ABSTRACT

Title of dissertation: ESSAYS ON REGULATORY UNCERTAINTY & ENERGY DEVELOPMENT IN THE AMERICAN WEST

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This dissertation undertakes an analysis of regulation in the American West, investigating the effects of expropriation uncertainty and technological change in the leasing process.

The first chapter explores the possible expropriation of drilling rights due to the addition of the sage-grouse under the Endangered Species Act. Leveraging prior decisions of the US Fish and Wildlife Service, I estimate there was a 52.6% chance the sage-grouse would be listed. Using the real-options framework of Kellogg (2014) and constructing an extension of his simulation to accommodate expropriation risk parameterized by real-world drilling data, I find that developers are expected to delay spudding wells to wait out the uncertainty. This result is corroborated with a Cox proportional hazards model. Additionally, using a difference-in-differences model I find robust evidence that developers reduce their bids for leases commensurate with the expected reduction in profits from possible regulation, and using a conditional logit discrete choice model I find evidence that firms abandon core sage-grouse habitat. Lastly, I find no evidence that developers increase the extraction rate of drilled wells.

The second chapter investigates expropriation risk in the context of ozone pollution controls from the Environmental Protection Agency. Here, I find a hurry-up-and-drill response. I place this result within the literature of the green paradox, and find that the EPA

regulation did not produce a green paradox but if costs were lower, or if the regulation were modified, a green paradox would have existed and briefly result in higher emissions under a stricter regulatory regime. The policy takeaway is that regulators should avoid a long announcement period, as it gives developers time to drain wells before regulation occurs.

The third chapter is a cost/benefit test of auctioning drilling leases online rather than in-person. I leverage the fact that only specific leasing jurisdictions transitioned to an online system called EnergyNet in late 2016 to estimate the causal effect of moving to online leasing. I estimate that a given parcel sold online versus in-person will generate 40% higher bids against only a 2% extra cost.

ESSAYS ON REGULATORY UNCERTAINTY & ENERGY DEVELOPMENT IN THE AMERICAN WEST

by

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Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2021

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Dedication

Dedicated to my parents Ken and Paula and my brother Adam for giving me the genetic makeup and work ethic necessary to complete this dissertation. They mean more to me than anyone in the world.

Also dedicated to my DC family of Keith, Matteo, and even Ajax for putting up with me while I completed this work.

Acknowledgments

Of course, my first round of thanks goes out to the members of my committee, who have provided invaluable advice and help throughout the dissertation process:

Dr. Joshua Linn, my adviser and committee chair, deserves significant recognition simply for taking me on as an advisee. He also gave me needed pushes at the right time to make sure this work was done and was instrumental in the design and structure of this paper. His experience was vital in forming arguments that are in the "language" of fellow economists.

Dr. Mary Zaki has been with me the longest, having been my adviser and research manager when I first joined the department in 2015. She believed in me even when I didn't believe in myself and helped me through a lot of trials in graduate school. She comes up with good ideas faster than any economist I've met and has used that skill to help me identify what is and is not a good idea to pursue.

Dr. James (Jim) Archsmith should be thanked by the entire department for his efforts assisting graduate students. His assistance can be found throughout this dissertation, but he must be specifically commended for his assistance in the first chapter, in which he significantly improved the theoretical model and gave me the idea of how to estimate listing risk likelihood.

Dr. Louis Preonas rivals Jim in his contributions to the graduate students and has always been immensely helpful to me. He provided more helpful comments to me at seminars than anyone else, and those comments directly made their way into the first and third chapter of this dissertation.

Lastly, Dr. Maureen Cropper has always been a positive force in my studies. Her class on valuation and cost/benefit analyses directly informed the last two chapters of this dissertation and was one of my favorite classes in graduate school. I am honored to have such an accomplished researcher on my committee. I very much appreciate her agreeing sight-unseen to serve as the Dean's Representative for this dissertation.

Outside of my committee, others in the department who have been especially helpful to me include my cohort of Dave, Han, Julian, Tianqi, Tina, and Yujie. Several other students have also contributed ideas that found their way into these papers, including Aldo and Alex, but special recognition must be made for fellow oil leasing scholars Dan and Lauren, who will be turning in superior dissertations on similar topics in the coming years.

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Chapter I

Introduction

The energy development industry is well-versed in uncertainty, as drilling for oil and gas is an inherently risky business with no guarantee of rewards. Although not as front of mind as production potential or price volatility, regulation is a primary risk to energy producers. The possibility government regulators intervene in markets to protect consumers or the environment can be just as threatening to producer profits as a dry well or collapsing prices. This dissertation considers two examples of government regulation of the energy development industry in the American West: expropriation of drilling rights by regulators and the method through which state and federal offices auction exclusive leases to explore these public lands.

Expropriation - the act of a governing body taking private property by force or decree - is an uncommon occurrence. Most examples of historical expropriation in otherwise capitalist societies concern foreign-owned extractive industries, such as the nationalization of oil companies during the 1970's and early 2000's Melek (2018)[45]. While it is difficult to think of examples of expropriation in developed nations other than small-scale eminent domain action and the seizure of productive capital during wartime, there have been numerous instances of environmental regulations that inherently expropriate property and/or development rights already granted to the energy development industry. In this sense, industries in developed countries like the United States are subject to expropriation of private property as well.

Expropriation of extraction rights has the important quality of being inherently uncertain and rarely sudden. There is typically an extended period during which rulemakers solicit feedback or plan the expropriation process. While the regulator conducts their review, firms are stuck in limbo waiting for a decision. In this intermediate period, the firm is subject to considerably uncertainty, and must weigh this uncertainty when making investment decisions. There has been little inquiry into the effect of regulation on energy developer behavior before the regulator's decision is complete.

This 'announcement' period between the time when expropriation is first considered a possibility and its resolution is of critical importance. Mineral extractors behave differently when they know regulation is likely or definite in the future, and adjust their drilling decisions appropriately. Developers may delay making large fixed-investments like spudding a well, which can cost anywhere from 3 from 10 million dollars per well. This practice is called 'wait-and-see' and as Stokey (2016)[58] notes, a wait-and-see reaction is most common when the resolution of the uncertainty cannot be predicted well either in timing or outcome. Conversely, a developer may decide to drill now to pre-empt the regulation, which is characterized as 'hurry-up-and-drill'. This can produce a perverse outcome in which hurried development increases the negative externalities of energy production. This is called the green paradox and has been the subject of a literature of climate change papers since Sinn (2008)[55].

I provide two tests of whether expropriation risk elicits a wait-and-see or hurry-up-and-drill response. The first subject of analysis is the 2007-2015 review of the greater sage-grouse by the US Fish and Wildlife Service (USFWS) in the state of Wyoming. The sage-grouse is a chicken-size bird living in several Western states and was added as a ‘candidate’ for inclusion in the Endangered Species List, which would have mandated Wyoming curtail drilling and extraction to protect the sage-grouse. The second context is the 2010-2018 review of ozone in the Uinta Basin in Utah by the Environmental Protection Agency (EPA). Unexpectedly high ozone readings were found in 2010, which could have triggered drilling or extraction restrictions if high levels were found over several years of monitoring the local ozone concentrations.

Both papers use agent-based modeling (ABM) simulation to model drilling timing and profits based on the real-options literature of Kellogg (2014)[35]. These simulations allow developers to choose whether or not to drill over several periods of the model, and within each period compare the expected profitability of drilling now versus drilling in each future period. Both simulations are nearly fully paramaterized by real-world drilling and meteorological data. Interestingly, simulations suggest that developers in the Uinta Basin drilled faster as a result of expropriation risk, while developers in Wyoming attempted to wait out the uncertainty. This result is corroborated later in the context of the sage-grouse, in which I use real-world drilling, production, and location data to estimate a Cox proportional hazard rate of 58.0%, indicating that in the case of the sage-grouse, developers really did ‘wait-and-see’.

The difference in results between the hurry-up-and-drill response to ozone regulation and the wait-and-see reaction to the sage-grouse uncertainty is explained by the difference in announcement structure. I find that the fact that the EPA’s ozone regulation had a definitive period of at least 3 years without expropriation occurring is critical in speeding spudding, but the effect is not so large as to create a green paradox in which emissions are higher for some time under regulation than without regulation. The window granted by the EPA regulation - in contrast with the sage-grouse decision from USWFS, which could have come at any moment - is critically important, because it gives developers the confidence that if they drill now they will be able to exhaust the well and cover their costs before regulation comes into effect.

Regulation shapes every aspect of the extraction process, not just the spudding timing decision. Expropriation risk may also affect factors like location selection, extraction rates and movement along production decline curves, and willingness to pay for future extraction rights. This dissertation explores all of these factors in the context of pending sage-grouse expropriation risk, and finds robust results that expropriation risk impacts bid levels in the auctions used to delegate leasing rights. I also find robust results indicating that developers do *not* adjust their extraction paths to bring extraction of already drilled wells forward, consistent with the findings of Andreson, Kellogg, and Salant (2018)[1]. The effect on location selection is less robust, but the preponderance of evidence suggests that there is a movement away from land under expropriation risk to land that is not subject to any uncertainty.

