas, including in our empirical setting and in much of the U.S. West, government ownership is scattered or checkerboarded across shale deposits. Panel B of Figure 2 illustrates the effect of introducing scattered government holdings in a subdivided and privately owned area of shale. To simplify the illustration, the figure ignores co-owned private parcels (i.e., it assumes $C = 1$) and holds constant the size of parcels at $S_i = \tilde{S}_i$, the threshold size for which $N_G = N_P$. The figure shows how the number of excluders changes as individual parcels (like those depicted in Figure 1) are converted from private $(\tilde{S}_P)$ to government ownership ($\tilde{S}_G$) when land is subdivided.

Importantly, adding the first government parcel causes a discrete jump in the number of excluders of N_G -1 because this replaces a single private excluder with N_G government excluders. Each additional parcel converted to government ownership removes another private excluder and adds zero additional government excluders because N_G is fixed. Hence, the potential scale advantages of government ownership in reducing N are undermined when ownership is scattered rather than consolidated.

D. *Testable Predictions from the Anticommons Model*

In our empirical setting and elsewhere in the United States, regulations require oil developers to form a "spacing unit" prior to drilling to compensate subsurface owners whose shale oil may be drained by a well. A lease is written with each owner who then receives a royalty on a share of the total project revenue that is proportional to his acreage in the unit.[14] Spacing units for shale range in size across locations but are generally matched with the technologically optimal scale of a horizontal drilling project. On the Bakken shale formation – our study area - most units are 1280-acre, 1-by-2 mile rectangles. Hence, the coordination problem facing a given landowner of parcel *i* depends on the number and type of separately owned parcels within a ½- mile to 1-mile radius. These *N* neighboring shale owners are

[14] Owners also typically receive a lump-sum bonus payment upon signing a lease. Fitzgerald and Rucker (2016) find that royalties typically comprise 85-90% of payments. Vissing (2016) finds that bonus payments are positively correlated with other aspects of the lease including royalty rates and terms that are favorable to the landowner.

potential excluders because their section of shale cannot be drained unless asking prices are paid to all (or the majority of) owners in the drilling unit.[15]

In the Mathematical Appendix, we apply the Buchanan and Yoon (2000) model of anticommons to an oil leasing framework to show that an increase in the number of potential excluders (N) in a neighborhood around a parcel leads to an increase in the aggregate price facing oil developers and reduces total oil production and royalty earnings for that parcel.[16] Applying these generic implications to the empirical variation in N depicted in Figure 2 leads to specific testable predictions about how patterns of resource ownership will affect shale oil development on a particular parcel i.

> *Prediction 1:* Holding constant the size and ownership type of neighboring parcels that would be members of the same oil drilling unit, oil production will be higher on privately owned land when compared to government land. This follows directly from the intercepts in Figure 2 (a), which indicate fewer excluders per parcel on private land.
>
> *Prediction 2:* Holding constant a parcel's ownership type, adding private neighbors (via finer subdivision) will increase royalty rates and reduce production. This follows from the negative slopes of the N_P line in Figure 2 (a).
>
> *Prediction 3:* Holding constant a parcel's ownership type, adding co-owned neighbors will increase royalty rates and reduce production to a greater extent than adding individually owned neighbors. This follows from $N_C < N_P$ line in Figure 2 (a).
>
> *Prediction 4:* Adding a single government-owned parcel to an otherwise private neighborhood around parcel i will reduce that parcel's production if it is private but adding additional government parcels will have no effect. A corollary is that adding government neighbors around a government-owned parcel will have no effect. This follows from the discrete change in excluders in Figure 2(b).

Predictions 1-4 jointly imply that shale in neighborhoods of contiguous government ownership will be less productive than shale in neighborhoods of private ownership unless private parcels are subdivided to a threshold size. The threshold size is empirically determined, but it is larger for

[15] Forced pooling laws in some US states compel minority mineral owners into horizontal drilling projects if a majority of neighboring acreage has already been leased. State-level forced pooling laws do not generally apply on sovereign Indian reservations (see Slade et al. 1996), but a 1998 federal law specific to Fort Berthold requires the consent of a super-majority of owners of co-owned lands before a mineral lease can be executed. Forced pooling reduces the potential for strategic hold-up in lease negotiations by preventing any single land-owner from blocking the formation of a unit. As Issac et al. (2016) demonstrate, the ability of hold-outs to block development falls dramatically when unanimity is relaxed because the number of feasible leasing arrangements increases combinatorically. In contrast, anticommons problems can still occur in the presence of forced pooling because the number of contracting parties necessary for a majority may still be large.

[16] The model applies the Buchanan and Yoon (2000) framework to a setting where N shale excluders set individual royalty rates by maximizing their individual expected royalty earnings, taking as given the royalty rates set by all other excluders. The oil driller, operating within a competitive industry, makes production decisions based on the aggregate royalty rate in a prospective drilling unit, which is the weighted mean of the individual royalty rates.

neighborhoods of co-owned parcels. The predictions also imply that parcels in highly fragmented neighborhoods – particularly those with a positive but small proportions of government land – will be the least productive.

4. Empirical Setting: Fragmented Ownership of the Bakken Shale

The Fort Berthold Indian Reservation is an excellent setting to assess the private vs. government tradeoff for three reasons.[17] First, it sits above the Bakken shale, which holds one of the world's richest endowments of unconventional oil. Second, the reservation contains all shale ownership regimes of interest: large and small private parcels; large and small co-owned parcels; contiguous government (tribal) ownership; and scattered government holdings. Third, the patterns of parcel sizes and ownership types were not selected based on the quality of the underlying shale. Instead, these patterns were determined by historical events occurring long before shale endowments were valuable.

A. Land Allotment

Fort Berthold was communally owned by the Three Affiliated Tribes until Congress approved land allotment under the Dawes Act of 1887. In 1900, 949 allotments were authorized. These early allotments, near the Missouri river (depicted in Figure 3B), distributed 160 acre farming parcels for families, 80 acres for single persons and orphans, and 40 acres for children under 18. During the next 29 years, 3,401 allotments were made further from the river, ranging in size from 40 to 320 acre parcels for ranching (Reifel 1952). Under the Act, allottees automatically acquired subsurface rights even though oil was not yet discovered.[18]

The total acreage on Fort Berthold exceeded that necessary for allotments to tribal members. The Act's treatment of residual land further contributed to ownership variation. Only 27,000 acres of unallotted lands were retained as tribal land. The remaining surplus land, approximately 360,000 acres in the reservation's North and Northeast sections, were opened in 1910 for homesteading by whites as 160-acre parcels and for smaller town lots.[19] Settlers who acquired surplus lands also acquired subsurface rights to yet-to-be discovered oil.[20]

[17] The reservation was established in 1870 and is now approximately 990,000 acres. Though the treaty established a reservation of over 12 million acres for three tribes—the Arikara, Mandan, and Hidatsa—subsequent policies reduced the reservation to its contemporary size of slightly less than one million acres.
[18] Conventional oil was not discovered in North Dakota until the 1950s. Unconventional oil (from shale) was not extracted from North Dakota until the 2000s (Zuckerman 2013).
[19] The surplus area was assumed to be detached from the reservation at the time of homesteading, but U.S. Courts ruled in 1972, in *The City of New Town, North Dakota v. U.S*, that the 1910 opening for homesteading had not altered the boundaries of the reservation.
[20] This was in contrast to rights to the already discovered coal, which was retained in communal tribal ownership beneath most of the surplus section (Ambler 1990).

Allotment created variation in whether or not a parcel became fractionated with co-ownership by heirs. When initially allotted, parcels were to be held in trust for 25-year or until allottees were deemed "competent" to manage a private, alienable, fee simple title (Carlson 1981). The 1934 Indian Reorganization Act (IRA) halted further titling when only 10 percent (63,510 out of 615,640 acres) of allotted land had been converted to fee simple.[21] Allotted parcels not converted to fee simple remained held in trust and, importantly, were probated when the original allottee owner died. Typically, the allottee left no will, so the parcel went to several heirs as undivided interests.

B. Garrison Dam

The controversial Garrison Dam, built during 1947-1953, contributed to further inadvertent variation in shale ownership. The Dam forced the relocation of families living near the river who comprised 80 percent of the reservation population (BIA 1948). Resettlement was accomplished with land exchanges and with federal settlement funds earmarked for relocation; most of this was allocated to individuals and some was retained by the tribal government. When tribal families resettled the reservation, they acquired both allotted trust and fee simple parcels, the latter from white owners. Relocation had two important implications for our study. First, it caused subdivision of existing parcels, creating smaller parcels. Second, it increased the proportion of fee simple lands owned by tribal members (rather than whites).[22] Based on the 2010 Census, Native Americans account for 81 percent of the reservation's population and represent the racial majority even in the surplus-area communities of New Town (77%) and Parshall (51%).

The Garrison Dam also created contiguous and scattered tribal ownership. The subsurface below the flood basin—approximately 160,000 acres—was converted back to tribal ownership (as in pre-allotment). Some of the surface land in this area is dry now, while some is underwater. The tribal government also used settlement funds to acquire scattered holdings of fee simple and allotted trust upland from the flood basin (in the South and Southwest corners of the reservation).[23] Overall, tribal

[21] These data are based on Table 15 of Reifel (1952).

[22] New Town was created after the flood, in 1950. The town platted fee simple parcels that some Native Americans purchased. Other towns were created on the reservation, but not in the surplus area, such as Mandaree and White Shields. These settlements also consolidated and divided ownership, but typically on allotted trust land.

[23] The tribe purchased tracts of allotted trust and fee simple in an effort to create tribal blocks of ranch land for use under permit by individual tribal members. Reifel (1952) recommended this acquisition to encourage more agricultural productivity than what was being achieved from the mosaic of fractionated allotted trust land, interspersed with fee simple. He described the problem faced by a prospective tenant farmer who wanted to engage in agriculture at a spatial scale exceeding the 40, 80, or 160 acre tracts noting that in "cases where there are a large number of heirs and the tenants have had experienced difficulty working out a satisfactory settlement amongst all of them, such tenants are beginning to question whether it is worth all the trouble it takes to get to use the land." (p. 426). Reifel emphasized how fragmentation rendered parcels of little value, because of the coordination problems of

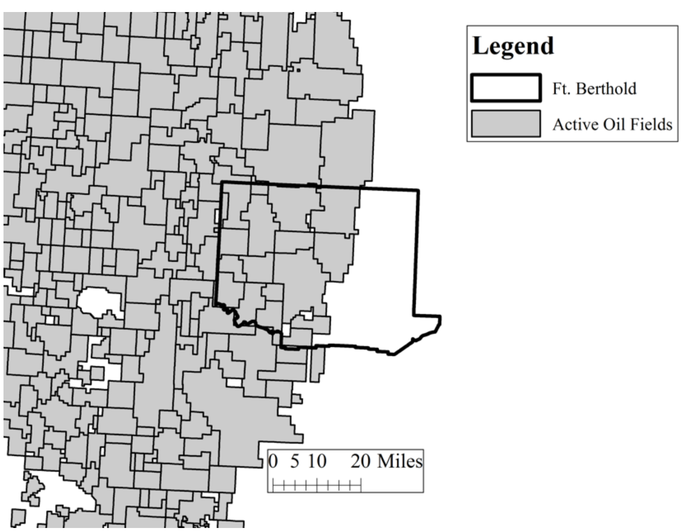
holdings increased from about 27,000 acres in 1947 to 33,000 in 1960, not counting the subsurface area of approximately 160,000 acres in the flood basin.[24]

C. Modern Shale Ownership and Regulation

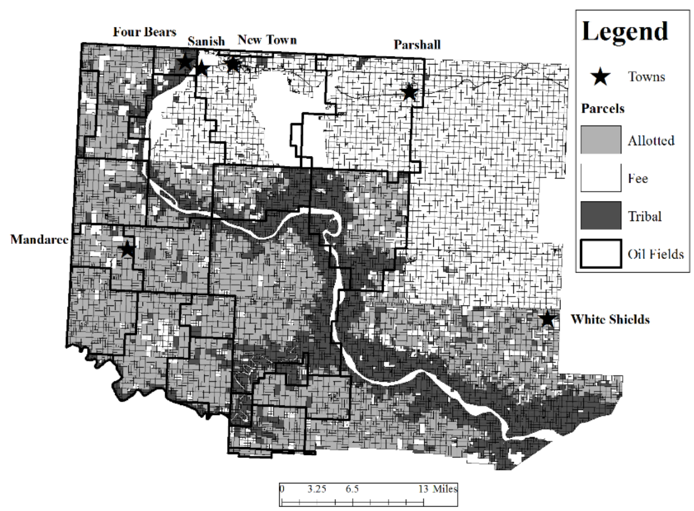
These historical episodes effectively determined modern ownership because surface and subsurface tenure on Indian reservations are fixed absent special approval from the Secretary of the Interior (Shoemaker 2003; C.F.R 150.1-150.11). Figure 3B illustrates the modern shale ownership mosaic that resulted from allotment and the Dam, based on data shared with us from the Bureau of Indian Affairs (BIA). There are 385,699 acres of allotted trust, 367,972 acres of fee simple, and 191,683 acres of tribal. The 6,190 allotted trust parcels are spanned by 91,707 ownership interests, resulting in an average of 15 co-owners per parcel (Dept. of Interior 2013).[25]

Figure 3: Fort Berthold and Adjacent Counties

(A) Ft. Berthold and Surrounding Counties



(B) Fort Berthold



Notes: Panel A depicts the Fort Berthold reservation within our broader study area of Dunn, McKenzie, McLean, Mountrail, and Ward Counties. The shapes show active oil fields as defined by the North Dakota Oil and Gas Commission. These fields contained at least one horizontal well drilled by May 2015. Panel B shows ownership mosaic on Fort Berthold, based on Bureau of Indian Affairs data. It illustrates parcels and the areas of active oil fields. The white area in the Central North part of the reservation depicts an area that we omit from our analysis because no ownership information is available from either the BIA or the State of North Dakota.

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using it in conjunction with the other key tracts. His arguments, with respect to farming and ranching, resembles our theory of the coordination problems for shale oil development across a fragmented ownership landscape.

[24] The pre-flood statistics come from BIA (1948) and Reifel (1952). The 1960 numbers come from the Bureau of Indian Affairs, 1960 *United States Indian Population and Land Report*.

[25] Although this degree of fractionation is extreme, it is actually below the average across reservations (Shoemaker 2003, Russ and Stratmann 2016). The average reservation with allotted trust land has 36.7 ownership interests per allotted trust parcel with a maximum of 115 (see Leonard et al. 2018).

Our empirical analysis focuses on the 62 percent of the reservation that sits above active oil fields as defined by the North Dakota Oil and Gas Commission (Figure 3). These are areas where profitable extraction has been feasible, given the shale endowment. On active oil fields, there are 291,471 acres of allotted trust spanning 3,623 parcels, 181,906 of acres of fee simple spanning 3,917 parcels, and 112,665 acres of tribal ownership.

The upshot for our study is that there is rich variation in the ownership of potentially productive shale under Ft. Berthold that enables us to assess all of the theoretical propositions described in Section 3. The 112,665 tribal acres include contiguous and scattered holdings that are north, south, west, and east of the river. Allotted and fee simple parcels also occur in all sections of the reservation, as shown in Figure 3. Less visible is the rich variation in parcel sizes across the allotted trust and fee simple parcels. In general, the small parcels tend to be closer to the river, where smaller-acre allotments dominated, and nearer to town sites, some of which were created by the Garrison Dam project. None of the ownership variation was selected on (unknown) inherent shale productivity. In Section 6, we explain how this fact helps in identifying the effect of ownership on oil production.

Another important difference across ownership regimes is the degree of regulatory oversight by various governments. The tribal government of Fort Berthold has the authority to regulate drilling within the reservation boundary, and it has passed some reservation-wide policies including set-back requirements for wells and technology standards that apply all ownership regimes, including fee simple parcels (MHA Energy Division, 2013). In addition, the drilling on allotted and tribal parcels is subject to approval by the Bureau of Indian Affairs, which holds these parcels in trust (Bureau of Indian Affairs 2012). BIA involvement also makes it more likely that drilling projects will trigger a National Environmental Policy Act (NEPA) review, although this is not the case for every well (Bureau of Indian Affairs 2012). NEPA does not apply on fee simple parcels (Bureau of Indian Affairs 2012). Federal government oversight on allotted and tribal parcels affects the interpretation of our coefficients but does not threaten identification. As we discuss in Section 8, federal involvement can be thought of as another set of government exclusion rights entailed in allotted and tribal ownership regimes.