The last aspect I study in Chapter II - the leasing process - is the sole subject of Chapter IV of the dissertation. In this chapter, I conduct a cost/benefit test of conducting the parcel leasing process online rather than in-person. Before late 2016, all leasing outside of the state of Colorado was done in-person, but in the second half of 2016 the federal government as well as some state leasing offices moved to an online system run by the private company EnergyNet. Moving to an online leasing system ostensibly brought in more money per acre for leasing jurisdictions, raising revenues for both the federal government and state budgets. This chapter provides causal evidence that online leasing actually raises revenues, and more than covers the 1.5-2% fee charged by EnergyNet for hosting the auctions. Using a difference in differences model comparing trends in prices from leasing offices that transitioned to an online system to trends for state offices that did not transition, I find a 40% increase in per-acre bids for parcels, far outweighing the cost charged by EnergyNet. The policy recommendation of this paper is that the holdout states that still maintain in-person lease auctions should adopt EnergyNet.

Using the economics and marketing literature spearheaded by Hagiu[23] concerning multi-sided platforms, I investigate the mechanism driving the increase in bids through a variety of tests leveraging information on the bidders and parcels. I find that thicker markets rather than lower search costs is the mechanism causing higher bids. The presence of additional bidders is driving up the price of parcels beyond what would have sold for in an in-person auction. The effect is particularly pronounced in providing a second bidder so that the price of the parcel exceeds the reservation price, which across jurisdictions is only $1 or $2 per acre. Additionally, there is convincing evidence that the extra bidders are high-information corporations rather than low-information winning bidders who may not have the ability to properly discern the value of what they are purchasing, mitigating equity concerns in online parcel leasing.

Chapter II

The Sage-Grouse in Wyoming

1 Introduction

One prominent example of American environmental legislation that has the power to expropriate private property rights is the Endangered Species Act. The ESA mandates rehabilitation of plant and animal species that are designated as endangered, and plays an outsize role in industries with pervasive effects on the environment like mineral development. One such possible case was the greater sage-grouse, a chicken-sized bird spread across 11 U.S. states and Canadian provinces but is concentrated in Wyoming. From 2010 to 2015 the US Fish and Wildlife Service (USFWS) reviewed the sage-grouse as a candidate for inclusion in the Endangered Species List (ESL) in response to a federal judge's 2007 order. Because the sage-grouse is so pervasive across a wide swath of the mineral-rich state, the danger a listing presents to the state's economy is well-known. Over the nearly 8 years between a mandated consideration to list the sage-grouse and the time USFWS declined to list the grouse, the bird could have been listed at any moment, which could possibly cause developers' right to drill to be revoked.

Figure 1: A Sage-Grouse

This ‘pre-listing’ candidate review period is of critical importance to understanding how developers behave under uncertainty, because once the review is complete the species is either not listed or the species is listed resulting in severe limitation of development. Melstrom (2017)[46] considers both the pre-listing review period and the listing period in his study of the the lesser prairie chicken and oil and gas well placement in Kansas and Oklahoma. Using a discrete choice framework in which prairie chicken habitat is interacted with different steps of the listing process to determine how expected and actual listing of the lesser prairie chicken affected well locations, Melstrom finds little evidence that energy producers switched development to non-habitat, noting a movement of just 4% of wells from habitat to non-habitat due to the listing of the lesser prairie chicken as ‘threatened’ under the ESA.

The Melstrom paper, while valuable as the first study that evaluates how ESA candidate listing affects oil and gas developer behavior, studies only one aspect of the drilling environment. My paper expands upon Melstrom (2017) by focusing not just on *where* firms choose to drill, but also explores the timing of drilling, production decisions, and bidding behavior of developers, and I particularly center the question of development under uncertainty.

Investment under uncertainty is a growing literature, and is especially salient to the question of energy exploration. Kellogg (2014) [35] finds that firms decrease drilling activity in the face of higher price volatility, reflecting the fact that firms are wary of investing in a high-cost well when they are unsure of what future prices will be. Kellogg views the firms' behavior as an example of a 'futures option'. The idea of considering the decision to drill as an 'option' is borrowed from the real options literature, representing the fact that a well is a large sunk cost that may not produce meaningful value. Because costs, prices, and (to a lesser extent) production are uncertain while drilling is irreversible, the optimal behavior is to wait until a particularly favorable drilling environment. However, not all uncertainty is caused by the inherent inability to predict a well's productive capacity, upcoming supply disruptions, or future oil prices. Some uncertainty is caused by government regulators who may distort the market or may put burdensome regulations upon producers. Stokey (2016)[58] presents a theoretical argument showing that in the face of an unresolved regulation firms will delay investments until resolution of the uncertainty. She calls this the 'wait-and-see' policy. The alternative to a 'wait-and-see' behavior in this context could be characterized as 'hurry-up-and-drill'. Rather than a delay of investment, in this alternative mineral developers rush drilling in order to beat a negative ruling from USFWS.

Another paper focusing on regulatory uncertainty and firm-decision making is

Dorsey (2019)[15], who uses a difference in differences (DiD) approach to analyze how power plants located in states exposed to either certainty or an uncertain policy change their behavior. The Clean Air Interstate Rule stupulates that power plants capture sulfur dioxide (SO_2). 4 states challenged the ruling, arguing that due to their geographic location it was unlikely they would increase concentration of SO_2 in neighboring states. While their lawsuit proceeded, it was clear that other states would have to comply with the new policy, while plants in the four challenger states may not have to comply with the more stringent requirements. Dorsey finds that plants located in challenger states underinvest in scrubbing equipment compared to non-challenger states.

Dorsey (2019)[15] provides two necessary conditions for identifying causal effects of regulatory uncertainty:

1. Policy uncertainty is difficult to measure. In the context of the sage-grouse, the applicable question is: What's the likelihood the sage-grouse was going to be listed by USWFS?
2. In most cases, all firms in an industry or country are simultaneously exposed to policy uncertainty, so establishing a credible comparsion group or counterfactual is difficult. In the context of the sage-grouse, the applicable question is: What would have happened in sage-grouse territory in the relevant time period without the uncertainty?

I believe my work adequately answers both questions. I measure the causal effect of the potential listing of the sage-grouse on oil development in Wyoming, the state most at risk due to the large local energy industry and the fact the state houses most of the world's remaining grouse. Using prior candidate review decisions of USFWS, I estimate that there was a 53% chance - effectively a coin flip - that USFWS was going to list the sage-grouse. I use this finding along with other local market conditions to calibrate a statistical simulation measuring the timing, extraction, and profitability of wells under exproproation uncertainty.

I derive theoretical conclusions using the optimal stopping work outlined by Stokey (2016)[58] and Kellogg (2014) [35] and methodologically follow the spatial and temporal DiD framework used by Dorsey (2019)[15] in his attempt to measure the impact of uncertain enforcement of the Clean Air Act. Moreover, the uncertainty in both papers was caused by the federal court system, although the ultimate arbiter in the case of the sage-grouse is FWS. Exploiting the fact that only sage-grouse habitat as defined by the USFWS and the state of Wyoming was at issue for a listing, I also use regression analysis of real-world well-specific production and drilling data and parcel lease auction data in Wyoming spanning 2001-2018, which account for years before, during, and after the uncertainty.

Using a difference in differences model (DiD), I compare the change in both spudding and well completion timing for wells located in core and non-core sage-grouse habitat. I show that developers responded to the candidate review consistent with economic theory given the constraints in production decisions inherent in the oil industry. Difference in differences regression comparing the before/after time periods of wells and parcels located inside and outside sage-grouse habitat show that developers delay drilling when faced with uncertainty, but are unable to speed up extraction of already drilled wells to beat the regulators' decision. Concerning the timing of drilling, I estimate a hazard ratio of 57.6%, meaning that during uncertainty developers are only about half as likely to drill each period than under a regime without expropriation risk. Additionally, firms discount the value of future development by 48% under the 50/50 chance of losing the right to drill sometime in the future. These empirical results are consistent with my simulation as well as recent research, and are robust to alternative specifications. Further, the statistical simulation finds that the vast majority of lower profitability is due to expropriation of drilling rights, rather than delayed well drilling or wells that are never drilled at all due to uncertainty.

This paper contributes to our understanding of energy investment under uncertainty, specifically existential threats to business stemming from government regulation and expropriation of property rights. These issues are becoming more common as consumers and voters demand more of energy producers, and there is a movement towards keeping mineral resources "in the ground". My work provides another example of the 'wait-and-see' models developed by Stokey (2016)[58] and extends Kellogg's (2014) [35] work of these models in the field of energy development, showing that threat of government regulation motivates firms to delay spudding and completion of wells in the same manner as price uncertainty. My paper also serves as valuable support to the idea that firms are unable to adjust the rate of extraction, which remains an unresolved issue with prior studies split on the issue. I also contribute to the nascent but growing literature using oil & gas production microdata to glean insights into energy developer's behavior, and have consolidated a unique dataset that can be used for other work on the Wyoming energy market.