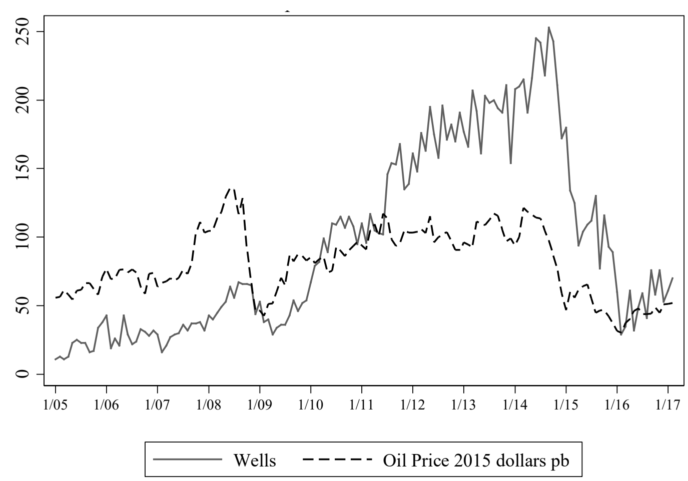
5. Data for Empirical Tests

Our data set combines data on well-level oil production, from the North Dakota Oil and Gas Commission, with the shale ownership data from the Bureau of Indian Affairs (see Figure 3B). The GIS data on oil wells contains information for every horizontal well bore and every lateral that has been drilled in the state. Our data set represents the accumulation of wells completed as of May 1, 2015, which corresponds with the beginning of a drilling 'bust.' We begin with an overview of the Bakken boom and bust before describing how we map well-level oil production into parcel-level production and revenue.

A. Regional Overview

Figure 4 shows the new wells drilled in North Dakota during 2005-2017. The Bakken produced the vast majority of these wells and accounted for 1.56 billion barrels of oil.[26] To understand the potential magnitude of royalty payments, multiply the average price per barrel over 2005-2015, which was $85.5 in 2015 dollars, by the average royalty rate, which was 17.6 percent. This amount—$15 billion—does not account for the flow of royalty payments earned on oil extracted over the well's full lifetime of perhaps 25 years (MacPherson 2012).

Figure 4: New Wells in North Dakota and Global Oil Prices, 2005-2017



Notes: The source for drilling information in North Dakota is https://www.dmr.nd.gov/oilgas/. The oil price data come from the U.S. Energy Information Administration (West Texas intermediate) and are adjusted to 2015 U.S. dollars based on the U.S. CPI. Oil prices are per barrel. The source for oil drilling in our study area is the North Dakota's Oil and Gas Commission website.

B. Well-Level Production

To measure production and revenue in different locations, we first estimate output from each horizontal well in our sample during its first 18 months of production. We focus on the first 18 months to normalize for differences in the timing of when wells were drilled. (Some wells were drilled near the end of our sample period, in May 2015, whereas others were drilled earlier, for example during 2011 or 2012). We choose an 18-month period because our data covers production through January 2017, spanning 18 months beyond May 2015. [27] We combine the production estimates with monthly global

[26] https://www.dmr.nd.gov/oilgas/stats/2015CumulativeFormation.pdf

[27] We estimate the monthly flow of oil from a well by combining information on production starting month and cumulative production with data from a representative (baseline) oil decline curve on the Bakken. The oil decline calculations are based on the rate of monthly decline in productivity from the baseline well, as estimated by Hughes (2013, p. 57). From the data we observe, $Q_T = \sum_{t=0}^{T} q_t$ where t = month, T = number of months since production began, and Q_T is cumulative production as of early 2017. The baseline well produced 127,785 barrels during the first 18 months and 213,488 barrels over the first 48 months. We fit a hyperbolic decline-curve (Satter et al. 2008) to Hughes' figures to extend the estimates from 4 to 29 years, the predicted length of production (MacPherson 2012).

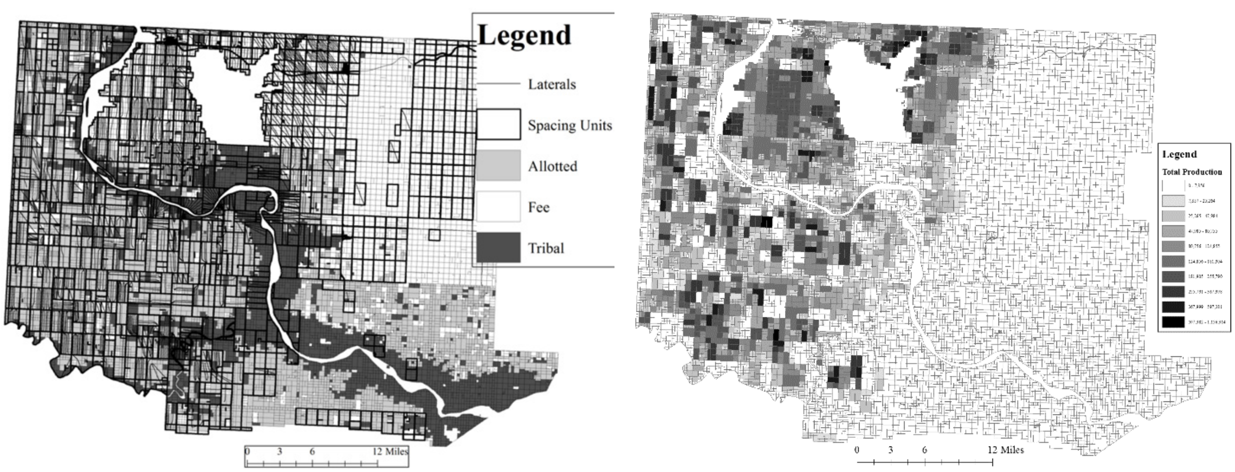
price data to estimate the revenue earned by each well, discounting at an annual rate of 3% from Jan. 2005 through May 2015.

C. Parcel-Level Production

We use individual parcels as the unit of observation in our empirical analysis because we wish to identify both the own-parcel and neighbouring parcel effects of ownership size, type, and fragmentation. The costs of contracting to extract oil from a given parcel depend on the ownership characteristics of that parcel *and* the parcels that could potentially be contained in the same oil spacing unit. Parcels are the most fundamental unit of analysis because their owners are potential excluders of oil wells and, unlike spacing units, parcel size and ownership were predetermined with respect to oil-boom production decisions. [28]

Figure 5: Estimating Parcel-Level Oil Revenue

(A) Well Laterals and Spacing Units **(B) Estimated Production**



Notes: This figure depicts our matching of lateral wells to spacing units (Panel A) and the spatial distribution of estimated parcel revenue (Panel B). Data on units, wells, and production come from the North Dakota Oil and Gas Commission. The variation in drilled vs. not drilled areas of the reservation align with the easternmost edge of active production off the reservation (Figure 3A).

From the oil-decline curve, we estimate the lifetime oil-productivity of each sample well and then infer productivity over the first 18 months.

[28] Spacing units themselves are not an appropriate unit of analysis because they are endogenously formed during the leasing process—the composition of spacing units is determined in part by contracting costs. Unit sizes are constrained by regulations, but drillers can affect their composition by deciding where to form units. Another disadvantage of unit-level estimates is that they introduce selection bias because not all parcels are members of units. Moreover, focusing on units would fail to account for how parcels adjacent to—but not contained within—a unit may reduce production by inducing suboptimal unit configuration.

We estimate parcel-level production by i) matching each well to the corresponding oil spacing unit, ii) determining which parcels are members of each unit, and iii) allocating production and revenue to each parcel based on its share of acreage in the unit. This approach mimics the actual formula for estimating royalties and accounts for the fact that some parcels are members of multiple productive units.[29] Panel A of Figure 5 depicts the laterals and spacing units, and Panel B maps parcel-level production across the reservation.[30] Some spacing units were formed but not drilled, presumably because drilling was not profitable. Figure 5 makes it clear that the eastern part of the reservation has produced almost no unconventional oil (see Panel B). No other clear regional pattern in parcel productivity is evident.

D. Neighboring Parcels

To measure the effects of subdivision and ownership mixes around a parcel, we focus on the neighborhood of parcels within a ½ mile radius of each parcel. This ½ mile radius includes the set of parcels surrounding parcel *i* that could potentially be included in the same unit and thus affect contracting costs for accessing parcel *i*'s shale.[31] Appendix Figure A1 illustrates our mapping from the spatial data to the variables. We choose the ½ mile radius because this yields an area close in size to the average spacing unit, but the results are robust to other distance choices.

The average area spanned by the ½ mile radius is 1550 acres, which is roughly the size of a the most common 1280-acre spacing unit.[32] Within the 1/2-mile radius, the number of neighboring fee simple parcels ranges from 0 to 819 and the number of neighboring allotted parcels ranges from 0 to 60. The average amount of tribal acreage in the radius is 355 acres; some ½ mile neighborhoods consist of fully contiguous tribal tracts, which are reported to us by the Bureau of Indian Affairs as "parcels." Some mineral parcels are potentially under water, based on the high flood lines of the Missouri River—we control for this to account for special rules governing drilling under water.

E. Shale Endowments and Other Covariates

[29] A parcel may be a member in multiple units because it is not neatly contained within a single unit or because additional units are formed later in time to drill to a different depth in the shale. The latter phenomenon is not common in our sample because the technology to do so was just becoming feasible around 2015.

[30] Note that some spacing units were formed but not drilled, presumably because drilling was not profitable.

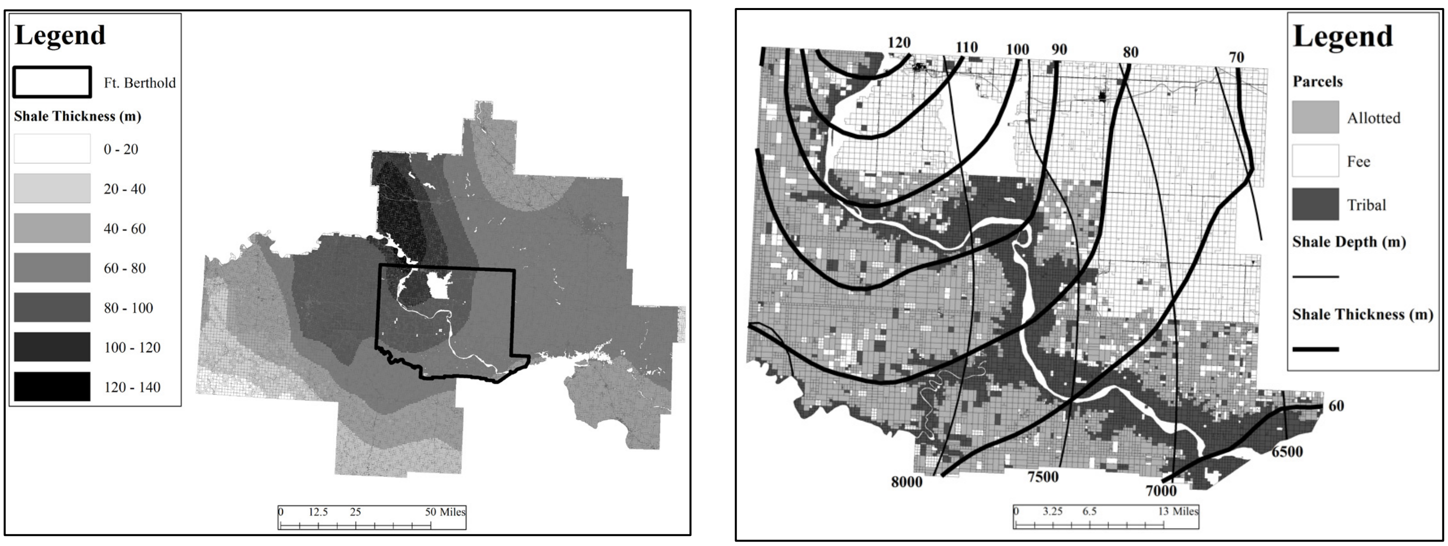
[31] An alternative approach would be to calculate every 1280-acre unit (the most common unit size) that could potentially include parcel *i* in some way, and then develop neighbor measures from the other parcels contained in these hypothetical units. In the limit our approach of simply drawing a circle around parcel *i* closely approximates the much more arduous task of drawing every 1280-acre rectangle that could include parcel *i.*

[32] There is some slight variation in the area within a ½ mile radius because we include any parcel that is touching the radius, and those perimeter parcel sizes vary.

To control for variation in the raw endowment of shale across the reservation, we collected spatial data from the North Dakota Oil and Gas Commission, depicted in Figure 6. The figure depicts contours of shale thickness and depth beneath the surface, both in meters. Thickness is a typical measure of shale quality because it is a critical determinant of oil drilling productivity and profitability (see Weber et al. 2016). Depth also affects productivity and drilling costs (Weber et al. 2016). We quantify this information by creating indicator variables for each thickness and depth contour depicted in Figure 6B, and assigning each parcel to a bin. Figure A2 in the appendix plots the distribution of reservation parcels in each bin.

Figure 6: Shale Endowment beneath Fort Berthold on Adjacent Counties

(A) Ft. Berthold and Surrounding Counties **(B) Fort Berthold**



Notes: This figure depicts the spatial distribution of shale thickness underneath the Ft. Berthold Indian Reservation and surrounding counties. Shale thickness estimates were obtained from the North Dakota Oil and Gas Commission. Reservation parcels represent mineral ownership and were obtained from the Bureau of Indian Affairs. Off-reservation parcels represent surface ownership and were obtained from Dunn, McKenzie, McLean, Mountrail, and Ward Counties. Parcel data were not available for Mercer County, which lies to the southeast of the reservation. This area lacks fracking activity, however (see Figure 3A). In In Panel B, thicker lines represent shale thickness contours and the thinner lines represent shale depth contours, both expressed in meters.

We create other variables to measure variation in topographic roughness, road density, and location within city limits. We use these covariates to control for variation in surface roughness and development, which could affect drilling production. Table 1 gives summary statistics and data sources.

Table 1: Summary Statistics for Parcel Level Data Set

	Mean	*Std. Dev.*	*Min*	*Max*	*Description*
Outcome Variables					
Production[a,b,c,f]	18,692.5	54,465.2	0	1,156,314	Estimated production over 1st 18 months
Production per Acre	284.855	493.75	0	9,199.286	Estimated production divided by parcel acres
Revenue, 3% dr[a,b,c,d,f]	773,697	2,253,393	0	5.02e+07	Estimated revenue 1st 18 months, discounted at 3%
Revenue per Acre[a,b,c,d,f]	11,804.8	20,803.5	0	399,534	Estimated revenue divided by parcel acres
Own-Parcel Variables					
Parcel Acres[b, c]	62.343	68.435	.00016	907.635	Area of parcel, in acres
Fee Indicator[b]	0.393	0.488	0	1	=1 if fee simple, otherwise =0
Allotted Trust Indicator[b]	0.349	0.477	0	1	=1 if allotted trust, otherwise =0
Tribal Indicator[b]	0.257	0.437	0	1	=1 if tribally owned, otherwise =0
City Indicator[f]	0.099	0.298	0	1	=1 if within a city boundary, otherwise = 0
Underwater [f]	0.243	0.429	0	1	=1 if under high water mark, otherwise = 0
Road density [f]	0.1592	0.353	0	2.875	Kilometres of roads touching parcel
Neighbor Variables					
Fee Neighbors[b, c]	73.845	181.853	0	819	# of fee parcels within ½ mile radius
Allotted Trust Neighbors[b, c]	8.317	9.456	0	60	# allotted trust parcels within radius
Tribal Neighbor Indicator[b, c]	0.578	0.494	0	1	=1 if there is a tribal parcels within radius
Neighbors Underwater [f]	6.057	8.925	0	53	# of parcels under high water within radius
Topographic Roughness[e]	610.517	42.296	560.59	787.191	St. Dev of elevation within radius, in centimeters

Notes: This table summarizes data for all parcels in our estimation sample on the reservation. We exclude parcels with off-reservation neighbors. The radius for neighbor variables is ½ half mile around the own parcel. N = 12,780 for all variables except roughness, which is N = 12,769. Data sources are: a) North Dakota Oil and Gas Commission website, b) U.S. Bureau of Indian Affairs, c) Real Estate Portal, d) U.S. EIA website e) Authors calculations from National Elevation Dataset, and f) Authors calculations from North Dakota GIS Portal data.

F. Lease-Level Data

To supplement the production data, we acquired lease data from DrillingInfo.com, which reports acreage, lease date, production status, approximate location, royalty rates, and the grantor for each lease. Leases are geo-referenced to the 1x1-mile Public Land Survey System (PLSS) section where production takes place, so we cannot directly match leases to our parcel-level dataset. Instead, we match leases to PLSS sections (1 square mile units in the land surveying system) and calculate the total number of parcels in each section in addition to aggregating the other parcel-level covariates up to the PLSS section-level.

DrillingInfo's data do not allow us to separately identify leases signed with fee vs. allotted trust owners because they are aggregated up to the section level. However, we can identify leases for which the tribe was the grantor. The upshot is that these lease data have two important limitations. First, we can only measure covariates at the section level. Second, we cannot differentiate the own-tenure effect for allotted vs. fee leases. Table 2 reports the summary statistics for the lease data.

Table 2: Summary Statistics from Well and Lease Level Data Sets

	Mean	*St. Dev.*	*Min*	*Max*	*Description*
Royalty[a]	0.176	0 .019	0.125	0.25	Royalty rate for lease *i*
Lease Term (Months)	50.393	14.127	0	120	Time until lease expires, in months
Non-tribal Lease Indicator	0.951	0.216	0	1	=1 if the grantor on the lease is not the tribe, otherwise 0
Acreage Under Lease	501.925	979.311	0	10,360	Area (in acres) of the land associated with a lease
Fee Parcels in Section	15.062	49.856	0	725	Number of fee simple parcels in PLSS section where lease is located
Allotted Parcels in Section	5.769	6.794	0	45	Number of allotted trust parcels in PLSS section where lease is located
Roughness	12.40	7.999	0	42.958	Std. dev. of elevation in the PLSS section where lease is located (m)
Road Density	1.769	1.346	0	6.002	Km of roads touching the PLSS section where lease is located
Underwater Indicator	0 .187	0 .389	0	1	=1 if the PLSS section where lease is located is partially underwater
City Indicator	0.037	0.188	0	1	=1 if the PLSS section where lease is located is in a city

Notes: N = 5,992 leases in our study area. The source is a) DrillingInfo.com data and b) author's calculations based on the PLSS section reported by DrillingInfo.com and land tenure variables and ownership data from U.S. Bureau of Indian Affairs and Real Estate Portal.

6. Empirical Estimates

We estimate the effect of ownership on oil production using the following model:

$$Barrels\ per\ acre_{itd} = \alpha_t + \alpha_d + \mu_o + \phi Acres_{itd} + \lambda_F 1(Fee)_{itd} + \lambda_A 1(ATrust)_{itd} + \beta_F FeeNeigh_{itd} +$$

$$\ldots \beta_A ATrustNeigh_{itd} + \beta_T 1(TribalNeigh)_{itd} + \beta_{T1} 1(Tribal)_{itd} + \gamma X_{itd} + \varepsilon_{itd} \quad (1)$$

where *i* = parcel, *t* = thickness, *d* = depth, and *o* = oil field. The notation α_t and α_d represent the shale thickness and depth bin fixed effects, and μ_o represents oil field fixed effects.

The key parameters are ϕ, the λ's, and the β's. We expect parcel acres to positively affect production per acre ($\phi > 0$) because larger parcels reduce anticommons and transaction cost problems. While this relationship is mechanically true if the dependent variable was total production (because oil production is allocated to parcels within drilling units in proportion to size), it is not mechanically true for production *per acre*.

The λ coefficients measure the extent to which parcel *i*'s own tenure influences drilling probabilities, conditional on the degree of neighborhood subdivision and ownership composition of neighbors. The omitted ownership type is a tribal parcel with zero fee or allotted neighbors, so the effects of fee and allotted ownership are relative to a large contiguous tribal tract. Theory predicts $\lambda_F > \lambda_A > 0$. This is the ordering of the vertical intercepts in Figure 2, Panel A, and these coefficients effectively compare the attractiveness of a single large parcel for drilling, based on whether that parcel is fee, allotted, or tribal.

The β's measure neighborhood fragmentation effects by ownership type. We expect $0 > \beta_F > \beta_A$ because more finely subdividing a radius around a parcel into either form of private ownership will increase N, the number of potential excluders to a drilling project, thereby reducing production. The negative effect will be larger for allotted trust than fee simple because there are multiple excluders per allotted trust parcel, corresponding to the steeper slope of the N_c vs. N_p lines in Figure 2. β_T measures the effect of having *any* tribal parcels within the neighborhood of parcel i, which would add the fixed number N_G excluders. We predict that $\beta_T < 0$. Finally, β_{T1} measures whether this effect of tribal neighbor presence is different when parcel i is tribal. We hypothesize that $\beta_T + \beta_{T1} = 0$, because adding tribal parcels does not alter N_G if parcel i is tribal (hence the zero slope of the N_G line in Figure 2).

A. Identification

The model in Equation 1 addresses the main concern for identifying the ownership parameters of interest (λ_i and β_i), which is that unobserved spatial heterogeneity in the profitability of shale could bias the estimates if it is correlated with ownership.[33] This concern is mitigated, in part, because ownership was determined by historical events and not selected based shale endowments (see Section 4). Even in the absence of intentional selection, however, systematic differences in the profitability of shale extraction across ownership regimes are possible because ownership is not spatially random. In the context of our predictions, the primary concern is that parcels associated with few excluders (e.g., large fee parcels surrounded by large fee parcels or by contiguous government land) and may be systematically endowed with more profitable shale than parcels associated with many excluders (e.g., small allotted trust parcels surrounded by other small allotted trust parcels and scattered government holdings).

A common approach for addressing unobserved spatial heterogeneity in subsurface resources is to focus on spatially random variation in ownership regimes, such as the "Wyoming checkerboard" where adjacent square-mile sections of land (and hence subsurfaces) are federally and privately owned due to historic land grant policies (Kunce et al. 2002, Edwards et al. 2018, Lewis 2019). This is appealing because unobserved subsurface differences become statistical noise when comparing outcomes across neighboring, randomly assigned, ownership units. This side-by-side comparison approach is not appropriate for testing our hypotheses about shale oil development, however, because we hypothesize that neighboring land ownership is a critical determinant of productivity. As emphasized in Section 2, side-by-

[33] This is a natural concern in any study of property rights is that ownership regimes are systematically correlated with the resource endowment due to selection. More valuable resource endowments foster greater effort to define private property rights (Demsetz 1967), limiting the econometrician's ability to identify causal effects of property regimes on resource use (Besley 1995, Goldstein and Udry 2008, Galiani and Schargrodsky 2012).

side comparisons of section-level productivity on government vs. private land cannot capture the effect of the checkboard itself on outcomes. While the comparisons could identify the λ parameters in Equation 1, they would miss the effects of fragmentation captured by the β parameters.

Our challenge is to identify the λ_i and β_i parameters without relying on spatially random assignment of ownership. We exploit the fact that, although shale quality was unknown at the time of ownership assignment, shale geology is known with a fair amount of certainty today. This allows us to control directly for shale quality. We do so by including fixed effects for shale thickness and depth bins. Thicker shale holds more oil, and deeper shale can be more costly to access but more productive (Weber et al. 2016). With the inclusion of thickness and depth indicators, we identify the key λ and β parameters from ownership variation within relatively homogenous bands of shale. As Figure 6B and Appendix Figure A2 indicate, there is variation in ownership within each thickness and depth category.

The thickness and depth indicators also act as spatial fixed effects that rely on variation from nearby parcels (within the same pair of bins) for identification. This is conceptually similar to a local linear regression in a traditional spatial regression discontinuity design, and the key identifying assumption is analogous: we must assume that the profitability of shale varies somewhat smoothly in space—within bins—so that comparisons with nearby parcels of different ownership regimes are not confounded. This approach also allows us to identify the average effect of ownership and fragmentation across the distribution of shale quality, rather than focusing within a single neighborhood around some particular discontinuity and delivering only a local average treatment effect.

Our hypothesis tests may still be biased towards finding the predicted effects if neighborhoods with large fee simple parcels and contiguous government land holdings systematically contain more profitable shale, even within thickness and depth bins. This is possible if within-bin shale profitability changes systematically from west to east or from north to south. To account for this possibility, we include additional controls for spatial heterogeneity such as linear controls for the longitude and latitude of each parcel's centroid and oil field fixed effects (see Figure 3). We also control for surface characteristics such as roughness of the terrain, the proximity of each parcel and its neighbors to water bodies (based on the high-water line of the Missouri River, and surface development (e.g., road density and for the presence of urban areas).

Remaining omitted variables threaten identification only if they i) are systematically correlated with ownership, ii) not captured by the controls in X_{itd}, and iii) affect shale productivity, all *within* thickness and depth bins and *within* oil fields. We think this threat is minor, particularly because one of the chief advantages of horizontal drilling is its ability to render surface characteristics less critical by enabling oil extraction from different surface points (see, e.g., Kellogg 2011).

B. Naïve Regression Estimates

To motivate the importance of neighboring ownership, we begin by showing naïve regression estimates that estimate own parcel coefficients – the λ parameters in Equation 1 – without controlling for neighborhood characteristics. Table 3 shows results. Column 1 includes the full sample of parcels whereas all other columns exclude parcels not on active oil fields. The preferred estimates in Columns 2-6 focus on variation across parcels within areas where shale endowments are profitable, based observed drilling behavior. Column 3 adds the covariate controls. Columns 4 adds the shale thickness and depth indicators. Columns 5 adds the latitude and longitude of each parcel's centroid. Column 6 adds the oil field fixed effects.[34] In all models, the standard errors are calculated to allow for arbitrary spatial correlation in the error structures following Conley (2008) and Hsiang (2010).

The productivity estimates for fee and allotted trust parcels are relative to tribal, which is the omitted category. Here we see that $\hat{\lambda}_F > \hat{\lambda}_A > 0$, although the magnitude and statistical significance of $\hat{\lambda}_A$ is sensitive to the controls. For context, the mean productivity for tribal parcels on oil fields is 240 barrels per acre. Hence, the Column 6 coefficients imply the average fee and allotted trust parcels are respectively 92 and 27 percent more productive than the average tribal parcel.

The productivity ordering is consistent with other studies not focused on spatial spillovers. Anderson and Lueck (1992) assess reservation-level data and conclude that agricultural productivity across Indian reservations was highest on fee land, then allotted trust, followed by tribal.[35] We are not aware of other studies that compare all three ownership types but Ge et al. (2018) find higher agricultural productivity on neighboring private versus tribal land within a rural Indian reservation and Akee and Jorgenson (2015) find no difference in business investment across neighboring tribal versus fee land within an urban Indian reservation. Outside of Indian reservations, Edwards et al. (2018) find longer delays for government versus private (conventional) oil and gas drilling within the Wyoming checkerboard.

Like other studies of resource use on private vs. government land, the naïve assessment suggests ownership matters but this approach is inadequate for studying shale development. Farming, business investment, and conventional oil drilling are all feasible on small parcels without coordination across neighboring landowners. In contrast, the technology of horizontal drilling, coupled with leasing regulations, make it impossible for a developer to begin an economically productive shale project without contracting with landowners over a relatively large 2 by 1-mile neighborhood. To fully understand the

[34] The benefit of oil field fixed effects is that they i) control for heterogeneity in the regulatory rules governing production (e.g., spacing unit sizes), which can vary by oil field, and ii) act as additional spatial fixed effects that control for variation in shale endowments and terrain that is unobservable to us.

[35] According to their estimates, "tribal-trust tenure and individual-trust tenure reduce the per-acre value of [agricultural] output compared to the fee-simple yardstick by 9.18 percent and 31.4 percent, respectively" (p. 446).

effect of ownership on shale development, we must move beyond the naïve $\hat{\lambda}_F$ and $\hat{\lambda}_A$ coefficients reported in Table 3 by accounting for ownership mosaics in a neighborhood around each parcel.

Table 3: Linear Estimates of Production per Acre, without Neighbor Controls

	(1)	(2)	(3)	(4)	(5)	(6)
Own Parcel Variables						
Parcel acres (ϕ)	0.466*	1.162***	0.277	0.343**	0.319	0.309*
	(0.257)	(0.313)	(0.216)	(0.172)	(0.189)	(0.175)
Fee parcel indicator (λ_F)	359.6***	481.8***	343.1***	299.3***	310.5***	212.9***
	(71.90)	(96.99)	(130.8)	(80.08)	(86.88)	(56.02)
Allot. trust parcel indicator (λ_A)	245.4***	305.1***	64.94	59.36	57.93	65.78
	(49.15)	(53.41)	(54.72)	(42.99)	(42.10)	(40.63)
<u>**Covariate Controls**</u>						
Underwater indicator			75.80	-51.42	-67.28	-67.72
Underwater neighbors			-8.205**	-11.40***	-11.17***	-9.781**
Topographic roughness			0.517***	-1.597*	-2.148*	-1.880**
Road density			-19.65	12.41	24.35	43.75
City indicator			-370.7***	-266.1**	-269.9**	-301.8***
Excludes parcels off fields		x	x	x	x	x
Shale thickness & depth FE				x	x	x
x & y coordinate controls					x	x
Oil field FE						x
Adjusted R-squared	12780	8635	8632	8524	8524	8524
Observations	0.269	0.384	0.429	0.524	0.566	0.648

Notes: Conley (2008) spatial HAC standard errors shown in parentheses. Following Hsiang (2010), these models are estimated using a GMM approach that allows for arbitrary forms of spatial correlation in the error term, as described in Conley (2008). * p<0.1, ** p<0.05, ***p<0.01. Column 1 employs all parcels, whether or not the parcels are on a designated oil field. Columns 2 and 3 use only parcels that are on a designated oil field. Columns 4 includes shale thickness and depth fixed effects, Column 5 adds controls for a parcel's longitude and latitude, and Column 6 adds oil field fixed effects. Column 7 excludes all parcels that were not drained of oil through May 2015.

C. Main Estimates

Table 4 shows the main estimation results which focus on identifying the neighbourhood-level effects of private and government ownership. As in Table 3, we sequentially introduce different controls and calculate standard errors to allow for arbitrary spatial correlation in the error structures following Conley (2008) and Hsiang (2010). Columns 4-6 drop underwater parcels, based on the high water mark of the Missouri River, to ensure that the tribal coefficients are not confounded by proximity to the river.

The coefficient on parcel acres is positive across specifications, as predicted. The Column 1 coefficient implies that a one standard deviation increase above the mean (i.e., from 59 to 130 acres) is associated with 0.92 x 71 = 65.3 barrel increase in expected production per acre. This is a 15.4% percent increase relative to the mean per acre production, which is 421.6 barrels for sample parcels on oil fields.

The point estimates on the ownership intercepts are $\hat{\lambda}_F > \hat{\lambda}_A > 0$, although the difference between $\hat{\lambda}_F$ and $\hat{\lambda}_A$ is not always statistically significant. Because the omitted category is a tribal parcel with no fee or allotted neighbors within a ½ mile radius, these estimates suggest that a privately owned parcel that spans the radius will be more productive than a block of contiguous tribal ownership, especially if the parcel is fee simple rather than allotted trust.