As mentioned above, beyond the timing of drilling, regulatory uncertainty might also affect the *speed* of extraction. Hotelling (1931)[30] provides that if extraction costs are negligible, the price of an exhaustible resource rises with the interest rate and the resource owner will extract the natural resource at the socially optimal rate by shifting production from period to period to maximize the net present value of the resource. In the case of a future expropriation event, a well operator would speed up extraction if expropriation were suspected. Based on the predictions from his purely theoretical model, Long (1975)[42] shows that oil firms facing nationalization speed up the production of liquid minerals. Firms increase extraction rates to 'beat' the regulator. In the face of a possible upcoming negative regulatory regime, the operator spurs extraction in the interim to take advantage of the current favorable regulation. By speeding extraction, the operator is effectively maximizing the present net value of his already-drilled well. The Long paper is especially germane to the case of the sage-grouse. While nationalization of the oil industry and a listing of an endangered species under the ESA are very different drilling environments, their impact on developers is the same: developers could lose the ability to drill and extract.

While the theoretical result that firms speed extraction under expropriation uncertainty is consistent, empirical analyses have come to starkly different conclusions concerning whether developers speed development under uncertainty. The only empirical analyses of expropriation other than Melstrom's work on well location comes from studies of the Venezuelan oil nationalization of 1975. Melek (2018)[45] and Portillo (2016)[49] find that the 'pre-announcement' period, in which nationalization was not officially planned but widely expected, caused faster extraction of liquid oil reserves by developers to beat the announcement. However, recent empirical studies concerning whether developers speed production during high price regimes and slow extraction during low price regimes have called into question whether developers even have the physical ability to adjust rates. Anderson, Kellogg and Salant (2018)[1] find that Hotelling's prediction does not match the data; developers do not seem to be impacted by price or cost concerns at all. Instead, once a well has been completed, firms extract the maximum allowable amount each period as constrained by the pressure remaining in the well. Anderson, Kellogg, and Salant (2018)[1] show that extraction rates are purely a function of well mechanics, rather than market environment, while drilling decisions are dictated by market prices. They liken oil production to a 'keg-tapping problem' rather than a 'cake-eating problem', alluding to the fact that the operator is simply deciding when to drill and cannot control how much is extracted (eaten) per period: "Extractors in our model choose when to drill their wells (or tap their kegs, per our analogy above), but the maximum flow from these wells is (like the libation from a keg) constrained due to pressure and decays asymptotically toward zero as more oil is extracted".

A similar result is found in gas extraction by Newell, Prest, and Vissig (2016)[48], who analyze three key stages of production of Texas gas wells: initial investment (spudding), completion (time when the well actually starts producing), and production (the rate of extraction post-completion) in response to price changes. The authors speculate that horizontal and/or fracked wells would elicit a stronger price response on all dimensions than conventional wells because of the perceived greater control operators have over new unconventional wells, suggesting that the technological improvement of fracking may increase observable responses to uncertainty. Instead, they also find that the fixed investment is the only dimension that firms can adjust. They do not find that firms can extract gas faster, or complete wells faster to enter the production phase quickly to take advantage of favorable prices.

As noted above, the results of my empirical analysis of extraction rates suggest that developers cannot adjust extraction rates once a well is drilled, placing my work in agreement with Anderson, Kellogg, and Salant (2018)[1] and Newell, Prest, and Vissig (2016)[48]. Section 6 provides an explanation of why Melek (2018)[45], and Portillo (2016)[49] interpret their results as an indication firms speed extraction, whereas in actuality they do not have the ability to do so. My conclusion is that this is caused by their data, which is annual, nationwide data, rather than discrete, well-specific data used in Anderson, Kellogg, and Salant (2018)[1] and Newell, Prest, and Vissig (2016)[48] and this paper.

Anderson, Kellogg and Salant (2018)[1] and Newell, Prest, and Vissig's (2016)[48] conclusion that drilling timing is the key choice variable of energy developers facing uncertainty puts their research in the nascent but growing literature of fixed investment under uncertainty, which plays such a large factor in any oil & gas drilling decision because modern oil wells cost $3-10 million[1] and cannot be undone once finished.

The rest of the paper is organized as follows. Section 2 provides a robust overview of the drilling environment to give the reader the necessary background to understand the interplay between government regulation and drilling in Wyoming, including an original analysis showing that the sage-grouse had an approximately 50/50 chance of being listed under the Endangered Species Act, making the species an ideal candidate to analyze regulatory uncertainty. Section 3 provides a brief dis-

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[1] http://www.buffalobulletin.com/news/article_139d34f8-4c78-11e3-97dd-001a4bcf6878.html, https://www.roseassoc.com/the-current-costs-for-drilling-a-shale-well/

cussion of the theoretical conclusions that are applicable to this case, and includes an overview of a simulation exercise meant to elucidate the theory and provide a comparison to the empirical results. Section 4 describes the source and structure of the data used in this paper, as well as work I performed to ready the data for analysis. In Section 5, I replicate the Melstrom (2017)[46] conditional logit discrete choice model of well location and find evidence that firms avoided habitat subject to uncertainty, preferring to drill in sections without uncertainty. Section 6 concerns my Cox proportional hazards tests showing that firms delay well completion due to sage-grouse uncertainty, and also DiD regressions showing that they do not increase the rate of extraction. Section 7 includes DiD models finding a decrease in auction bid values commensurate with lost expected revenues due to regulatory uncertainty. Section 8 provides concluding remarks. There are also two appendices: the first provides details on the simulation of Section 3 and the second provides alternative models of the regressions in Sections 6 and 7 as well as extra robustness checks.

2 Policy and Institutional Background

2.1 Drilling Environment

Being a Western state, the federal government is the top landowner in Wyoming, with 46.7% of state lands managed by the Bureau of Land Management (BLM), the National Park Service, and the United States Forest Service[2]. The state itself owns another 7.2% of land in Wyoming[3].

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[2] https://fas.org/sgp/crs/misc/R42346.pdf

[3] https://wgfd.wyo.gov/Public-Access/Access-Summary

When considering drilling for oil and gas, well operators need to pass several regulatory hurdles before drilling can begin. First, the operator must hold the exclusive right to drill on a parcel of land, which is delegated by a lease. This exclusive right is auctioned off by state and federal agencies or is sold by a landowner if the land is privately held. Leases obtained from the state of Wyoming receive a 5 year 'primary term' (10 years for federal parcels) in which the operator is granted the sole right to drill[4]. Firms use these five to ten years to test for mineral accessibility. If the well is drilled and begins producing within the primary period of the lease, the operating firm retains the ability to drill until the pool is emptied, which is called the 'secondary period'[5].

However, each well requires its own permit to drill, which is granted by a state-level governing body following the submission of an APD (Application for Permit to Drill). The APD process includes a rights-of-way analysis and surface use permits check to confirm the applicant has the legal right to drill. It also may include an environmental review, in which the governing body confirms that the proposed drilling does not run afoul of any local, state, or federal laws concerning environmental/wildlife conservation efforts or water quality protections. All Wyoming-state APDs are subject to this environmental review process, and regulations involving the sage-grouse are arguably the most significant aspect of the environmental review. In Wyoming, the governing body is the Wyoming Oil and Gas Conservation Commission (WOGCC), a department based in Casper to ensure the state's mineral wealth is used for the benefit of Wyoming citizens. If the state approves an APD, the firm has the right to begin drilling. See Table 1 for a succinct checklist of the

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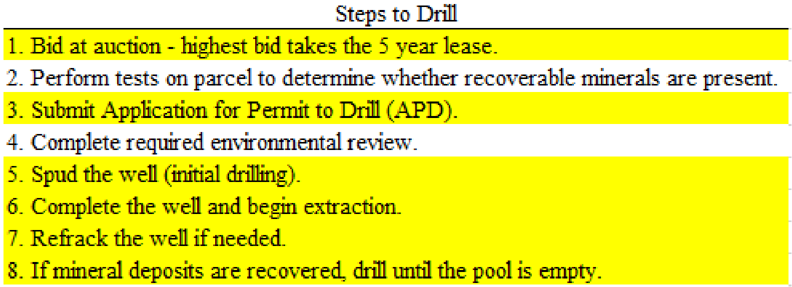
[4] https://frascona.com/sign-oil-gas-lease-long-will-last/

[5] A sample lease from the state government can be viewed here: http://slf-web.state.wy.us/mlease/samplelease/oilandgas.pdf

Table 1: The Extraction Process



Steps to Drill
1. Bid at auction - highest bid takes the 5 year lease.
2. Perform tests on parcel to determine whether recoverable minerals are present.
3. Submit Application for Permit to Drill (APD).
4. Complete required environmental review.
5. Spud the well (initial drilling).
6. Complete the well and begin extraction.
7. Refrack the well if needed.
8. If mineral deposits are recovered, drill until the pool is empty.

steps needed to drill in Wyoming on state leases. Highlighted steps are evaluated in response to regulatory uncertainty at some point in this paper.

The study of regulation in Wyoming oil & gas markets are relatively numerous due to the importance of the energy industry in the state and the relative abundance of Wyoming drilling data. A paper by Lewis (2015)[40] uses the setting to evaluate the impact of government policy. He finds that extra federal regulation incentivizes firms to expand exploratory drilling on state land instead of federal land, as parcels near federal land presumably have similar productive capacity but have lower costs and regulation impeding development. Piggybacking off Lewis's paper, a preliminary study by Edwards et al (2016)[17] also looks at the Wyoming oil & gas market. They find that private and state land production and drilling is more responsive to price changes in fossil fuels.