Table 4: Linear Estimates of Production per Acre, with Neighbor Variables

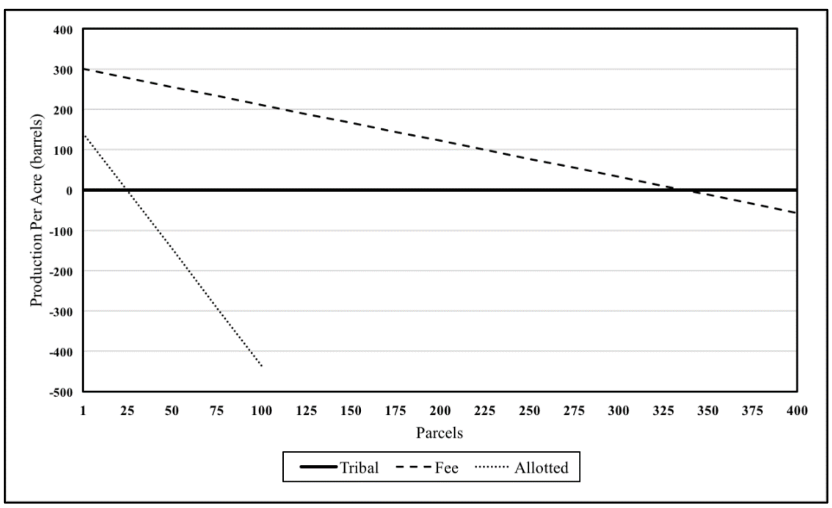
	(1)	(2)	(3)	(4)	(5)	(6)
Parcel Variables						
Parcel acres (ϕ)	0.919***	0.898***	0.739***	1.118***	1.085***	0.831***
	(0.232)	(0.221)	(0.187)	(0.260)	(0.241)	(0.215)
Fee parcel indicator (λ_F)	300.6***	291.6***	238.9***	262.0***	249.4***	215.1***
	(103.9)	(104.0)	(82.74)	(100.8)	(102.8)	(84.10)
Allotted trust parcel indicator (λ_A)	141.5*	122.8*	126.3*	159.6**	131.8*	138.7**
	(73.10)	(73.39)	(66.29)	(76.53)	(78.99)	(67.63)
Private Neighbor Variables						
Fee neighbors (β_F)	-0.893***	-0.868***	-0.917***	0.837***	-0.800***	-0.820***
	(0.200)	(0.190)	(0.190)	(0.185)	(0.172)	(0.162)
Allotted trust neighbors (β_A)	-5.784**	-6.013**	-3.217	-8.224***	-8.476***	-4.485*
	(2.562)	(2.434)	(2.366)	(2.954)	(2.818)	(2.686)
Government Neighbor Vars.						
Tribal Neighbor Indicator (β_T)	-179.4***	-175.2***	-166.4***	-165.3***	-157.1***	-154.7***
	(52.68)	(51.80)	(42.90)	(47.03)	(44.99)	(37.95)
Tribal Neighbor Indicator X	71.49	50.80	67.22	119.4	89.99	100.6
Tribal Indicator (β_{T1})	(76.75)	(79.37)	(65.16)	(96.45)	(99.21)	(78.15)
Excludes parcels off fields	x	x	x	x	x	x
Excludes underwater parcels				x	x	x
Covariate controls	x	x	x	x	x	x
Shale thickness & depth FE	x	x	x	x	x	x
x & y coordinates		x	x		x	x
Oil field FE			x			x
Adjusted R-squared	0.552	0.553	0.589	0.591	0.594	0.622
Observations	8524	8524	8524	6750	6750	6750

Notes: Conley (2008) spatial HAC standard errors shown in parentheses. Following Hsiang (2010), these models are estimated using a GMM approach that allows for arbitrary forms of spatial correlation in the error term, as described in Conley (2008). * p<0.1, ** p<0.05, ***p<0.01. A parcel's neighborhood includes all parcels touching a half-mile radius from the parcel's boundary. All specifications control for the slight variation in the total area of the radius, due to variation in the size of parcels on the exterior of the radius. All specifications also control for topographical roughness, an indicator for whether or not the parcel is in a city, an indicator for whether or not the parcel is underwater, nearest distance to a road, and the number of mineral parcels within the radius that lie beneath the high water mark of the Missouri River. Columns 4-6 drop all parcels that are underwater.

The point estimates on the tenure slopes are $\hat{\beta}_A < \hat{\beta}_F < (\hat{\beta}_T + \hat{\beta}_{T1}) \approx 0$. This ordering follows our predictions, and the differences between coefficients are statistically significant. Based on the Column 1 estimates, expected production falls by 5.8 barrels per parcel for *each* allotted trust neighbor, which is 6.5 times the negative effect of adding a fee neighbor. Holding all other variables constant, increasing the number of allotted trust neighbors by one standard deviation (9.6) decreases expected production by 55.5 barrels. This is a 13.2% reduction relative to the mean. According to these estimates, converting the 9.6 parcels into fee simple would increase expected production by 9.6 x (5.784 – 0.893) = 46.9 barrels.

Together, the λ and β coefficients imply a subdivision threshold for fee and allotted trust ownership, after which contiguous government ownership generates more expected production. Figure 7—an inverse of the excluder graph in Panel A of Figure 2—depicts predicted values of production for neighborhoods of a single ownership type as a function of the number of neighboring parcels based on the coefficient estimates in Column 1 of Table 4. The figure holds constant the spatial span of the project and plots expected production the neighbourhood is more finely subdivided into a given ownership regime. As the figure illustrates, comparison of ownership regimes depends crucially on the level of subdivision—estimated production is higher in privately owned areas unless parcels are too finely subdivided.

Figure 7: Difference in Tribal vs. Private Production due to Subdivision



Notes: This figure plots the predicted effect of subdividing a 1,550-acre neighborhood into each tenure type, based on the Column 1 coefficient estimates in Table 4. The vertical intercepts are based on the $\hat{\lambda}$'s and represent expected production on a single large parcel, relative to production from tribal shale with zero fee or allotted trust neighbors and. The slope of each line is determined by the corresponding estimated neighbour coefficient (the $\hat{\beta}$'s).We omit standard error bars for the sake of clarity. Separate plots of fee vs. tribal and allotted vs tribal with 95% confidence intervals can be found in Appendix Figures A3 and A4.

For fee simple, the threshold is 300.6/0.893 = 336 parcels. Because the average half-mile radius spans 1,550 acres, this implies a threshold parcel size of 4.6 acres. In the estimating sample, the average fee parcel is 42 acres but, as discussed in the introduction, agricultural parcels in many areas of the world are smaller than 4.6 acres. For allotted trust, the threshold is 141.5/5.78 = 24.5 parcels, implying a threshold size of 63.3 acres. The average allotted trust parcel in the sample is 82.4 acres, but 58% of the allotted parcels are smaller than 63.3 acres. We note that the ratio of threshold sizes for fee versus allotted, which is 82.4/4.6 = 17.9 closely aligns with the average number of allotted trust owners per parcel on Fort Berthold, which is N = 15. While only suggestive, this comparison is consistent with our theory that the number of excluders to a shale development project is a critical determinant of productivity.

Turning to the $\hat{\beta}_T$ estimates, their negative signs in Columns 1-3 mean that adding a tribal parcel to the neighborhood causes a 39% to 42% reduction in parcel i's expected production relative to the conditional mean of 421.6 if parcel *i* is not tribally owned. If parcel *i* is tribally owned, the effect is $\hat{\beta}_T + \hat{\beta}_{T1}$. The summation of these coefficients is not statistically different from zero.[36] This pair of results – that $\hat{\beta}_T < 0$ and $\hat{\beta}_T + \hat{\beta}_{T1} = 0$, is consistent with the theory that adding tribal land to the neighborhood adds a large, fixed number of excluders if parcel *i* is fee or allotted but does not add excluders if parcel *i* is tribal. Considered together with the negative estimates of $\hat{\beta}_F$ and $\hat{\beta}_A$, the findings mean the productivity advantages of private and government ownership are diminished when private shale borders government shale. This result underscores the importance of accounting for both the λ_i and the β_i coefficients when assessing the effect of ownership on shale production.

D. Robustness

Table 5 shows the results for revenue per acre (at a 3% discount rate) and provides robustness checks. The specifications are identical to the baseline from Column 1 in Table 4 (also included as Column 1 of Table 5 for reference), and the point estimates follow the same pattern with $\hat{\phi} >0$, $\hat{\lambda}_F > \hat{\lambda}_A > 0$, and $\hat{\beta}_A < \hat{\beta}_F < (\hat{\beta}_T + \hat{\beta}_{T1}) \approx 0$. A comparison of the coefficients with the baseline make it clear that patterns of revenue mimic patterns of production, in terms of the effects of parcel sizes and ownership.

The baseline coefficients are based on linear estimation of a dependent variable that is zero in 28% of occurrences. The estimates in Columns 3, which are conditional on drilling, reveal the same

[36] The p values for the test of $\hat{\beta}_T + \hat{\beta}_{T1} = 0$ range from 0.16 to 0.61.

patterns. The similar patterns imply that most of the subdivision and ownership effects occur on the intensive margin of drilling.[37]

Table 5: Robustness of Main Production Estimates

	Baseline	Y=Revenue	Production > 0	Production > 0	No Cities	1-Mile Radius
	(1)	(2)	(3)	(4)	(5)	(6)
Parcel Variables						
Parcel acres (ϕ)	0.919***	35.81***	0.978***	0.922***	0.919***	1.007**
	(0.232)	(9.624)	(0.310)	(0.236)	(0.260)	(0.331)
Fee parcel indicator (λ_F)	300.6***	11677.5***	351.2***	348.1***	312.3***	331.5***
	(103.9)	(4426.1)	(115.3)	(120.8)	(100.8)	(108.2)
Allotted parcel indicator (λ_A)	141.5*	5930.8*	236.5**	243.4**	148.6**	138.4*
	(73.10)	(3178.7)	(95.57)	(101.8)	(72.68)	(81.83)
Neighbor Variables						
Fee neighbors (β_F)	-0.893***	-36.00***	-1.079***	-1.030***	-1.148***	-0.772***
	(0.200)	(8.302)	(0.167)	(0.168)	(0.149)	(0.160)
Allotted trust neighbors (β_A)	5.784***	-232.3**	-8.231**	-7.803**	-5.984***	-3.120**
	(2.562)	(105.3)	(3.337)	(3.230)	(2.360)	(1.385)
Tribal Neighbor Indicator (β_T)	-179.4***	-7761.2***	-215.4***	-222.6***	-223.7***	-159.1***
	(52.68)	(2245.3)	(53.92)	(55.58)	(49.33)	(53.49)
Tribal Neighbor Indicator	71.49	2579.9	117.2	122.0	62.91	85.72
X Tribal Indicator (β_{T1})	(76.75)	(3266.5)	(101.4)	(107.1)	(72.02)	(87.02)
Excludes parcels off fields	x	x	x	x	x	x
Covariate controls	x	x	x	x	x	x
Shale thickness & depth FE	x	x	x	x	x	x
Excludes parcels w/o production			x	x		
Control for timing of production				x		
Excludes city parcels					x	
Excludes underwater parcels						
One mile radius						x
Adjusted R-squared	0.552	0.537	0.651	0.653	0.591	0.562
Observations	8524	8524	8524	6204	7281	7630

Notes: Conley (2008) spatial HAC standard errors shown in parentheses. Following Hsiang (2010), these models are estimated using a GMM approach that allows for arbitrary forms of spatial correlation in the error term, as described in Conley (2008). * p<0.1, ** p<0.05, ***p<0.01. Columns 1-3 discount revenue per acre at 1%. 3%, and 5%, respectively. The specifications are identical to those in Column 2 of Table 4. Columns 4-6 are robustness checks, based on the revenue estimates discounted at 3%. Column 4 adds controls for the longitude and latitude of each parcel's centroid. Column 5 omits parcels in cities. Column 6 defines the neighborhood with a one-mile radius rather than a ½ mile radius.

[37] This finding is consistent with additional results, not shown here, which indicate that the probability of parcel membership in a drilled unit is less sensitive to ownership patterns when compared with production per acre.

Transaction costs could delay the timing of leasing and drilling, potentially leading to unanticipated benefits for large-*N* projects if landowner bargaining power improved over time or if prices and drilling technology improve unexpectedly.[38] Though this is possible, the evidence in Column 4, which controls for the timing of drilling, suggests the role of timing delays is minor.

Another concern addressed in Table 5 is the possibility that the parcel size estimates are driven by difficulties of producing oil around urban infrastructure rather than anticommons or transaction costs. This is possible if drilling through shale damages surfaces and smaller parcels have higher surface value per acre. We do not think this mechanism is driving the results because horizontal drilling can and does occur below dense development (see, e.g., Vissing 2017 and Weber et al. 2016). Nevertheless, to address this concern, Column 5 drops the 1,243 parcels within the most urban area of the reservation that has small parcels. The results are similar.

Column 6 measures all of the neighbor variables based on a 1-mile radius, rather than the ½ mile radius. In this and the other columns, the pattern of estimates follows the baseline, indicating the results are robust to variations in estimating sample, control variables, and the measurement of "neighborhoods." Additionally, Appendix Table A1 reproduces Table 4 using a tobit rather than a linear estimator and demonstrates that accounting for censoring of production at zero does not change the results.[39]

E. Royalty Rates

According to the anticommons model, the price that excluders charge developers for shale use is a mechanism that drives differences in oil production. Although the full price includes components we cannot measure, such as leasing bonus payments, we do have data on royalty rates as summarized above. Royalty rates account for 85-90% of shale owner compensation in typical leases (Fitzgerald and Rucker 2016) and tend to positively correlate with bonus payments (see Vissing 2017), implying that higher royalty rates are unlikely to be offset by bonus payment reductions. Moreover, the results indicate that ownership and subdivision affect oil investment primarily on the intensive margin (e.g., drilling inputs per drained acres) rather than the extensive margin (whether or not to extract at all from a parcel). This suggests that royalty rates—rather than bonus payments borne at the time of leasing and sunk with respect to output—are more likely a mechanism.

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[38] In these cases, the demand for oil shifts outward after royalties are set, leading to greater production and revenue at a higher royalty rate. If this happens, payouts to shale owners increase with *N* precisely because high-*N* projects end up being drilled under favorable price and technological conditions. However, if future changes in prices and costs are anticipated, then large *N* cannot benefit shale owners because the Buchanan and Yoon (2000) logic still applies and individually rational attempts to capture expected future surpluses will dissipate potential rents.

[39] We do not use a tobit as our main estimator because it does not readily account for spatially correlated standard errors and is subject to incidental parameter problems with large numbers of fixed effects.

Here we provide tests of whether or not the royalty rate charged by excluder *i* increases with *N*, the total number of excluders in the neighborhood. Holding constant neighborhood characteristics, a relationship of $r_T > r_A > r_F$ would be consistent with anticommons predictions, where r_A is the average royalty rate requested by allotted owners, r_F is the average rate requested by fee owners, and r_T is the average rate requested by the tribe.

The lease data have two limitations: we can only measure lease covariates at the section level and we do not know if a lease is associated with allotted trust owner or a fee simple owner. Given these limitations, we estimate the following regression model:

$$royalty_{ltds} = \alpha_t + \alpha_d + \lambda_P(NonTribal)_{ltd} + \beta_A(AllotNeigh)_{tds} + \cdots$$
$$\ldots + \beta_F(FeeNeigh)_{tds} + \gamma X_{itd} + \varepsilon_{ltds} \quad (2)$$

where *l* = lease, *t* = thickness bin, *d* = depth bin, and *s* = PLSS section. As before, α_t and α_d represent the vector of shale thickness and depth bin fixed effects and X_{itd} represents controls for surface characterstics.

Table 6 shows the estimation results.[40] In Columns 1-2, the royalty rates are logged. In Columns 3-4, they are not. Columns 2 and 4 omit leases in the most urban sections of the reservation because these sections are outliers in terms of parcel size. In all models, the standard errors are calculated to allow for arbitrary spatial correlation in the error structures.

The Columns 1-2 estimates for the non-tribal indicator suggest that royalty rates for allotted or fee simple leases are 4.1% to 4.4% less than the royalty rates in tribal leases, after controlling for the neighborhood covariates. This corresponds to a 0.66 to 0.71 percentage point decrease in royalty rates, based on the Columns 3 and 4 estimates. This finding is consistent with the anticommons model if a single tribal lease entails satisfying a larger number of excluders relative to a single lease on a non-tribal parcel.