2.2 The Sage-Grouse in Wyoming

There are currently approximately half a million remaining sage-grouse, down from a population of 16 million in the early 19th century[6]. Wyoming is home to

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[6] https://www.audubon.org/news/trump-administration-moves-open-sage-grouse-strongholds-oil-and-gas, https://www.eenews.net/landletter/stories/83743/

54% of all sage-grouse in the world[7], making it far and away the epicenter of the endangered listing debate. Loud noises from drilling frighten the grouse, causing them to scatter from their leks (groups formed for mating) where they can easily be picked off by predators[8]. Although noise is most prevalent during the initial drilling stage of oil & gas extraction, there is significant noise throughout the entire extraction process, mainly from trucks servicing the rigs. Blickley, Blackwood, & Patricelli (2012)[5] played simulated drilling and vehicular regular servicing noise around leks in western Wyoming. The level of lek dispersion was significant from both types of noise, and was actually greater from the regular truck-related noise. Additionally, sage-grouse get their name because they primarily live in and eat sagebrush, which is often removed or even burned when drilling is expanded. A February 2020 meta-analysis comparing the different threats to the sage-grouse, including sagebrush height, residential development, agricultural development, and energy development. Smith & Olsen (2020)[56] found that energy development is the single largest threat to the grouse.

The inherent trade-off between species conservation and economic development under the ESA is a well-studied literature. Brown & Shogren (1998)[7] write that "It is no wonder the Act has proven controversial. Although the benefits of protecting endangered species accrue to the entire nation, a significant fraction of the costs imposed by the Act are borne by private landowners. About 90 percent of the nearly 1,100 species of plants and animals listed as endangered or threatened under the Act are found on private land. The combination of broad benefits and concentrated costs can fan political firestorms." They also state that the ESA is the "most

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[7] https://www.eenews.net/landletter/stories/83743/

[8] http://commongroundrising.org/oil-and-gas-noise/

comprehensive of all our environment laws" and is the example of "one of the most extreme forms of government intervention", because the ESA is one of the few laws with the ability to completely choke off otherwise legal private commercial activity.

Moreover, the 'cost' side of including animals on the ESA is often overlooked. Aufhammer et al (2020)[2] explain that "The federal government maintains that in most situations, its designation of critical habitat has little economic consequence. This stance is repeated in dozens of agency analyses of critical-habitat designation. However, the government's arguments on this point are theoretical, not empirical." In fact, regulators cannot consider costs at all when considering whether or not to list a species under the ESA. Some economists have sought to fill in this gap. Perhaps the most well-studied cost of listing is that borne by home and landowners whose property is now less valuable due to development restrictions on construction and natural resource extraction. Aufhammer et al (2020)[2] find that land under ESA mandate loses roughly at least half its value. Zabel and Patterson (2006)[63] note that the effect of critical habitat designation is not limited to just price level impacts, finding that the critical habitats reduce housing supply by 37% in the long run, and that the effect is homogeneous for all sizes of habitat.

It is hard to overstate how big a threat the sage-grouse is to the state of Wyoming. Contemporaneous news reports write that "[The grouse] is arguably the biggest Endangered Species Act decision in history. At stake is the survival of an iconic bird whose numbers tumbled in the 20th century after settlers mowed down sagebrush with cows, plows and drill pads...The Fish and Wildlife Service's decision will be the most scrutinized ESA verdict since 1990, when it listed the owl as threatened in the Pacific Northwest, decimating the region's timber industry"[9]. Likewise, listing the greater sage-grouse could tie up access to 165 million acres of the West, causing hardship for ranchers, farmers and energy producers. Extractive industries comprise over 20% of the state's GDP and nearly 7% of the workforce. It is by far the largest coal-producing state in the nation[10] and is the eighth-largest producer of both natural gas and crude oil[11]. All of these industries would be de-facto shut down within sage-grouse territory if the bird is declared active on the Endangered Species List. The BLM would not be able to lease sage-grouse habitat, and both the state and the FWS would be required to develop a comprehensive recovery plan that would almost certainly severely curtail if not outright ban drilling on sage-grouse territory[12]. Scott Streater writes that "[A]n ESA listing would force states like Wyoming with substantial sage-grouse populations to adopt sweeping conservation measures that could cripple not only oil and gas activity but all forms of energy development"[13]. While projecting loss of sage-grouse habitat across Western states, Copeland et al (2009)[10] warn that "The economic ramifications of listing species are substantial with estimated costs of recovery plans and their implementation reaching into the multi-millions, if not billions of dollars for wide-ranging species such as sage-grouse." In an indication of how serious the issue is, Copeland et. al note that lease buybacks and even revocation of development rights were a possible mitigation strategy to protect the grouse. Perhaps the most likely outcome is a drilling ban near breeding grounds during mating season (February-June)[14].

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[9] https://www.eenews.net/greenwire/stories/1060019129/

[10] https://revenuedata.doi.gov/explore/WY/

[11] https://www.wsgs.wyo.gov/energy/oil-gas-facts

[12] https://www.fws.gov/endangered/esa-library/pdf/listing.pdf , https://www.eenews.net/greenwire/stories/72272 , https://www.fws.gov/endangered/what-we-do/listing-overview.html

[13] https://www.eenews.net/landletter/stories/83743/

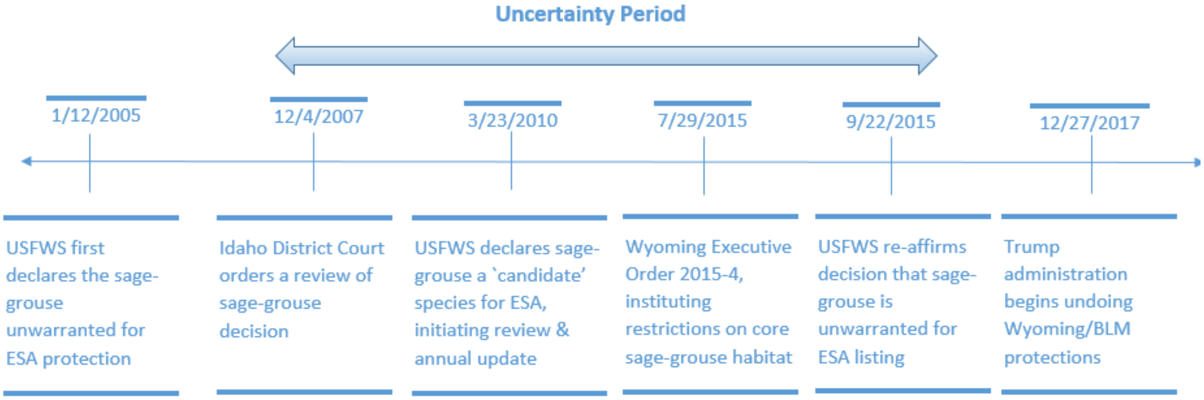
[14] https://www.eenews.net/greenwire/stories/16841/

The effects of a listing would be widely felt throughout the state. Bob Budd, executive director of the Wyoming Wildlife and Natural Resource Trust Fund said that, "If that [listing] happens everybody is affected. If you're a school district, your revenues just went down. If you're a merchant, you're affected. If will affect every business in this state[15]." He references that not only are mineral developers' jobs at risk, but also those who depend on the industry, which include local schools whose revenues are financed by mineral leasing.

The state of Wyoming takes the sage-grouse threat seriously, and its Game and Fish Department (WG&FD) is focused on sage-grouse management, devoting almost $2 million per year to population management and territory monitoring[16]. Dr. Holly Copeland, the lead author of a study projecting sage-grouse populations impacted by mineral development, saluted Wyoming's mapping of sage-grouse territory, as the state was the first to widely and comprehensively map sage-grouse habitat and breeding grounds[17].

2.3 The Sage-Grouse and USFWS

Figure 2: Sage-Grouse Uncertainty



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[15] https://www.wylr.net/wildlife/182-sage-grouse/1750-sage-grouse-core-areas-compromise-private-leases
[16] https://wgfd.wyo.gov/WGFD/media/content/PDF/About%20Us/Commission/WGFD_ANNUALREPORT_2018.pdf
[17] https://www.eenews.net/landletter/stories/83743/

In 2005, FWS declined to add the sage-grouse to the endangered species list, effectively keeping regulations as they were previously. However, on December 4, 2007 a federal judge in Idaho ordered that this decision be reconsidered due to a failure on the part of FWS to consider the 'best science' at hand when evaluating the impact energy development has on the grouse[18]. This prompted a review by FWS on March 23, 2010[19], when the U.S. Fish and Wildlife Service (FWS) declared the sage-grouse a 'candidate species' under the Endangered Species Act.

The immediate effects of being listed as a 'candidate species' can be summarized succinctly: there aren't any. There are no extra protections afforded to candidate species[20], and although they are supposed to be subject to a final decision within a year of being placed on the list, this deadline is rarely met in practice[21].