The estimated effects of adding fee and allotted parcels to a section support an anticommons explanation for the main results in Table 4. The royalty rate increases by 0.015% for each additional fee parcel in a section and by 0.122% for each additional allotted parcel, which involves more excluders.

[40] The number of observations differs from out parcel-level regressions for several reasons. First, we are not able to directly match leases to parcels. Second, our parcel-level data treats individually-demarcated tribal parcels as unique observations. In reality, a tribe may lease collections of contiguous parcels with a single lease, reducing the number of leases relative to parcels. Third, a parcel may have been forced into a unit (with forced pooling) rather than by signing a lease.

These estimates imply that leases in areas with more finely subdivided fee and allotted mineral rights have higher royalty rates than leases in areas with larger parcels.

The limitations of the lease data prevent us from precisely identifying subdivision thresholds for fee or allotted vs. tribal leases as with production in Figure 7 because we cannot separately identify fee and allotted leases. Still, we note that the magnitudes are similar. A 640-acre section of all fee land would have to be subdivided into 275 2.3-acre parcels to have a higher royalty rate than the average tribal lease. Similarly, a solely allotted trust section would have to be subdivided into 32 20-acre parcels to exceed the tribal royalty rate.

Table 6: Lease Level Estimates of Royalty Rates

	Ln(Royalty)		Royalty	
	(1)	(2)	(3)	(4)
Non-tribal indicator	-0.0413***	-0.0441***	-0.00660***	-0.00711***
	(0.0105)	(0.0109)	(0.00185)	(0.00191)
Fee parcels in section	0.000150***	0.000683***	0.0000255***	0.000115***
	(0.0000510)	(0.000224)	(0.00000873)	(0.0000394)
Allotted Trust parcels in section	0.00126*	0.00152**	0.000217*	0.000259**
	(0.000693)	(0.000710)	(0.000120)	(0.000122)
Topographic roughness	0.000371	0.000477	0.0000467	0.0000709
Road Density	-0.00445	-0.00531*	-0.000764*	-0.000899*
City indicator	-0.0488**		-0.00885**	
Underwater indicator	-0.00356	-0.00681	-0.000400	-0.00106
Area under lease	-0.00000129	-0.000000695	-0.000000255	-0.000000152
Lease term (months)	-0.00303***	-0.00306***	-0.000539***	-0.000548***
Shale Thickness & Depth FE	x	x	x	x
Excludes Off Field Observations	x	x	x	x
Omits City Parcels		x		x
N	5882	5655	5882	5655
adj. R^2	0.997	0.997	0.992	0.992

Notes: Conley (2008) spatial HAC standard errors shown in parentheses. Following Hsiang (2010), these models are estimated using a GMM approach that allows for arbitrary forms of spatial correlation in the error term, as described in Conley (2008). * p<0.1, ** p<0.05, ***p<0.01. The right-hand side variables are calculated at the section (640 acre) level.

Combining the royalty rate results with intensive margin estimates of oil production outside of cities (the specification of Column 3 of Table 5 but with cities dropped) implies that an additional fee parcel is associated with a -0.18% change in oil production, relative to the sample mean. Dividing by the 0.068% coefficient on fee parcels in Column 2 of Table 6 implies a -0.18/0.068 = -2.64 elasticity of output.[41] The large implied elasticities may suggest that factors additional to royalty rates are contributing to the lower production in finely subdivided areas of the reservation. For example, we do not measure non-pecuniary legal clauses in leases that protect landowners from drilling disamenities (see Vissing 2017). If the "price" of these clauses to developers rises with N, as anticommons theory predicts, then this might help explain the large elasticities with respect to the "use price" as measured by royalty rates. On the other hand, we have no a-priori expectation about how large royalty rate elasticites should be. Output elasticities with respect to ad valorem taxes—which are conceptually equivalent to royalty rates—can be large compared to traditional price elasticities of output, suggesting the implied elasticities may be reasonable (see, e.g., Fagan and Jastram 1939 and Pritchard 1943).[42]

7. Policy Implications

A 2010 settlement of federal litigation (*Cobell vs. Salazar*) created a $1.9 billion "land consolidation fund" for Native American tribes to buy fractionated allotted trust interests and convert them into tribal ownership.[43] This settlement explicitly recognizes the potential drag that fractionated ownership has on productive resource use, and implicitly assumes that consolidated tribal ownership will be an improvement. On Ft. Berthold, $56,589,204 has been allocated for consolidation (Department of Interior 2013).

We apply the coefficients from Table 5, Column 2 to estimate the effect of replacing allotted parcels with tribal parcels on expected revenue from the fracking boom.[44] Table 7 provides the results and the appendix Table A4 provides details for our calculations. Consolidation from allotted trust to fee simple is not part of the Cobell settlement, but we include it here as part of the thought experiment for context. Assuming that the tribe collects its average royalty rate of 18%, the net increase in royalty income from the boom would have been $132,043,014.[45] This amounts to $20,824 per American Indian

[41] This implied elasticity is about 2.5 times larger (in absolute value) if we try to adjust for differences in the size of a ½ mile radius versus a PLSS section or if we use a specification that includes city parcels.
[42] Anderson et al. (2018) estimate a drilling elasticity of -0.6 with respect to crude oil prices. Elasticities with respect to royalty rates are plausibly larger because of their ad valorem structure, and because drillers on the Bakken during the boom were deciding on where to allocate scarce drilling capital across units with different known aggregate royalty rates rather deciding whether or not to invest in a drilling rig based on uncertain future prices. Distinguishing output price elasticities from royalty rate elasticity is a topic for future research, outside the scope of this paper.
[43] See the Indian Trust Settlement website at www.indiantrust.com/prdoj.php.
[44] The calculations in Table 6 might understate foregone income because they focus on only the first 18 months of royalty payments. Estimates of oil decline curves from Hughes (2012) suggest that only 33 percent of oil from a typical Bakken well will be extracted within the first 18 months. In spite of this, the $132 million in estimated income gains from consolidation into tribal ownership exceeds the $57 million purchase ceiling that the Cobell Settlement initially allocated to Ft. Berthold to consolidate fractionated interests (Dept. of Interior 2013, p. 13).
[45] The data show that 449 of the 503 tribal leases in our sample charge exactly 18%.

living on the reservation, \$10,819 per tribal member, or \$26,702 per fractionated interest owner.[46] The per capita income for American Indians living on Ft. Berthold in 2010 was \$13,543.

Table 7: Income Gains from Consolidating Allotted Trust

	Convert to Tribal Ownership	Convert to Fee Simple Ownership
Δ in Total Oil Revenue	\$733,572,301	\$806,838,105
Average Royalty Rate	18.0% (Tribal)	17.5 (Non-Tribal)
Δ in Oil Royalty Income	\$132,043,014	\$141,196,668
Fort Berthold Native Am. Population (2010)[a]	6,341	6,341
Δ in Oil Royalty Income, per capita	\$20,824	\$22,267
Three Affiliated Tribes Enrollment (2011)	12,204	12,204
Δ in Oil Royalty Income, per member	\$10,819	\$11,570
Owners of Fractionated Interests (2012)	4,945	4,945
Δ in Oil Royalty Income, per owner	\$26,702	\$28,553

Sources: (a) 2010 U.S. Census; (b) http://indianaffairs.nd.gov/statistics/; (c) Dept. of Interior (2013)

The finding that fractionated allotted trust ownership is relatively unproductive is consistent with Russ and Stratmann (2017), who find that higher degrees of fractionation across allotted trust lands reduce agricultural lease income. At the same time, our findings provide an interesting contrast with Anderson and Lueck (1992), who find that agricultural productivity was higher on fee simple land than on allotted trust land, which was higher than tribal land. Our results also contrast with Akee and Jorgensen (2015) in an interesting way. They compare business investment on neighboring fee versus trust parcels within the checkerboard of the Agua Caliente Indian Reservation (which was subject to limited fractionation and allowed long-term leasing of trust lands) and find little evidence of differences. Our approach is complementary because we are interested in the effects of development across, rather than within, checkerboarded landscapes in a setting where fractionation is high. Our results suggest that tribal

[46] The calculations might overstate the per capita income gains to tribal members from consolidation into tribal ownership because there is no guarantee that tribal government revenues would be distributed to individual members. The distributional effects of private versus government ownership are important, but outside the scope of this study. Oil revenues accrued by governments are sometimes subject to corruption (see, e.g., Caselli and Michaels 2013). In our empirical case, the former Tribal Chairman of the Three Affiliated Tribes was the subject of a "Tale of Oil, Corruption and Death" (Sontag and McDonald 2014). The narrative highlights, among other things, the tribal government's purchase of a 96-foot yacht costing \$2.5 million. The new Tribal Chairman recently said that 85% of royalty earnings were distributed to each member, who also received added health insurance. See http://www.kfyrtv.com/content/news/Fort-Berthold-reservation-oil-and-gas-royalties-help-insure-tribal-members-480845371.html.

land—if spatially contiguous—is more conducive than allotted trust land for large-scale natural resource production

Our findings extend the important literature on fractionation and allotted trust lands by highlighting a) how fractionation can impair the productivity of neighboring land and b) how the benefits and costs of tribal ownership depend on its spatial configuration. Our explanation for these findings focuses on how the costs of resource use vary with the number of excluders, which in turn varies based on ownership arrangements. This focus on transaction costs is supported by case studies of the barriers to resource development on fractioned trust lands that emphasize large-*N* problems. For example, Shoemaker (2003, 760) describes the problem of leasing on fractionated Indian reservation land and cites an example in which an oil company did not complete a lease "…after realizing how much work was involved in obtaining the necessary signatures from 101 heirs, of whom the BIA had no address for 21 and 6 were deceased with estates still pending agency probate."

Given concerns about environmental damages and other negative consequences of resource booms, we emphasize that our estimates reflect foregone earnings rather than welfare impacts. The income benefits of more aggressive drilling may overstate the associated welfare gains because of greater risk of local environmental harm (e.g., Olmstead et al. 2013, Boomhower 2019). We recognize this issue but point out that, on Fort Berthold and elsewhere, residents were exposed to drilling disamenities (e.g., noise, pollution, crime, congestion) regardless of the extent to which they were compensated for their shale ownership. The worst scenario, it seems, is to face institutional constraints on compensation while still being exposed to the disamenities of a resource boom on neighboring lands.

8. Alternative Interpretations and External Validity

Our empirical estimates come from Ft. Berthold, which contains three ownership arrangements prevalent across the world: private, co-owned, and government. Because the setting is a Native American reservation, however, the reader might wonder if the results are i) explained by cultural preferences rather than by transaction costs, anticommons, and bureaucratic red tape and ii) if the results generalize to other settings where cultures and preferences towards drilling may differ.

The main issue is that tribal and allotted trust parcels are owned by Native Americans, whereas some fee simple parcels are owned by whites. Hence, cultural differences could lead to estimated differences in λ_F vs. λ_A or β_F vs. β_A. We emphasize there is no *ex ante* reason to expect that preferences necessarily correlate with ethnicity and we are not aware of empirical evidence suggesting that Native and non-Native residents of Ft. Berthold have systematically different preferences. We do know the tribal government of Ft. Berthold aggressively pursued shale oil development over the period we study—the tribal chairman unscored this enthusiasm in a statement where he declared, "Our sovereignty, our independence, can be maximized by the number of barrels of oil taken from Mother Earth. We call it sovereignty by the barrel" (MHA Energy Division, 2013). Assuming the government represents the preferences of tribal members, this may indicate the Native population majority is amenable to fracking.[47]

Nevertheless, two additional points are worth emphasizing. First, the resettlement of 80% of the reservation population in 1951 induced relatively high rates of Native American ownership of fee simple land and subsurfaces. Even in the surplus-area towns, the majority of the population is Native American. Population data from census block groups indicate that all but one portion of the reservation has a majority Native American population (see Appendix Figure A5). This segment lies on the eastern edge that does not contain oil fields and is hence excluded from our main analysis (see Figure 3). As a robustness check, we employ subsamples that drop the portions of the reservation overlapping oil fields where Native American populations are lowest (the intersect of oil fields and the red shaded region in Figure A5 where Native Americans account for only 50% of the population). Although this eliminates 1,483 out of 3,661 fee simple parcels, the regression estimates are very similar, further suggesting that unobserved preferences are not driving our main results (see Appendix Table A2).

Second, we emphasize that any systematic preference differences across ownership regimes would bias both the λ and β coefficients in the same direction, contrary to the predictions of our model. For example, if the average fee owner is more amenable to drilling than the average tribal member, this would bias both λ_F and β_F upwards because both the own and neighbor effects for fee parcels would be positive relative to tribal parcels. Recall, however, that our model predicts $\beta_F < 0$ due to contracting costs. Hence, omitted preferences would bias the results toward finding an "own parcel" effect, but away from finding a fragmentation or neighbor parcel difference between fee and tribal parcels. The upshot is that a preference-based explanation of results from our empirical model could explain either differences in the intercepts (λ_i), or in the slopes (β_i), but not both. This is important because our main predictions, the crossing point estimate (see Figure 7), and the policy thought exercise (see Table 7) do not rely on a single λ_i or β_i parameter but consider both.

An additional issue is the role of the federal government oversight on allotted and tribal parcels. We argue that this affects the interpretation of our coefficients but does not threaten identification—the BIA and associated NEPA concerns merely represent additional government excluders. This "federal effect" will be reflected in the difference in the intercepts—the λ_i coefficients—because federal

[47] There is of course variation within and across tribes in preferences towards subsurface extraction. For example, neighboring tribes in Montana – the Northern Cheyenne and the Crow – have different views towards coal mining with the Crow favoring it and the Northern Cheyenne being opposed. See, e.g., www.reuters.com/article/us-usa-trump-energy-tribes-insight-idUSKCN1B10D3.

involvement represents another set of excluders that must be satisfied to initiate drilling on allotted and tribal lands. However, the logic about government excluders from Figure 2 still applies—federal oversight occurs at the project level and does not entail additional excluders for a marginal fee simple or allotted trust parcel. This suggests that the allotted trust slope coefficient β_A will reflect issues associated with co-ownership rather than federal involvement.

Though we do not think the Fort Berthold results are best explained by cultural preferences, we do recognize that variation in culture and governance will likely condition the severity of transaction costs and coordination challenges as emphasized by Ostrom (1990). However, the theoretical framing implies that transaction costs and coordination challenges should grow with N across contexts, albeit at potentially different rates. To the extent that our main predictions hold in other contexts, it provides additional evidence that our results are not driven by systematic bias due to unobservables on the reservation.

While a thorough investigation of other settings is outside the paper's scope, we can provide some evidence that our findings apply to broader comparisons of government versus subdivided private land. Table 8 replicates our approach from Table 4 but focuses on patterns of drilling on and around private vs. federal Bureau of Land Management and Forest Service land. Figure A6 in the appendix illustrates the off-reservation sample used for the estimation. We emphasize the data used here measure surface ownership rather than subsurface ownership. As a consequence, the Table 8 coefficients are less precisely estimated than those in Tables 4 and 5.

The results in Table 8 are similar to our comparisons of private versus tribal land on the reservation, although less precise (presumably due to measurement error). Based on the Column 6 coefficients, which are the most precisely estimated, the threshold parcel size is 8.8 acres, which is comparable to the 4.6-acre threshold for the fee vs. tribal comparison. The Table 8 results suggest that our main findings—that resource use decreases with subdivision and ownership fragmentation—are reflective of general trade-offs associated with private vs. public ownership that exist on and off Indian reservations, albeit to differing degrees. We emphasize that greater resource use does not necessarily imply greater social welfare and that environmental and conservation concerns may be at the heart of why government entails many exclusion rights. We have simply shown—as a matter of positive economics—some of the conditions that affect usage under governmental versus private ownership. Future research should explore this trade-off in the context of other spatially expansive natural resources such as wind development and wildlife habitat.[48]

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[48] Lueck (1995) argues that the explanation for government versus private ownership of wildlife depends in part on the size of private landholdings.

Table 8: Off Reservation Estimates of Per Acre Production and Revenue

	Y = Production per Acre			Y = Revenue per Acre		
	(1)	(2)	(3)	(4)	(5)	(6)
Parcel Variables						
Parcel acres	0.146	0.131	0.0887	4.312	3.748	3.001
	(0.140)	(0.139)	(0.0671)	(5.029)	(5.001)	(2.512)
Fee parcel indicator	77.57*	41.99	46.80	3492.7**	2392.1	2134.6*
	(45.18)	(58.93)	(31.43)	(1776.3)	(2277.4)	(1278.3)
Neighbor Variables						
Fee neighbors	-0.267**	-0.284**	-0.289**	-9.325*	-10.05*	-10.66**
	(0.122)	(0.130)	(0.128)	(4.836)	(5.163)	(4.996)
Govt. land in neighborhood	-9.511**	-7.584*	-8.511**	-414.9***	-348.7**	-347.3**
	(3.955)	(3.965)	(4.191)	(157.5)	(159.4)	(159.2)
Govt. land in neigh. X	1.793	-0.931	4.552	93.55	11.71	192.2
Govt. parcel indic.	(4.708)	(5.334)	(4.715)	(185.4)	(211.6)	(177.2)
Excludes parcels off fields	x	x	x	x	x	x
Covariate controls	x	x	x	x	x	x
Shale thickness & depth FE	x	x	x	x	x	x
x & y coordinates		x	x		x	x
Oil field FE			x			x
Adjusted R-squared	0.479	0.489	0.633	0.502	0.510	0.647
Observations	33354	33354	33354	33354	33354	33354

Notes: Conley (2008) spatial HAC standard errors shown in parentheses. Following Hsiang (2010), these models are estimated using a GMM approach that allows for arbitrary forms of spatial correlation in the error term, as described in Conley (2008). * p<0.1, ** p<0.05, ***p<0.01. A parcel's neighborhood includes all parcels touching a half-mile radius from the parcel's boundary. All specifications control for the slight variation in the total area of the radius, due to variation in the size of parcels on the exterior of the radius. All specifications also control for topographical roughness, an indicator for whether or not the parcel is in a city, an indicator for whether or not the parcel is underwater, nearest distance to a road, and the number of mineral parcels within the radius that lie beneath the high water mark of the Missouri River. All columns use only parcels that are on a designated oil field. Columns 3 and 6 include oil field fixed effects. Appendix Table A3 provides summary statistics for the off-reservation sample.

9. Conclusion

Does bundled or contiguous government ownership lead to greater shale utilization? It depends. This paper studies a key tradeoff. Under both forms of ownership, resource use depends on the cost of access, which in turn depends on the number of agents with authority to preclude shale use. The number of government-agent excluders varies with bureaucratic structure, but it is invariant to the spatial scale of resource extraction. The number of excluders under private ownership varies with parcel size, land fragmentation, and the spatial scale of resource extraction. Together these factors determine a threshold minimum size of private parcels below which government ownership yields greater resource use.

We find that tribal ownership yields more output than private, fee simple ownership for shale oil extraction on the Fort Berthold Indian reservation if parcel sizes are less than five acres. Tribal ownership yields more output allotted trust (heirship ownership) if parcels sizes are less than 63 acres. For context, we note that 84% of the world's farms are smaller than five acres and a significant proportion of the world's land is held by heirs who share fractionated ownership interests. These findings suggest that government ownership may be an appropriate regime in many countries, in spite of the corruption, bureaucratic red tape, and mismanagement that can accompany governmental control.

Our policy thought experiment indicates significant gains from consolidating subsurface ownership and highlights another angle from which to view the legacy of Native American land allotment. Accounts written by sociologists, historians, and legal scholars characterize the injustices of allotment by documenting the large transfers of resource wealth from Native Americans that resulted (see, e.g., Banner 2005). We join other economists by emphasizing that allotment did more than transfer wealth; it also affected resource productivity by creating new systems and mixtures of ownership. Our contribution is to emphasize how fragmentation impaired development of a valuable, large-scale natural resource. Back-of-the envelop estimates suggest fragmentation reduced Fort Berthold's earnings from the fracking boom by an amount comparable to annual income from other sources. Moreover, we expect that fragmented ownership has reduced rents on other Native Americans lands that hold other spatially expansive resources with value such as wind.[49]

Our findings quantify a barrier to the development of large-scale resources that matters beyond Indian reservations—checkerboarded private and public ownership. Projects spanning scattered government holdings within a mostly privatized landscape cannot avoid the fixed costs of negotiating with government agents, nor can they capitalize on the relative advantages of large, contiguous government ownership that avoid the marginal cost of contracting with additional private owners. This finding highlights the need for future research on resource development across, rather than just within, mosaics of private and public ownership such as the Wyoming checkerboard.

It is worth emphasizing that ownership fragmentation may inhibit conservation as well as extraction. In the case of fracking, coordination challenges from fragmentation can make it difficult for neighbors to act collectively to prevent oil drilling at a scale large enough to eliminate exposure to adverse effects. This is analogous to Hansen and Libecap (2004), who explain how high coordination costs among small landowners exacerbated environmental pollution during the U.S. dust bowl era. We note that some tribes such as the Turtle Mountain Band of Chippewa in North Dakota banned fracking

[49] The findings contribute to a literature on how historical policies toward indigenous people have affected modern economic outcomes. This literature includes Brown et al. (2017), Feir (2016), Feir et al. (2017), Akee et al. (2015), Dippel (2014), Dimitrova-Grajzl et al. (2014), Cookson (2010), Akee (2009), Anderson and Parker (2008), Cornell and Kalt (2000), Anderson and Lueck (1992), Carlson (1981), and Trosper (1978) among others.

entirely within reservation boundaries, a policy that would likely not be possible for reservations that are checkerboarded with fee simple and allotted trust parcels.[50]

Our study also raises questions for future research about how to mitigate the drawbacks of private ownership while still capitalizing on its advantages, particularly in the context of modern land reform and titling programs (see, e.g., Alston et al. 1996, de Soto 2000; de Janvry et al. 2015; Aragon and Kessler 2018). One approach might be for governments to retain default ownership to undiscovered resources and to resources that are inaccessible under present technologies. Rights to such resources (e.g., shale oil, wind) could be privatized only after the appropriate scale of resource use is revealed. This may benefit future generations because the costs of reassembling rights once they have been subdivided generally exceed the costs of dividing large interests into smaller ones (Parisi et al. 2004).

Another alternative is to weaken the exclusion rights of private owners *ex-post*, through the use of eminent domain. In the context of oil development in the United States, this approach comes in the form of forced pooling rules that limit the power of individual landowners to hold up development (Libecap and Wiggins 1985; Vissing 2017). Our findings suggest that contracting problems persist in spite of these rules. Furthermore, such rules are politically difficult to impose ex-post, after property right entitlements have been assigned. The end result is that assigning property rights at a particular scale can create costly barriers to time-sensitive investment opportunities, such as those arising during resource booms.

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[50] For details on the fracking ban, see www.huffingtonpost.com/sarah-van-gelder/in-north-dakotas-booming_b_9078378.html.

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Mathematical Appendix

Most compensation to shale owners comes in the form of royalty payments that allocate a proportion of project revenue to mineral owners (Brown et al. 2016, Fitzgerald and Rucker 2016).[1] With royalty payments, the project-level expected profit for the oil developer is

$$\pi_D = Pq(1-R) - C(q). \tag{1}$$

Here, R denotes the project-level royalty rate which is $= \sum_i^N w_i r_i$. Each shale owner charges $r_i \in [0,1]$, where $w_i \in [0,1]$ are weights representing the proportion of owner *i's* mineral acreage in the project. We assume equal shares so that $R = \sum_i^N r_i / N$. Taking royalty rates as given, an oil developer maximizes profits by choosing oil extraction q that solves:

$$\max_q \pi_D = Pq(1-R) - C(q) \tag{2}$$

where P is the expected price of oil, q is the total oil extracted and $C(q)$ is the total cost function satisfying $C'(q) \geq 0$ and $C''(q) \geq 0$. Developers can increase q, the oil recovered from a project, by drilling additional laterals within a spacing unit or increasing their use of inputs such as silica and other ingredients in the fracking solution, and waste disposal after drilling commences. Hence, $C(q)$ reflects increased costs associated with the use of additional inputs for each lateral as well as the costs of drilling multiple laterals in a given area.[2]

Abstracting from uncertainty and discounting, π_D represents the expected present value of the well to the developer.[3] Changes in any parameter can change whether or not a project yields positive surplus in expectation, thereby influencing the probability of drilling. Kellogg (2014) highlights the importance of volatility when analysing the effect of expected output price and other parameters on the drilling decision.

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[1] Fitzgerald and Rucker (2016) find that royalty payments typically comprise 85-90 percent of payments from a lease with bonus payments comprising 10 to 15 percent. Vissing (2016) finds that bonus payments are positively correlated with other aspects of the lease including royalty rates and terms that are favorable to the landowner.

[2] We model the cost function this way to be as general as possible. An alternative approach is to introduce a fixed cost per well drilled and model the decision of whether or not to drill an additional well. We solved this model in a previous draft and developed qualitatively identical testable predictions. This alternative model is available upon request.

[3] A more realistic expression is $\pi_D = \sum_{t=1}^T \rho^t [E(p_t, q_t) - C(q_t)]$, where T is the life of the well, which is projected to be about 25-30 years in our study area, q_t represents declining production over time, $E(p_t)$ indicates expected prices over the life of the well, and ρ^t is a discount factor. We abstract away from uncertainty and dynamics because making these features explicit would add complexity to the theory without providing additional insights.

We take those dynamics—and the interest rate—as given and focus on how changes in leasing behaviour alter the demand for oil.

A. The Landowner's Problem

We now develop the intuition for the anticommons in our setting, building on Buchanan and Yoon (2000), Schulz et al. (2002) and Parisi and Depoorter (2004). Each of N excluders to a resource charges an individual price for use. Permission to use the resource is not granted unless all excluders consent, and consent is granted only if each excluder's asking price is paid. The unique feature of our setting is that, rather than charging a fixed fee, each shale owner chooses a royalty rate r_i in an attempt to maximize his expected payout:

$$\max_{r_i} \pi_i = \frac{r_i}{N} Pq(P,R) \tag{3}$$

where N is the total number of excluders in the unit and $q(P,R)$ is the demand for oil, derived from the solution to the developer's problem. Each landowner chooses an individually optimal royalty rate, taking as given the royalty rates requested by the other excluders in the unit.

B. Equilibrium and Comparative Statics

Following Buchanan and Yoon (2000), we focus on the symmetric Nash equilibrium where r_i is the same for all landowners. We highlight several comparative statics associated with the equilibrium oil demand $q^*(P,R)$ and royalty rate $r_i^*(N)$:

P1) $\frac{\partial r_i^*(N)}{\partial N} = \frac{\partial R}{\partial N} > 0$ (The aggregate royalty rate is increasing in N)
P2) $\frac{\partial q^*(P,R)}{\partial N} < 0$ (Oil production is decreasing in N)
P3) $\frac{\partial \pi_D(P,N)}{\partial N} < 0$ (Project-level surplus is decreasing in N)
P4) $\frac{\partial \pi_i(P,N)}{\partial N} < 0$ (Landowner compensation is decreasing in N)

1. Proof that $\frac{\partial q^*(P,R)}{\partial R} < 0$

The oil driller's decision problem is:

$$\max_{q} \pi_D = Pq(1-R) - C(q)$$

First-Order Necessary Condition:

$$\frac{\partial \pi_D}{\partial q} = P(1-R) - C'(q) = 0$$

Second-Order Sufficient Condition:

$$\frac{\partial^2 \pi_D}{\partial q^2} = -C''(q) \leq 0 \qquad \Leftrightarrow \qquad C''(q) \geq 0$$

When the second order condition holds, the first-order condition defines an implicit function:

$$q^* = q^*(P, R)$$

Plugging the optimal q^* back into the first-order condition yields the following identity:

$$P(1-R) - C'(q^*(P,R)) \equiv 0$$

Which can be differentiated with respect to R:

$$-P - C''(q^*(P,R))\frac{\partial q^*(P,R)}{\partial R} \equiv 0$$

Which implies:

$$\boldsymbol{\frac{\partial q^*(P,R)}{\partial R} \equiv \frac{-P}{C''\left(q^*(P,R)\right)} < 0}$$

This expression is less than zero by the second order condition. I.e. the demand for oil is decreasing in the royalty rate. QED.

2. Proof that $\boldsymbol{\frac{\partial r_i^*(N)}{\partial N} = \frac{\partial R}{\partial N} > 0}$

Recall the landowner's problem:

$$\max_{r_i} \pi_i = \frac{r_i}{N} P q(P, R)$$

Where $R = \frac{\sum_{i=1}^{N} r_i}{N}$ and hence $\frac{\partial R}{\partial r_i} = \frac{1}{N}$

First-order condition:

$$\frac{\partial \pi_i}{\partial r_i} = \frac{Pq(P,R)}{N} + \frac{r_i}{N}\frac{\partial q(P,R)}{\partial R}\frac{\partial R}{\partial r_i} = 0$$

$$\frac{P}{N}\left[q(P,R) + \frac{r_i}{N}\frac{\partial q(P,R)}{\partial R}\right] = 0$$

Which requires

$$q(P,R) + \frac{r_i}{N}\frac{\partial q(P,R)}{\partial R} = 0$$

Second-order condition:

$$\frac{\partial q(P,R)}{\partial R}\frac{\partial R}{\partial r_i} + \frac{1}{N}\frac{\partial q(P,R)}{\partial R} + \frac{r_i}{N}\frac{\partial^2 q(P,R)}{\partial R^2}\frac{\partial R}{\partial r_i} \leq 0$$

$$\Leftrightarrow$$
$$\frac{\partial q(P,R)}{\partial R}\frac{1}{N}+\frac{1}{N}\frac{\partial q(P,R)}{\partial R}+\frac{r_i}{N}\frac{\partial^2 q(P,R)}{\partial R^2}\frac{1}{N}\leq 0$$
$$\Leftrightarrow$$
$$\frac{1}{N}\left[2\frac{\partial q(P,R)}{\partial R}+\frac{r_i}{N}\frac{\partial^2 q(P,R)}{\partial R^2}\right]\leq 0$$
$$\Leftrightarrow$$
$$2\frac{\partial q(P,R)}{\partial R}+\frac{r_i}{N}\frac{\partial^2 q(P,R)}{\partial R^2}\leq 0$$
$$\Leftrightarrow$$
$$2q'+\frac{r_i}{N}q''\leq 0$$

At landowner i's optimum the first-order condition defines an implicit function:

$$r_i^* = r_i^*(N, r_{-i})$$

Plugging back into the FOC yields the following identity

$$q\left(P,\frac{\sum_{i=1}^{N} r_i^*(N,r_{-i})}{N}\right)+\frac{r_i^*(N,r_{-i})}{N}\frac{\partial q(P,\frac{\sum_{i=1}^{N} r_i^*(N,r_{-i})}{N})}{\partial \frac{\sum_{i=1}^{N} r_i^*(N,r_{-i})}{N}}\equiv 0$$

And, in the symmetric Cournot-Nash equilibrium,

$$r_i^* = r_i^*(N) \quad \forall i$$

This implies

$$R=\frac{\sum_{i=1}^{N} r_i^*(N)}{N}=\frac{N r_i^*(N)}{N}=r_i^*(N)$$

Updating the identity:

$$q\big(P,r_i^*(N)\big)+\frac{r_i^*(N)}{N}\frac{\partial q(P,r_i^*(N))}{\partial r_i^*(N)}\equiv 0$$