Instead, candidate species are placed in limbo, and a candidate species could be de-listed or declared endangered at any time[22]. FWS annually publishes the relative priority of different species in their Candidate Notice of Review, rather than move down the list in sequential order of the species being added to the list. More critical species are placed higher on the list, expediting their review. From October 2011 on, the greater sage-grouse was given a listing priority number (LPN) of 8[23]. LPNs are measured on a scale from 1-12, with 1 being the most likely to trigger inclusion

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[18] https://www.eenews.net/greenwire/stories/59554

[19] https://www.eenews.net/landletter/stories/72825

[20] The only new requirement of becoming a 'candidate species' is that the state and BLM would be required to notify FWS of any new development activity occurring on review territory, although FWS would be powerless to stop it https://www.eenews.net/landletter/stories/87950/

[21] https://www.eenews.net/landletter/stories/82028/

[22] In 2014 USFWS agreed to a unique settlement with environmentalists that put a 1-year time limit on a final listing decision. Before that agreement, there was no implicit or explicit deadline for FWS. Additionally, there was doubt as to whether FWS would abide by this timeline even through 2015. See: https://www.eenews.net/greenwire/stories/1060005729/ , https://www.eenews.net/greenwire/stories/1060019129/

[23] https://www.federalregister.gov/documents/2011/10/26/2011-27122/endangered-and-threatened-wildlife-and-plants-review-of-native-species-that-are-candidates-for

on the ESL, and 12 being the least likely. Three factors determine which LPN is given to each species:

1. Magnitude of threat: "Species facing the greatest threats to their continued existence would receive highest listing priority[24]."
   (a) High
   (b) Moderate to low
2. Immediacy of threat: "Species facing actual, identifiable, threats are given priority over those for which threats are only potential or that are intrinsically vulnerable to certain types of threat but not known to be presently facing such threats. In assigning a species to a priority category under immediacy of threat, the Service would consider the known occurrence or lack of documented detrimental trade or harvest, **habitat modification**, significantly detrimental disease or predation, and other present or potential threats[25]."
   (a) Imminent
   (b) Non-imminent
3. Taxonomy: "[Taxonomy] is intended to devote resources on a priority basis to those species representing highly distinctive or isolated gene pools, as reflected by the taxonomic level at which they are recognized. The more isolated or distinctive a gene pool, the greater contribution its conservation is likely to make to the maintenance of ecosystem diversity."
   (a) Monotopic genus

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[24] All quotes in this section sourced from: https://www.fws.gov/endangered/esa-library/pdf/1983_LPN_Policy_FR_pub.pdf

[25] Emphasis my own.

(b) Species

(c) Sub-species

Note that these three criteria are hierarchical in order of importance. Thus, a sub-species facing a non-imminent but *high* threat of extinction would be considered more important than a monotopic genus facing an imminent but moderate to low threat of extinction. Since the greater sage-grouse is not the only species in its genus and USFWS has determined that it is facing an 'imminent but moderate to low' threat of extinction, the greater sage-grouse received a score of 8. This suggests that while sage-grouse population numbers may not be so low as to warrant a top-rating, the species is at a tipping-point, and continued habitat destruction could cause a sudden collapse of the remaining population. This score, along with a short written explanation of USFWS's decision, remained unchanged each year on the Candidate Notice of Review from 2011-2014. The note read, "We consider the threats to the greater sage-grouse to be of moderate magnitude, because the threats are not occurring with uniform intensity or distribution across the wide range of the species at this time, and substantial habitat still remains to support the species in many areas. The threats are imminent because the species is currently facing them in many portions of its range. Therefore, we assigned the greater sage-grouse an LPN of 8." It is common for species with a relatively low rating to remain on the candidate list for up to a decade[26].

Please see Table 2 for a complete table of possible LPNs, ranked in order or priority:

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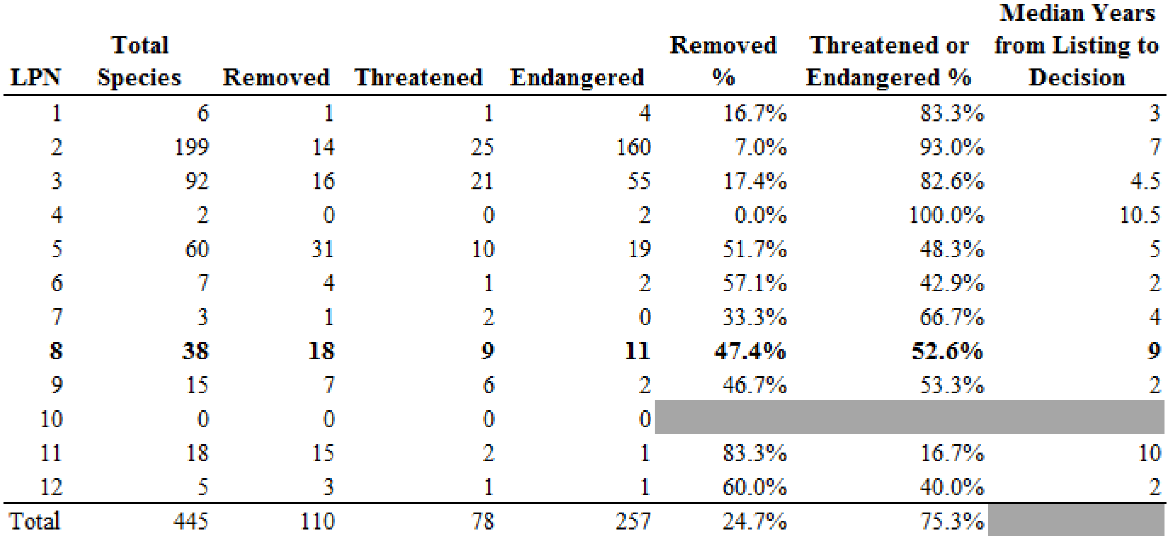
[26] https://www.eenews.net/landletter/stories/87950/

Table 2: LPN Dichotomies

Magnitude	Immediacy	Taxonomy	LPN
High	Imminent	Monotopic genus	1
High	Imminent	Species	2
High	Imminent	Sub-species	3
High	Non-imminent	Monotopic genus	4
High	Non-imminent	Species	5
High	Non-imminent	Sub-species	6
Moderate/low	Imminent	Monotopic genus	7
Moderate/low	**Imminent**	**Species**	**8**
Moderate/low	Imminent	Sub-species	9
Moderate/low	Non-imminent	Monotopic genus	10
Moderate/low	Non-imminent	Species	11
Moderate/low	Non-imminent	Sub-species	12

Of course, this chart says little about the absolute or relative chances that a candidate under review for inclusion on the Endangered Species List is actually listed. One major element of evaluating the effect of regulatory uncertainty is the 'amount' of uncertainty. Generally, it could be assumed that as less information is known about a certain regulation or policy, firms will become even more cautious and further avoid downside risk. However, measuring uncertainty in a systematic, objective way is difficult because there aren't many sources available to quantify uncertainty. Most papers measuring policy uncertainty use financial markets as the source of their variation and measurement, such as Kellogg (2014)[35] and Kelly, Pastor, & Veronesi (2014)[36]. One alternative measurement is Baker et al. (2015)[4], who use the quantity of news articles mentioning some form of 'uncertainty' to generate uncertainty measures and find that their measurement is a good proxy for uncertainty in the economy. Their measurement accurately predicts disinvestment in long-term fixed cost projects. While a financial measurement of oil futures like Kellogg (2014)[35] would be ideal, the focus of my work is too localized to be reflected

Table 3: LPN Summary Statistics



LPN	Total Species	Removed	Threatened	Endangered	Removed %	Threatened or Endangered %	Median Years from Listing to Decision
1	6	1	1	4	16.7%	83.3%	3
2	199	14	25	160	7.0%	93.0%	7
3	92	16	21	55	17.4%	82.6%	4.5
4	2	0	0	2	0.0%	100.0%	10.5
5	60	31	10	19	51.7%	48.3%	5
6	7	4	1	2	57.1%	42.9%	2
7	3	1	2	0	33.3%	66.7%	4
8	**38**	**18**	**9**	**11**	**47.4%**	**52.6%**	**9**
9	15	7	6	2	46.7%	53.3%	2
10	0	0	0	0			
11	18	15	2	1	83.3%	16.7%	10
12	5	3	1	1	60.0%	40.0%	2
Total	445	110	78	257	24.7%	75.3%	

in international oil prices.

I performed an analysis summarizing the reviews of 445 species from 1999-2015 performed by the USFWS. Each year, USFWS publishes its list of decisions made within the prior year and the remaining candidate species, along with its current Listing Priority Number, in the Federal Register. I located these annual reviews from 1999-2015[27] and connected listing decisions to LPNs. If a candidate had a fluctuating LPN[28], I used only the LPN most up-to-date before the listing decision was made. A chart plotting the LPNs against the chance of being listed can be found in Table 3. Note that being listed as 'endangered' or 'threatened' both count as being 'listed' on the Endangered Species List - they are simply different levels indicating the acuity of the threat. While being 'threatened' does not come with as strong legal repercussions as being 'endangered', both categories legally demand a plan to improve the species' chance for survival and would existentially threaten drilling rights in Wyoming, most especially in core territory.

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[27] The review from year 2000 could not be located.
[28] This is uncommon.