Differentiating with respect to N:

$$\frac{\partial q(P,r_i^*(N))}{\partial r_i^*(N)}\frac{\partial r_i^*(N)}{\partial N}+\frac{\partial r_i^*(N)}{\partial N}\frac{1}{N}\frac{\partial q(P,r_i^*(N))}{\partial r_i^*(N)}+\frac{r_i^*(N)}{N}\frac{\partial^2 q(P,r_i^*(N))}{\partial r_i^*(N)^2}\frac{\partial r_i^*(N)}{\partial N}-\frac{r_i^*(N)}{N^2}\frac{\partial q(P,r_i^*(N))}{\partial r_i^*(N)}\equiv 0$$
$$\Rightarrow$$
$$\frac{\partial r_i^*(N)}{\partial N}\left[\frac{\partial q(P,r_i^*(N))}{\partial r_i^*(N)}+\frac{1}{N}\frac{\partial q(P,r_i^*(N))}{\partial r_i^*(N)}+\frac{r_i^*(N)}{N}\frac{\partial^2 q(P,r_i^*(N))}{\partial r_i^*(N)^2}\right]\equiv\frac{r_i^*(N)}{N^2}\frac{\partial q(P,r_i^*(N))}{\partial r_i^*(N)}$$
$$\Rightarrow$$

$$\frac{\partial r_i^*(N)}{\partial N}\left[\frac{\partial q(P,r_i^*(N))}{\partial r_i^*(N)}\frac{N+1}{N}+\frac{r_i^*(N)}{N}\frac{\partial^2 q(P,r_i^*(N))}{\partial r_i^*(N)^2}\right]\equiv\frac{r_i^*(N)}{N^2}\frac{\partial q(P,r_i^*(N))}{\partial r_i^*(N)}$$

$$\Rightarrow$$

$$\frac{\partial r_i^*(N)}{\partial N}\equiv\frac{r_i^*(N)}{N^2}\frac{\partial q(P,r_i^*(N))}{\partial r_i^*(N)}\Bigg/\left[\frac{\partial q(P,r_i^*(N))}{\partial r_i^*(N)}\frac{N+1}{N}+\frac{r_i^*(N)}{N}\frac{\partial^2 q(P,r_i^*(N))}{\partial r_i^*(N)^2}\right]$$

Note that the numerator, $\frac{r_i^*(N)}{N^2}\frac{\partial q(P,r_i^*(N))}{\partial r_i^*(N)}<0$ (See Driller's Problem)

Therefore $\frac{\partial r_i^*(N)}{\partial N}$ is positive if and only if the denominator is negative:

$$\frac{\partial r_i^*(N)}{\partial N}>0\;\Leftrightarrow\frac{\partial q(P,r_i^*(N))}{\partial r_i^*(N)}\frac{N+1}{N}+\frac{r_i^*(N)}{N}\frac{\partial^2 q(P,r_i^*(N))}{\partial r_i^*(N)^2}<0$$

$$\Leftrightarrow (N+1)q'+r_i^*(N)q''<0$$

$$\Leftrightarrow r_i^*(N)q''<-(N+1)q'$$

By the second order condition,

$$2q'+\frac{r_i}{N}q''\leq 0$$

$$\Leftrightarrow r_i q''\leq -2Nq'$$

This implies that

$$\frac{\partial r_i^*(N)}{\partial N}>0\;\Leftrightarrow -(N+1)q'>-2Nq'$$

$$\Leftrightarrow 2Nq'>(N+1)q'$$

$$\Leftrightarrow 2N>(N+1)$$

$$\Leftrightarrow N>1$$

Therefore,

$$\frac{\partial r_i^*(N)}{\partial N}=\frac{\partial R}{\partial N}>0$$

Individual and aggregate royalty rates are increasing in N. QED.

3. Proof that $\frac{\partial q^*(P,R)}{\partial N}<0$

This follows directly from results 1 and 2:

$$\frac{\partial q^*(P,R)}{\partial N} \equiv \underset{(-)}{\frac{\partial q^*(P,R)}{\partial R}} \times \underset{(+)}{\frac{\partial r_i^*(N)}{\partial N}} < 0$$

The demand for oil is decreasing in the number of exclusion right holders. QED.

4. Proof that $\frac{\partial \pi_D(P,N)}{\partial N} < 0$

The oil driller's optimized profit function is given by:

$$\pi_D(P,N) = Pq^*\big(P, r_i^*(N)\big)\big(1 - r_i^*(N)\big) - C\left(q^*\big(P, r_i^*(N)\big)\right)$$

Differentiating wrt N:

$$\frac{\partial \pi_D(P,N)}{\partial N} = P\frac{\partial q^*(P,R)}{\partial N} - Pr_i^*(N)\frac{\partial q^*(P,R)}{\partial N} - P\frac{\partial r_i^*(N)}{\partial N}q^*\big(P, r_i^*(N)\big)$$
$$- C'\left(q^*\big(P, r_i^*(N)\big)\right)\frac{\partial q^*(P,R)}{\partial N}$$

$$= \frac{\partial q^*(P,R)}{\partial N}\left[P\big(1 - r_i^*(N)\big) - C'\left(q^*\big(P, r_i^*(N)\big)\right)\right] - Pq^*\big(P, r_i^*(N)\big)\frac{\partial r_i^*(N)}{\partial N}$$

$$= -Pq^*\big(P, r_i^*(N)\big)\frac{\partial r_i^*(N)}{\partial N} < 0$$

because the term in brackets is equal to zero by the FOC from the driller's problem. QED.

5. Proof that $\frac{\partial \pi_i(P,N)}{\partial N} < 0$

The landowner's optimized profit function is:

$$\pi_i(P,N) = \frac{r_i^*(N)}{N}Pq^*\big(P, r_i^*(N)\big)$$

Differentiating wrt to N:

$$\frac{\partial \pi_i(P,N)}{\partial N} = P\left[\frac{r_i^*(N)}{N}\frac{\partial q^*(P,R)}{\partial r_i^*}\frac{\partial r_i^*(N)}{\partial N} + \frac{\partial r_i^*(N)}{\partial N}\frac{q^*\big(P, r_i^*(N)\big)}{N} - \frac{r_i^*(N)q^*\big(P, r_i^*(N)\big)}{N^2}\right]$$

$$= P\left[\underset{(+)}{\frac{\partial r_i^*(N)}{\partial N}}\underset{(?)}{\left(\frac{r_i^*(N)}{N}\frac{\partial q^*(P,R)}{\partial r_i^*} + \frac{q^*\big(P, r_i^*(N)\big)}{N}\right)} - \underset{(-)}{\frac{r_i^*(N)q^*\big(P, r_i^*(N)\big)}{N^2}}\right]$$

The first-order condition from the landowner's problem requires:

$$\frac{r_i^*(N)}{N}\frac{\partial q^*(P,R)}{\partial r_i^*}+q^*(P,R)=0$$

This implies

$$\frac{r_i^*(N)}{N}\frac{\partial q^*(P,R)}{\partial r_i^*}+\frac{q^*\left(P,r_i^*(N)\right)}{N}<0=\frac{r_i^*(N)}{N}\frac{\partial q^*(P,R)}{\partial r_i^*}+q^*(P,R)$$

Hence

$$\frac{\partial \pi_i(P,N)}{\partial N}=P\left[\underset{(+)}{\frac{\partial r_i^*(N)}{\partial N}}\underset{(-)}{\left(\frac{r_i^*(N)}{N}\frac{\partial q^*(P,R)}{\partial r_i^*}+\frac{q^*\left(P,r_i^*(N)\right)}{N}\right)}-\underset{(-)}{\frac{r_i^*(N)q^*\left(P,r_i^*(N)\right)}{N^2}}\right]<0$$

QED.

These are the familiar outcomes of the anticommons model applied to a setting where excluders charge a royalty rate rather than a fixed fee for access. The intuition behind the results is that each landowner trades off the direct benefit of a higher royalty rate against the decrease in the driller's demand for oil. This reduction in demand affects all N landowners but each only considers the effect on his own profits, resulting in a suboptimally high royalty rate that reduces overall compensation.

C. Clarifications and Assumptions

Four clarifications are useful before proceeding. First, shale owners could inadvertently benefit from an anticommons if the price of oil unexpectedly increases after leasing but before drilling. In that case, the demand for oil increases and payouts to shale owners, conditional on drilling, increase because requested royalty rates are high. If future changes in prices and costs are all anticipated, however, then large N cannot benefit shale owners.

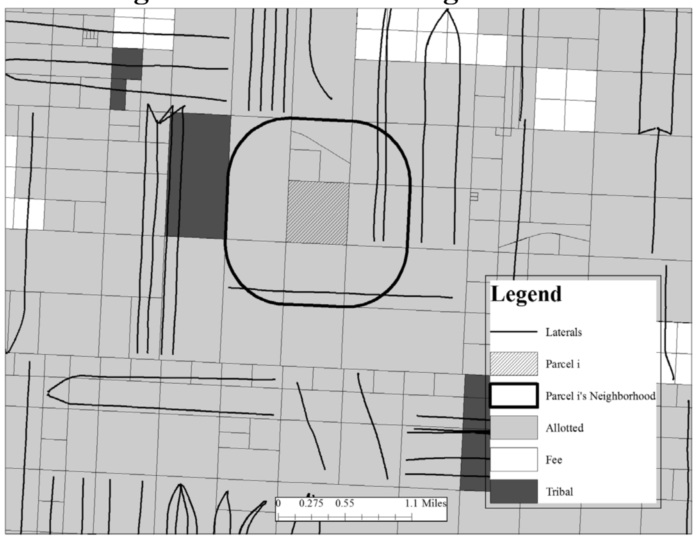
Second, the model does not consider institutional responses to contracting problems. Forced pooling laws, passed by US states, compel minority mineral owners into horizontal drilling projects if a majority of neighboring acreage has already been leased. State-level forced pooling laws do not generally apply on sovereign Indian reservations (see Slade et al. 1996), but a 1998 federal law specific to Fort Berthold requires the consent of only a majority of owners of allotted trust lands before a mineral lease can be executed. These institutional responses decrease but do not eliminate the problems modeled above.

Third, though the model focuses on a continuous demand function $q^*(P,R)$, the anticommons could affect both the intensive and extensive margin of the drilling decision. The result that $\frac{\partial q^*(P,R)}{\partial N}<0$ may manifest itself as zero laterals drilled in certain areas.

Fourth, the model does not explicitly differentiate government excluders from private individuals. This is abstraction—consistent with Buchanan and Yoon (2000) and Schleifer and Vishny (1993)—assumes the overall "price" of resource use rises with the number of excluders, whether they are government agents (e.g., bureaucrats, interest group lobbyists, local politicians), or individual private shale owners. Although this is a simple view of complex governmental decision-making, it is a framework that is testable in our empirical setting, where we can observe royalty rates charged in government leases versus leases with private owners, in areas of shale with small and large parcels.

Data Appendix

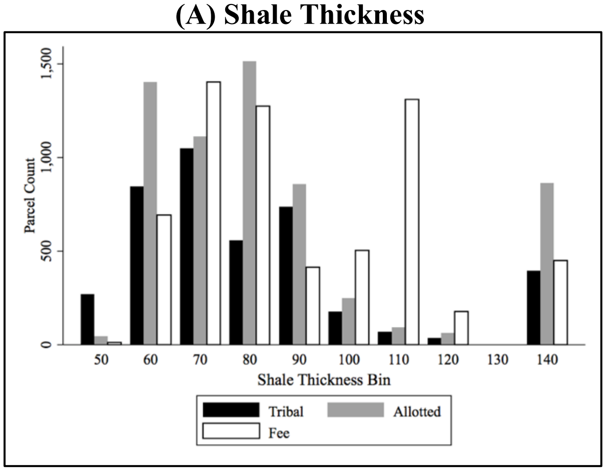
Figure A1: Parcel i's Neighborhood

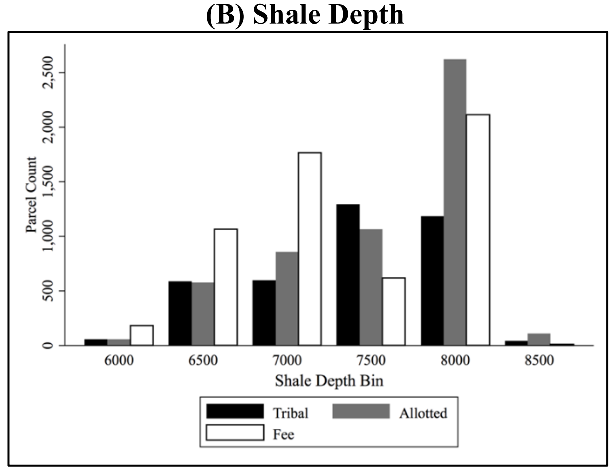


Notes: This figure illustrates our mapping from the spatial data to the variables. We determine the total number and acreage of parcels of each tenure within a ½-mile radius of each parcel.

Figure A2: Mineral Tenure and Shale Endowment on Ft. Berthold

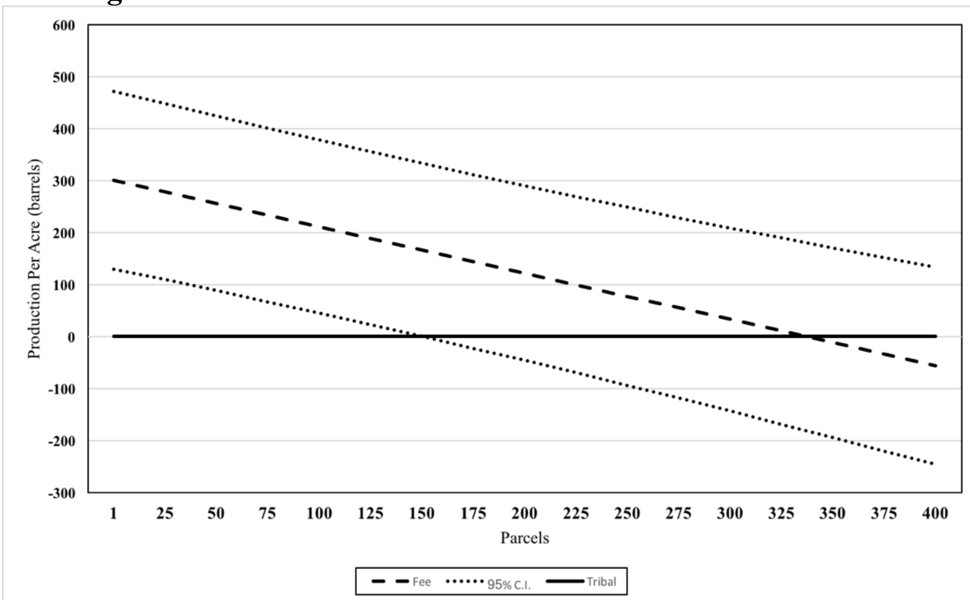
(A) Shale Thickness **(B) Shale Depth**





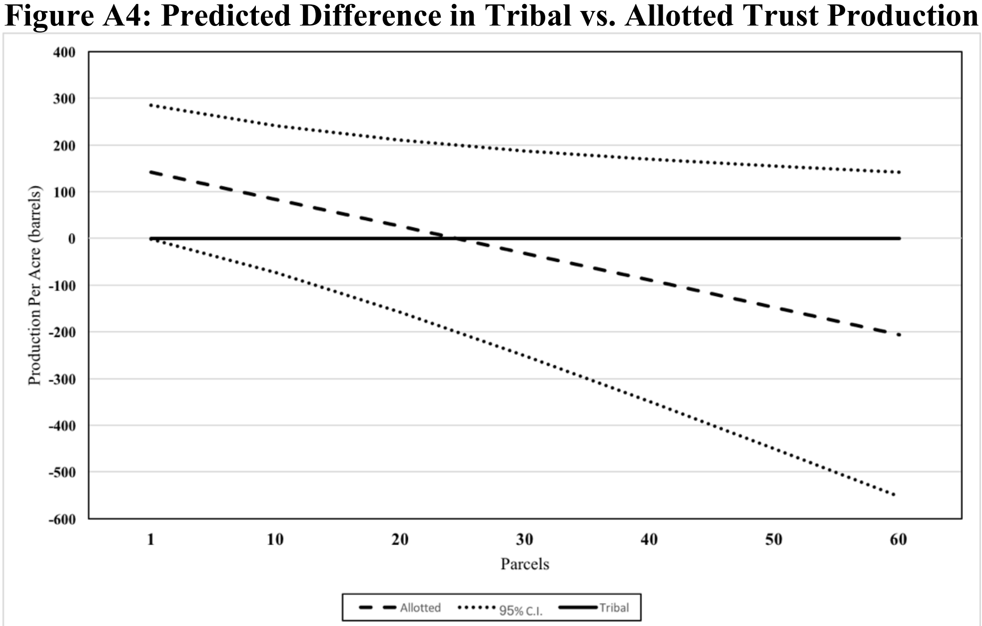
Notes: This figure depicts the number of parcels from each tenure category in each shale thickness and depth bin on the Ft. Berthold Indian Reservation depicted in Figure 6B. Shale thickness and depth estimates obtained from the North Dakota Oil and Gas Commission. Reservation parcels represent mineral ownership and were obtained from the Bureau of Indian Affairs.

Figure A3: Predicted Difference in Tribal vs. Fee Production



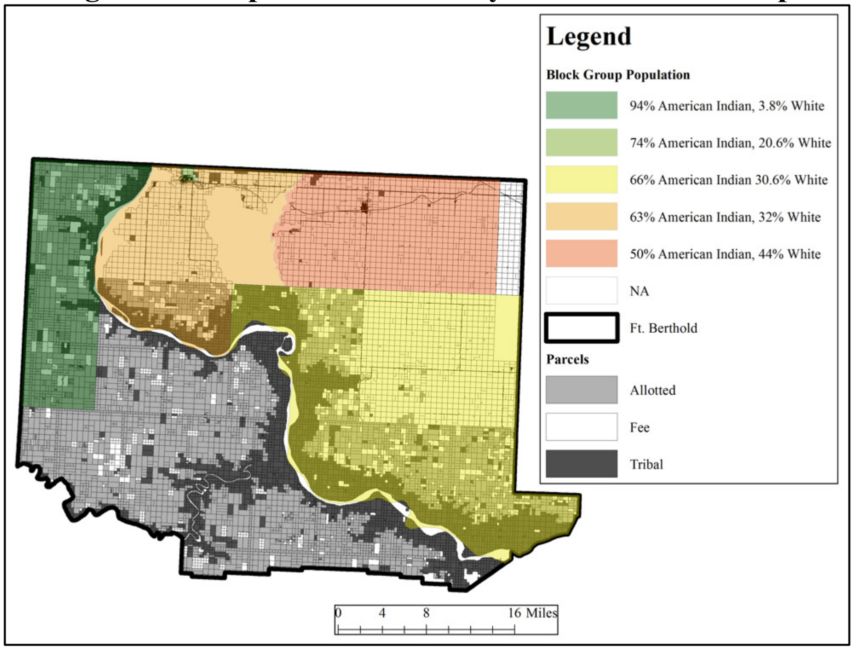
Notes: This figure plots the predicted effect of subdividing a 1,550-acre neighborhood into each fee vs. tribal ownership, based on the coefficient estimates in Table 4. The vertical intercept represents expected production on a single large fee parcel and is based on $\hat{\lambda}_F$. The slope of the line is determined by the estimated neighbor coefficient ($\hat{\beta}_F$).

Figure A4: Predicted Difference in Tribal vs. Allotted Trust Production



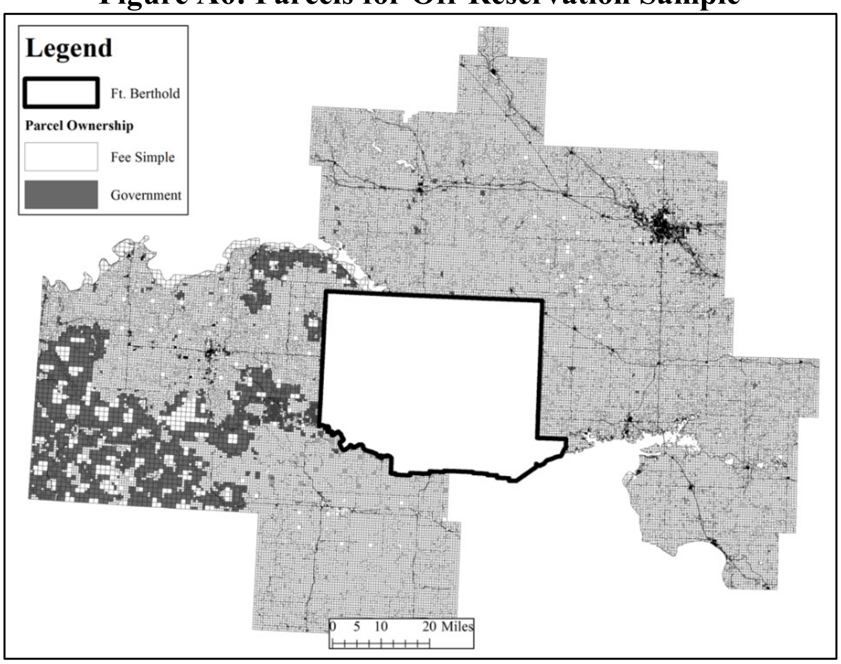
Notes: This figure plots the predicted effect of subdividing a 1,550-acre neighborhood into allotted trust vs. tribal ownership, based on the coefficient estimates in Table 4. The vertical intercept represents expected production on a single large allotted parcel and is based on $\hat{\lambda}_A$. The slope of the line is determined by the estimated neighbor coefficient ($\hat{\beta}_A$).

Figure A5: Population Shares by Census Block Group



Notes: This figure depicts reported population shares for census block groups that are contained entirely within the Fort Berthold Reservation. The census block groups that cover the Southwest portion of the reservation also include off-reservation areas from adjacent counties, so we do not report their population shares. From the perspective of our estimation, these areas are of least concern because they are primarily in tribal or allotted trust ownership, both of which require Native American ancestry. Where we do observe pure population shares, the areas with fewest allotted and tribal parcels on the far Northeast of the reservation have the lowest Native American population (50%). **[Update]**

Figure A6: Parcels for Off-Reservation Sample



Notes: This figure depicts private and government parcels in shale-producing counties adjacent to the Ft. Berthold Indian Reservation as of May, 2015. Data were obtained from the USDA Geospatial Data Gateway (government land) and from county assessors' offices (private land). Shaded areas indicate parcels owned by either the National Forest Service or the Bureau of Land Management. **[Update]**

Table A1: Tobit Estimates of Production per Acre, with Neighbor Variables

	(1)	(2)	(3)	(4)	(5)	(6)
Parcel Variables						
Parcel acres (ϕ)	1.269***	1.226***	0.992***	1.458***	1.400***	1.066***
	(0.290)	(0.270)	(0.249)	(0.327)	(0.290)	(0.273)
Fee parcel indicator (λ_F)	311.9**	296.4**	203.0**	282.6**	261.6*	205.5**
	(146.6)	(144.3)	(103.3)	(139.7)	(140.3)	(102.5)
Allotted trust parcel indicator (λ_A)	132.4	101.5	85.41	176.2	132.1	135.1
	(108.9)	(111.0)	(86.87)	(108.6)	(113.4)	(88.01)
Private Neighbor Variables						
Fee neighbors (β_F)	-0.937***	-0.902***	-0.976***	-0.834***	-0.781***	-0.822***
	(0.294)	(0.275)	(0.301)	(0.261)	(0.232)	(0.238)
Allotted trust neighbors (β_A)	-7.594**	-8.063**	-2.224	-11.28***	-11.88***	-5.157
	(3.578)	(3.379)	(4.094)	(3.728)	(3.331)	(3.828)
Government Neighbor Vars.						
Tribal Neighbor Indicator (β_T)	-179.9***	-170.6***	-162.3***	-167.6***	-151.8***	-153.9***
	(59.96)	(59.97)	(44.57)	(51.62)	(50.68)	(40.15)
Tribal Neighbor Indicator X	46.27	13.09	14.40	140.6	96.51	97.02
Tribal Indicator (β_{T1})	(115.6)	(123.5)	(92.06)	(122.7)	(133.7)	(98.90)
Excludes parcels off fields	x	x	x	x	x	x
Excludes underwater parcels				x	x	x
Covariate controls	x	x	x	x	x	x
Shale thickness & depth FE	x	x	x	x	x	x
x & y coordinates		x	x		x	x
Oil field FE			x			x
Adjusted R-squared	0.033	0.034	0.044	0.030	0.031	0.039
Observations	8524	8524	8524	6750	6750	6750

Notes: p<0.1, ** p<0.05, ***p<0.01. A parcel's neighborhood includes all parcels touching a half-mile radius from the parcel's boundary. All specifications control for the slight variation in the total area of the radius, due to variation in the size of parcels on the exterior of the radius. All specifications also control for topographical roughness, an indicator for whether or not the parcel is in a city, an indicator for whether or not the parcel is underwater, nearest distance to a road, and the number of mineral parcels within the radius that lie beneath the high water mark of the Missouri River. Columns 4-6 drop all parcels that are underwater. **[Update]**

Appendix Table A2: Exclude Parcels in Census Region with 50% White Population

	(1)	(2)	(3)	(4)	(5)	(6)
Parcel Variables						
Parcel acres (ϕ)	0.994***	0.982***	0.757***	1.224***	1.199***	0.857***
	(0.247)	(0.234)	(0.187)	(0.275)	(0.253)	(0.212)
Fee parcel indicator (λ_F)	373.0***	369.9***	270.0***	321.1***	315.5***	234.1***
	(128.0)	(126.3)	(87.30)	(119.4)	(119.4)	(87.47)
Allotted trust parcel indicator (λ_A)	181.5**	175.2**	140.5**	184.5**	171.0**	140.6**
	(86.71)	(84.74)	(65.55)	(86.65)	(87.20)	(65.52)
Private Neighbor Variables						
Fee neighbors (β_F)	-1.000***	-0.993***	-1.030***	-0.940***	-0.918***	-0.917***
	(0.184)	(0.185)	(0.219)	(0.176)	(0.171)	(0.184)
Allotted trust neighbors (β_A)	-7.264***	-7.339***	-3.845*	-9.704***	-9.789***	-4.786*
	(2.340)	(2.299)	(2.220)	(2.796)	(2.755)	(2.707)
Government Neighbor Vars.						
Tribal Neighbor Indicator (β_T)	-241.6***	-237.6***	-197.9***	-223.5***	-216.0***	-185.4***
	(51.10)	(48.22)	(40.43)	(44.87)	(42.39)	(34.02)
Tribal Neighbor Indicator X	108.9	102.5	87.36	137.1	122.6	97.78
Tribal Indicator (β_{T1})	(85.83)	(85.17)	(61.47)	(103.5)	(103.8)	(75.01)
Excludes parcels off fields	x	x	x	x	x	x
Excludes underwater parcels				x	x	x
Covariate controls	x	x	x	x	x	x
Shale thickness & depth FE	x	x	x	x	x	x
x & y coordinates		x	x		x	x
Oil field FE			x			x
Adjusted R-squared	0.561	0.562	0.600	0.600	0.601	0.633
Observations	7369	7369	7369	5595	5595	5595

Notes: [Update]

Table A3: Summary Statistics for Off-Reservation Parcel Level Data Set

	Mean	*Std. Dev.*	*Min*	*Max*	*Description*
Outcome Variables					
Revenue per Acre[a,b,c,d,f]	50,208.699	13,785.7	0	332,230.8	Total revenue for the unit associated with a parcel as of May 1, 2015, discounted at 3%, divided by parcel acres
Production per Acre	122.8522	349.424	0	4,468.5	Total production from wells in the unit associated with a parcel as of May 1, 2015, divided by parcel acres
Parcel Size, Shape, and Tenure					
Parcel Acres[b, c]	58.520	82.4277	0.0028	921.835	Area of the parcel, in acres
Fee Parcel Indicator[b]	0.969	0.174	0	1	=1 if the off-reservation parcel is fee simple, otherwise =0
Neighbor Parcels (1/2 mile radius)					
Fee Neighbors[b, c]	301.85	457.56	0	2651	Number of fee parcels within ½ mile radius around parcel
Government Neighbor Dummy[b, c]	0.179	0.383	0	1	=1 if BLM or US Forest Service own parcels within a ½ mile radius around parcel, otherwise =0
Neighbors Underwater [f]	3.134	8.903	0	83	Number of parcels under a body of water within ½ mile radius around parcel
Government Acres in Neighborhood[b, c]	145.72	533.36	0	5,348.37	Total acreage of parcels owned by BLM or US Forest Service within ½ mile radius around parcel
Other Covariates					
Topographic Roughness[e]	602.504	82.309	459.46	995.745	Standard deviation of elevation in the neighbourhood around a parcel, measured in centimeters
City Indicator[f]	0.312	0.463	0	1	= if the parcel is within a city boundary, otherwise = 0
Road density [f]	0.203	0.410	0	17.365	Kilometres of roads touching parcel

Notes: This table summarizes data for all parcels in our estimation sample off the reservation. We exclude government parcels and parcels with off-reservation neighbors. N = 94,865 for all variables. Data sources are: a) North Dakota Oil and Gas Commission website, b) U.S. Bureau of Indian Affairs, c) Real Estate Portal, d) U.S. EIA website e) Authors calculations from National Elevation Dataset, and f) Authors calculations from North Dakota GIS Portal data.

Policy Thought Experiment Appendix

We apply the estimates from Table 4, Column 2 to estimate the effect of replacing allotted parcels with tribal parcels separately for the average allotted, fee, and tribal parcel in the estimating sample. For the average allotted parcel, there are three effects. First, there is the direct reduction in revenue, which is $\hat{\lambda}_A$. Second, there is an increase in revenue associated with replacing the mean number of neighboring allotted parcels ($\hat{\beta}_A \; x \; \overline{N}_A$) with tribal parcels. Third, there is an expected increase in revenue associated with reducing the probability of the checkerboarding of tribal land interspersed among neighborhoods of allotted land: $\hat{\beta}_T$ x ($\overline{N}_T | Allotted = 1$).

The calculation is similar for fee parcels, with the noted difference that the change in the probability of a tribal neighbor applies only to those fee parcels that had at least one allotted neighbor but no tribal neighbors (otherwise the marginal effect of converting allotted to tribal is zero). For tribal parcels, the benefit is an increase in expected revenue from removing $\overline{N}_A$ allotted neighbors.

Panel A of Table A6 gives the results. Converting all allotted tracts to tribal ownership would increase expected revenues for the average allotted and tribal parcel, but reduce expected revenue for the average fee parcel. Summing across the reservation, this back-of-the-envelope exercise suggests a $733,572,301 net increase in total revenue over first 18 months of each well. This increase in revenue is accrued by creating more contiguous blocks of tribal ownership (that eliminate checkerboarded neighborhoods of allotted and tribal ownership), and the negative marginal effect of allotted parcels on oil production.

Panel B shows that that the regression estimates from Table 4 imply a similar oil revenue increase if the allotted trust interests had been consolidated into fee simple parcels prior to the fracking boom. The calculations simply multiply the per parcel revenue gain from the tenure switch ($(\hat{\beta}_A - \hat{\beta}_F)$ by the average number of allotted neighbors, $\overline{N}_A$. (We ignore the differences between $\hat{\lambda}_A - \hat{\lambda}_F$ here because those differences are statistically insignificant). Consolidation from allotted to fee simple is not part of the Cobell settlement, but we include it here as part of the thought experiment for context.

Table A4: Increase in Oil Revenue from Consolidating Allotted Trust

Tenure	Calculation for Average Parcel Effect	Change in per acre revenue, for average parcel	Total change (per acre Δ x total acres)
Panel A: Conversion to Tribal			
Allotted Trust	$\hat{\beta}_A \times \overline{N}_A \mid (Allotted = 1) - \hat{\beta}_T \times \overline{N}_T \mid (Allotted = 1) - \hat{\lambda}_A$ $= 232.3 \times 17.8 + 7761 \times 0.52 - 5930$	\$2,252	\$578,296,732
Fee Simple	$\hat{\beta}_A \times \overline{N}_A \mid (Fee = 1) - \hat{\beta}_T \times \Delta\overline{N}_T \mid (Fee = 1)$ $= 232.3 \times 2.3 + 7761 \times (0.46 - 0.37)$	-\$120	-\$18,596,187
Tribal	$\hat{\beta}_A \times \overline{N}_A \mid (Tribal = 1) = 232.3 \times 4.4$	\$1,017	\$173,871,756
All Parcels			**\$733,572,301**
Panel B: Conversion to Fee			
All Parcels	$(\hat{\beta}_A - \hat{\beta}_F) \times \overline{N}_A = (232.3 - 36.0) \times 8.05$	\$1,580	**\$806,838,105**