Although the chance of being listed does not montonically decrease from LPN 1-12, there is a clear downward trend as a species receives a lower-priority rating. The sage-grouse's annual LPN of 8 corresponds to a 52.6% chance of listing. Contemporary news articles make clear that no one was certain whether the sage-grouse would be listed, matching up with an approximate coin flip's chance based on recent USFWS's listing history. Exploiting this roughly 50/50 possibility of listing gives me the ability to analyze what could accurately be considered 'true' regulatory uncertainty. The sage-grouse being listed for only 5.5 years is short relative to other species under LPN 8, but is in line with species across the LPN spectrum. It is perhaps peculiar that there does not appear to be a meaningful relationship between assigned LPN and the median years from listing to decision, because the 'priority' in Listing Priority Number refers to both the urgency of the threat to the species as well as to how quickly USFWS is expected to resolve its candidate review.

I ran alternative analyses of the listing data to account for the possibility that using all American species is inappropriate. I excluded non-continental species from states and territories like Hawaii, Alaska, Guam, and Puerto Rico, because those areas are disproportionately represented in the data (exceeding 25% of the total species) and may not be strong indicators for the likelihood of the sage-grouse being listed. Removing these species provided an exactly 50% listing percentage for LPN 8, and a 70.8% chance of listing across all species. I also limited the data to only the states harboring sage-grouse populations[29], which eliminated 290 of the

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[29] The states are: Arizona, California, Colorado, Idaho, Montana, North Dakota, Nebraska, Nevada, Oregon, South Dakota, Utah, Washington, and Wyoming.

total 445 species. Among the 17 species with an LPN of 8, 35.3% were listed, while 61.9% of the 155 total species were listed.

On July 29, 2015 the state of Wyoming released Executive Order 2015-4[30], which detailed new protections for the sage-grouse in an effort to head off federal intervention that would shut down energy production across the state. FWS accepted this compromise and declared the sage-grouse did not warrant inclusion on under the ESA on September 22, 2015[31] which was made official on October 2, 2015 [32]. This decision explicitly named the regulations put in place by the state of Wyoming in 2015 as a reason to de-list the sage-grouse. The period between the Idaho District Court mandating a new review and when the sage-grouse was removed from consideration from the Endangered Species List (December 4, 2007-September 22, 2015), forms the basis of my 'uncertainty period', in which there was a high probability that new wells would not be allowed on sage-grouse territory.

Although I am not studying the current effects of the sage-grouse, the battle over its territory continues to this day. After Donald Trump was elected President in 2016, his administration began undoing protections instituted by this agreement[33] in 2018, and the protections afforded to the sage-grouse today look much like they did before 2015. In February 2020, Judge Ronald Bush of the same U.S. District Court of Idaho that required the initial review of the sage-grouse cancelled $125 million worth of leases on sage-grouse territory to protect the bird, with most of the cancelled leases in Wyoming, and mandated that future sales would require an extended comment period[34].

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[30] https://www.wyoleg.gov/InterimCommittee/2019/09-201908288-01LSOSageGrouseIssueBrief.pdf

[31] https://www.doi.gov/pressreleases/historic-conservation-campaign-protects-greater-sage-grouse

[32] https://www.federalregister.gov/documents/2015/10/02/2015-24292/endangered-and-threatened-wildlife-and-plants-12-month-finding-on-a-petition-to-list-greater

[33] https://www.blm.gov/policy/im-2018-026

[34] https://www.nevadaappeal.com/news/government/judge-cancels-oil-and-gas-leases-on-some-sage-grouse-

3 Model & Simulation

3.1 Theoretical Model

3.1.1 Value and Timing of Drilling

When considering the optimal investment time, I start with the basic model provided by Kellogg (2014)[35]:

$$V_{it} = \max_{\Omega} E\left[\sum_{\tau=1}^{\infty} \delta^{\tau-t} I_\tau \pi_i(P_\tau, D_\tau)\right] \tag{1}$$

The valuation problem above can also be expressed as the Bellman Equation

$$V_i(P, D, \sigma) = max\Big\{\pi_i(P, D), \delta \cdot E\Big[V_i(P', D', \sigma')\Big]\Big\} \tag{2}$$

In these equations, the well operator is selecting a time t to drill that maximizes the present value of the well V_{it}. Ω is a decision rule specifying when the well should be drilled as a function of P_t and D_t, which respectively represent the price of oil and the dayrate cost of leasing a drilling rig, discounted by factor δ. Kellogg proves that there is a specific 'trigger' that determines the value of binary variable I_τ providing the optimal outcome of the decision rule each period. As Kellogg notes, the volatility of oil prices (σ) is present in the Bellman Equation but not the profit function because it is a key determinant in optimal drilling timing. Kellogg notes that a firm will not necessarily drill at the first instance in which expected profits of drilling $\pi \geq 0$, because by doing so the firm is losing out on the possibility that prices increase in the future - there is a 'storage value' to waiting.

I expand upon the Kellogg model by adding the impact of the regulator on both

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lands/

valuation (expected discounted profit) and optimal drilling time. When deciding whether to drill, a developer must consider two factors: 1) when a decision from the regulator is expected, and 2) how likely it is that decision will discontinue drilling, making any drilling investment lost past the decision time. I have simplified the equation by assuming a constant likelihood of listing l (firms do not adjust their initial belief of how likely a listing is) and assume that the listing decision time follows an exponential distribution. This implies that the process is 'memoryless', meaning that each period firms expect the decision to be made on average $1/\lambda$ periods in the future if a decision has not yet been made, regardless of what period the developer finds itself in. Adjusting the 'wait' decision of Kellogg's Bellman equation for this consideration results in the following equation:

$$E\Big[V_{i+1}(P\prime, D\prime, \sigma\prime)\Big] = \delta\Big[e^{-\lambda}V_{i+1} + L^0(1-e^{-\lambda})(1-l)\Big] \tag{3}$$

There are two terms in this equation[35]. The first, $-e^{-\lambda}V_{i+1}$, indicates the possibility that the regulator will not make a decision in the next period either, allowing the firm to play the decision game again with the same parameters. The final term, $L^0(1-e^{-\lambda})(1-l)$, represents the value of drilling after a favorable decision in the next period multiplied by the likelihood the sage-grouse is *not* listed. The value of drilling post-decision with no restrictions, L^0, is equal to the discounted profit of future production, or $\sum\limits_{i=1}^{\infty} P_iQ_i - D_i$.

Breaking out Equation 3 into corresponding period-specific values, I consider a mineral developer estimating the value of oil from a given well drilled in the present period t. The well is expected to produce into the future, with future production

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[35] Note that the possibility that the sage-grouse is listed and the right to drill is revoked is not included in this optimization problem because that state holds no value to the developer.

discounted by factor δ. Each period i's production depends primarily on that period's revenues minus costs, or $P_iQ_i - D_i$. I have simplified this expression of period-specific profit to π_i in the equations below.

0. π_0
1. $\delta\Big[e^{-\lambda}\pi_1 + (1-e^{-\lambda})(1-l)\pi_1\Big]$
2. $\delta^2\Big[e^{-2\lambda}\pi_2 + (1-e^{-\lambda})(1-l)\pi_2 + [(1-e^{-2\lambda}) - (1-e^{-\lambda})](1-l)\pi_2\Big] = \delta^2\Big[e^{-2\lambda}\pi_2 + (1-e^{-\lambda})(1-l)\pi_2 + (e^{-\lambda} - e^{-2\lambda})(1-l)\pi_2\Big]$
3. $\delta^3\Big[e^{-3\lambda}\pi_3 + (1-e^{-\lambda})(1-l)\pi_3 + [(1-e^{-2\lambda}) - (1-e^{-\lambda})](1-l)\pi_3 + [(1-e^{-3\lambda}) - (1-e^{-2\lambda})](1-l)\pi_3\Big] = \delta^3\Big[e^{-3\lambda}\pi_3 + (1-e^{-\lambda})(1-l)\pi_3 + (e^{-\lambda} - e^{-2\lambda})(1-l)\pi_3 + (e^{-2\lambda} - e^{-3\lambda})(1-l)\pi_3\Big]$

For each specific period $i > 0$ in the future, the element $e^{-i\lambda}$ represents the probability that a listing decision has not been made. The developer is free to drill without restriction if a decision is still forthcoming.

Summing together all periods from 0 to ∞, the total discounted present value of drilling over all periods (Π) starting in the current period is:

$$\Pi_i = \pi_0 + \delta^t \sum_{t=1}^{\infty}\left(\left[e^{-t\lambda}\pi_t + \sum_{i=1}^{t}(e^{-(i-1)\lambda} - e^{-i\lambda})(1-l)\pi_t\right]\right) \tag{4}$$

Note that there is a double summation in this equation. In any period t, the discounted profit includes both the value of the production that period if a decision has not been made, as well as the expected production dependent on which period the regulator made a listing decision discounted by the likelihood of a favorable regulatory decision. The developer wants to drill on a parcel it considers either unlikely to be listed at all, or not listed for many periods. The developer wants to avoid drilling and then soon have USFWS revoke its right to finish drilling, or curtail extraction so severely that the well is not profitable to operate.

3.1.2 Comparative Statics

Comparative statics concerning the likelihood and timing of the listing decision behave as expected. Increasing the likelihood of listing decreases the value of a well, and reducing the expected time before a decision lowers values as well.

Showing higher likelihood of listing → lower profits is straightforward:

$$\frac{d\Pi}{dl} = \delta^t \sum_{t=1}^{\infty} \left(\left[\pi_t \sum_{i=1}^{t} (e^{-i\lambda} - e^{-(i-1)\lambda}) \right] \right) < 0 \tag{5}$$

Equation 5 is unambiguously negative provided π_t is positive, as the inner summation is a sum of negative values. Thus, increasing the likelihood of listing leads to lower profits.

Likewise, a shorter wait time lowers profits:

$$\frac{d\Pi}{d\lambda} = \delta^t \sum_{t=1}^{\infty} \left(\pi_t(-e^{-\lambda t} t) + \left[(1-l)\pi_t \sum_{i=1}^{t} (i-1)e^{-(i-1)\lambda} - e^{-i\lambda} i \right] \right) < 0 \tag{6}$$

Equation 6 is unambiguously negative provided π_t is positive. The outer summation is unambiguously negative, because the expression $e^{-\lambda t}$ multiplied by a negative number results in a negative number. The inner summation is also unambiguously negative, because the first term, $(i-1)e^{-(i-1)\lambda} - e^{-i\lambda} i$ which simplifies to $-e^{-\lambda}$ because $i = 1$, is always negative. Terms after the first may be positive or negative depending on λ, but their summation will never exceed the value of the first term in the series, $-e^{-\lambda}$[36], ensuring the inner summation is negative as a whole. This relationship holds for any value of λ, including times when $\lambda > 1$ (implying the decision is expected to come before the end of the first period).

Thus, since both the inner and outer summations are unambiguously negative, the derivative is negative and an increase in λ causes profits to fall. This conclusion is logical. λ represents the *inverse* of the expected decision wait time, so a higher λ represents a shorter wait time for a decision, lowering the time in which firms have the ability to operate without obstacles.

3.2 Simulation

3.2.1 Introduction

Using the Kellogg paper as a guide, I ran a theoretical simulation using agent-based modeling (ABM) to estimate how developer behavior changes under the threat of listing activation. Like Kellogg, I am interested in developer profits, but the primary goal of the simulation is to determine how drilling timing changes with a change in the developers legal ability to drill in the future.

The simulation models the role of 2,500 distinct risk-neutral well owners, who determine the optimal time to drill (or whether to drill at all) based on current and future expected market conditions like price, drilling costs, volatility, and drilling regulations. The goal of each developer is to maximize the expected value of the well by drilling at the most profitable time given their contemporaneous expectations of how market conditions will evolve. Despite the operator discounting future

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[36] That is to say, for any λ, t, and i, $e^{-\lambda} > \sum_{i=2}^{t} (i-1)e^{-(i-1)\lambda} - e^{-i\lambda}i$

revenue streams, the optimal drilling period is not necessarily the initial period, because price and cost volatility (and in my work, threat of expropriation) produces a ‘storage value’ that may make waiting for a future period more valuable. For a detailed explanation of the simulation, see Appendix A.

3.2.2 Results

Results match the theoretical predictions - the uncertainty due to the sage-grouse listing is simulated to decrease profits and delay drilling. Specifically, the uncertainty causes a 5.4 month delay in spudding (a 7.8% increase in wait time), a $165,805 loss in expected profit per well (a 30.1% decrease in value)[37], and the average well is anticipated to produce 22,000 fewer barrels of oil (a 42.5% loss) across its lifetime due to restrictions on extraction[38]. Additionally, 2.6% of all wells would have been drilled without uncertainty, but are not drilled under expropriation uncertainty. In the empirical section of this paper (Sections 7 and 6), I compare real-world data from Wyoming to these simulation results. Alternative parameterizations of the model and full results are presented in Appendix A .

4 Data

To estimate the effect listing uncertainty had on drilling timing, extraction rates, and bidding behavior, I used data from Wyoming state government agencies. The Wyoming energy market is studied relatively often by researchers because of the high-quality data available on state office websites. All data used in this paper is

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[37] If only non-dry wells are considered, the loss in profit is $453,405, corresponding to a 48.0% decrease in value

[38] Note that extraction rates per active well remain constant - firms do not ‘speed’ extraction in the simulation. The simulation does not allow developers to adjust or control extraction rates. Initial production and extraction rates are given exogenously.

publicly available at the links provided below in Section 4.1. In order to determine the effect the uncertainty had on these developer decisions, I need information detailing when and where wells were spudded and completed, the monthly rate of extraction of liquid minerals, the individual bids of parcels at auction and where the parcels were located, and geodata on state-defined sage-grouse territory.

4.1 Data Sources

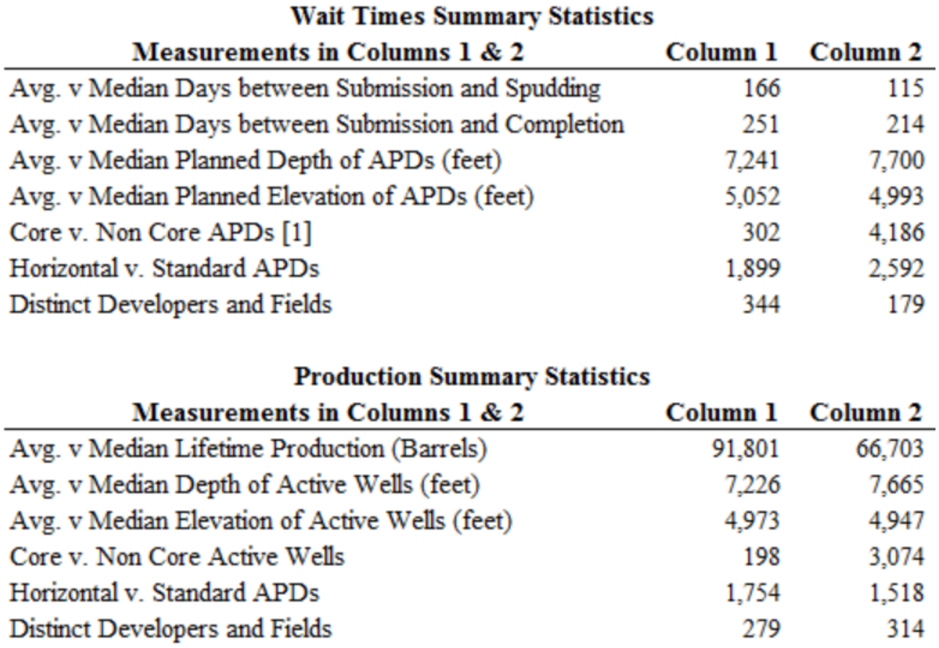
There are three primary data sources used in this paper:

1. Wyoming oil drilling and production data, provided by the Wyoming Oil and Gas Conservation Commission (WOGCC)
2. State and federal lease sales in Wyoming, provided by the Wyoming Office of State Lands and Investment (WOSLI) and the Bureau of Land Management (BLM)
3. Sage-grouse core and secondary territory, provided by the Wyoming Game and Fish Department (WG&FD).

Additionally, I use several other public datasets in my well location discrete choice model based on a similar model from Melstrom (2017)[46]. For this model described in Section 5, I include the following publicly available controls in combination with the primary data sources linked above:

1. Annual population of Wyoming counties for 2000-2009 and 2010-2019, provided by the United States Census Bureau.
2. Sedimentary basin locations, provided by the United States Geological Service.
3. Oil refinery locations, provided by the United States Energy Information Agency

Table 4: Wait and Production Summaries



Wait Times Summary Statistics

Measurements in Columns 1 & 2	Column 1	Column 2
Avg. v Median Days between Submission and Spudding	166	115
Avg. v Median Days between Submission and Completion	251	214
Avg. v Median Planned Depth of APDs (feet)	7,241	7,700
Avg. v Median Planned Elevation of APDs (feet)	5,052	4,993
Core v. Non Core APDs [1]	302	4,186
Horizontal v. Standard APDs	1,899	2,592
Distinct Developers and Fields	344	179

Production Summary Statistics

Measurements in Columns 1 & 2	Column 1	Column 2
Avg. v Median Lifetime Production (Barrels)	91,801	66,703
Avg. v Median Depth of Active Wells (feet)	7,226	7,665
Avg. v Median Elevation of Active Wells (feet)	4,973	4,947
Core v. Non Core Active Wells	198	3,074
Horizontal v. Standard APDs	1,754	1,518
Distinct Developers and Fields	279	314

4. Soil moisture regimes, provided by the Sage Grouse Initiative

4.1.1 Drilling and Production Data

Applications to drill, spud information, and monthly well production data are provided by the Wyoming Oil and Gas Conservation Commission (WOGCC). Any well drilled in the state of Wyoming regardless of the lease landowner (even those on private leases) requires approval from the WOGCC. Fields in the data include API number (the unique identifier assigned to each individual well in the United States), monthly production, lease number, depth, elevation, APD received date, spud date, completion date, land type, oil field location, and the developer's name.

The reader may be surprised to see that the total number of wells (3,272) is 72.9% of the APDs (4,491). This is not meant to suggest that Wyoming has a disproportionate ratio of APDs that turn into wells. Instead, this is reflective of the fact that I am only analyzing APDs submitted from April 2001 through 2018 while I am analyzing any well that was active after 1997 through 2018. Thus, there are thousands of wells included that were spudded before the data begins but still produce oil.

4.1.2 Lease Sale Data

To my knowledge, this is the only study to utilize Wyoming state oil & gas lease sales, and only the second paper to use lease sale data generally after Fitzgerald (2010)[21]. I construct a unique dataset by compiling lease-level data from federal and Wyoming state sources. Federal lease sales listings and results are provided for the Bureau of Land Management (BLM) and run from August 1998-June 2018, available here. State lease sales listings and auction results are provided by the Wyoming Office of State Lands and Investments (OSLI) and run from to April 2003 to July 2018. The state data is available for download here[39]. Fields included are the parcel size, location (Township, Range, and Section), winning developer, winning developer business location, the royalty rate of the parcel, and the date of sale. Township-ranges (TRs) are subdivisions of states subject to the Land Ordinance of 1785, which includes all western states like Wyoming. They functionally serve as latitude/longitude and generally split states into 6-mile by 6-mile rectangles. TRs are used by the BLM and state & local governments as an organizational tool to administer public lands. BLM and state mineral rights auctions provide the location of parcels at the TR, section (1x1 mile subsets of the TR), and lot (irregular subsets of the section) level. The royalty rate of a parcel indicates the percentage of future

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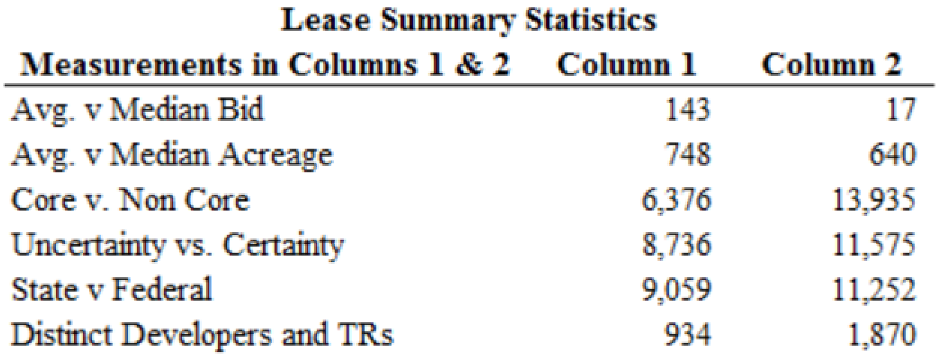
[39] Wyoming has recently released data going back to 1960 if needed, but leases sold before 2003 would require significantly more data cleaning to be rendered reliable.

Table 5: Lease Summary Statistics



Lease Summary Statistics

Measurements in Columns 1 & 2	Column 1	Column 2
Avg. v Median Bid	143	17
Avg. v Median Acreage	748	640
Core v. Non Core	6,376	13,935
Uncertainty vs. Certainty	8,736	11,575
State v Federal	9,059	11,252
Distinct Developers and TRs	934	1,870

mineral revenues that return to the landowner, whether that is the federal or state government.

I programatically inputted standard lease results as best I could, but because of the non-standard format of the data (each sheet of the lease data results are different), most of the lease results were inputted by hand. I spot checked several hundred programatically standardized records for accuracy. I believe I am the first researcher to construct a tabular form of this PDF data, other than Fitzgerald (2010)[21], who analyzed a subset of 57 federal lease sales to determine whether 'split-estate' leases are seen as less valuable by developers.

One gap in the lease data is a lack of any data on the leasing of private lands. Beyond moving from sage-grouse habitat to other parts of the state, there is also the possibility that firms engage private leases instead of bidding on state or federal leases, moving out of the auctions entirely. However, there are several reasons to discount this concern:

1. While it is true that private leases are not subject to all the regulations of state and federal leases, they are by no means immune to sage-grouse rehabilitation

measures[40]. For example, any restrictions on drilling instituted by USFWS if the sage-grouse were declared endangered would also apply to private leases. Thus, private leases are a poor substitute for state or federal leases if mineral developers are seeking to avoid drilling restrictions.

2. Private leases make up an insignificant portion of the overall Wyoming oil market. Only 0.06% of APDs submitted are for private leases[41].

4.1.3 Sage-Grouse Territory

Sage-grouse territory was obtained from the WG&FD and is available for download here, and makes a distinction between 'core', 'secondary', and 'non-habitat' territory that I leverage in analyses. The 'core' territory is the primary habitat of the sage-grouse and serves as their 'breeding grounds'. The process to determine what land is sage-grouse territory, and what territory comprises the breeding grounds, was determined by the WG&FD with the permission of USFWS[42]. Sage-grouse generally live their entire lives within a three miles of their leks, and so conservationists are able to create sharp determinations of what qualifies as sage-grouse territory.

If the sage-grouse were listed as endangered post-review by FWS, it is possible that only the 'core' territory will be impacted, with the 'secondary' territory found unwarranted for extra protection[43]. It is also possible that both the core territory

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[40] https://www.wylr.net/wildlife/182-sage-grouse/1750-sage-grouse-core-areas-compromise-private-leases

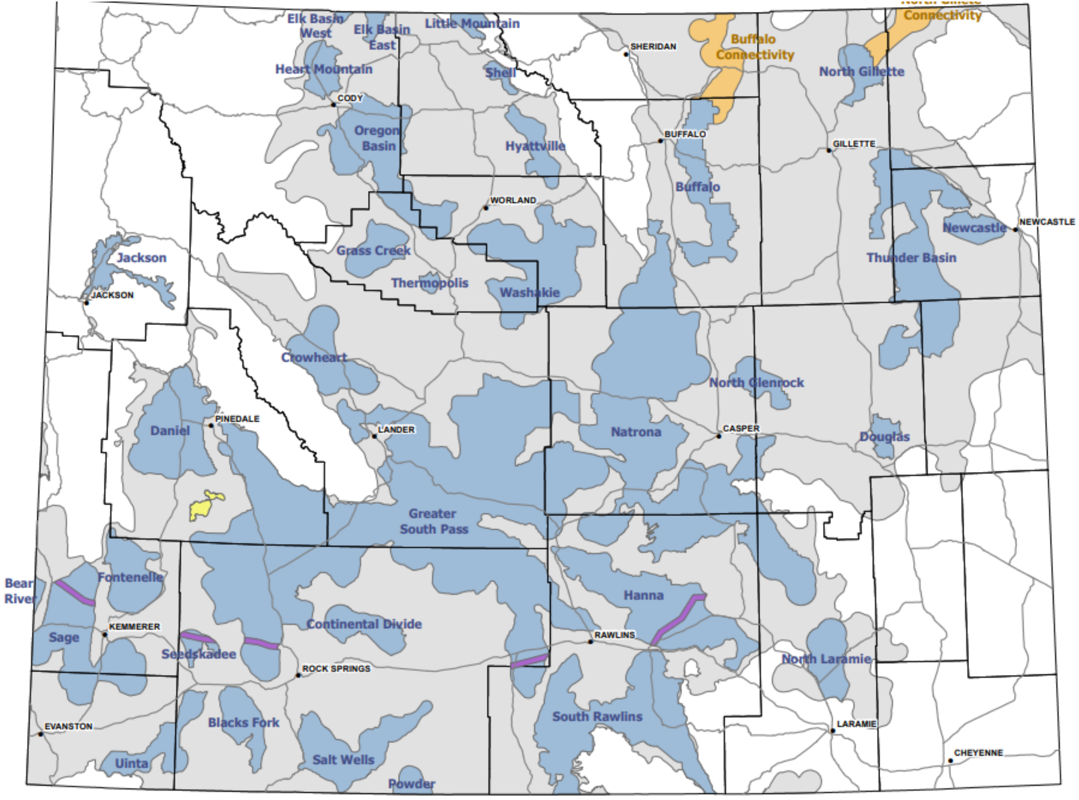
[41] This was identified by searching for 'FEE' in the APD data, which Robert Meyer said would pertain to privately-held parcels. I divided this number (40) by the total number of leases with a lease number (70,940). It is possible that among APDs with no lease number given a significantly higher portion of APDs are in privately-held parcels.

[42] I have not found any evidence that Wyoming manipulated these boundaries for political or economic advantage, and to the extent of my knowledge the core territory represents the precise breeding locations of sage-grouse within the state. Moreover, the location of the sage-grouse appears to be a commonly-known fact among developers and state & federal regulators since at least 2003 (see https://www.eenews.net/greenwire/stories/19724/). The map of core, secondary, and other territory has not changed substantially over time (see this link: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_026366.pdf) for an earlier version of the sage-grouse map.

[43] https://www.eenews.net/eenewspm/stories/88353 , https://www.audubon.org/news/the-greater-sage-grouses-most-important-habitat-auction-block , https://eplanning.blm.gov/epl-front-office/projects/nepa/112234/167289/203768/20190221.Final.20184Q_201902SupplementalSale.EA.pdf

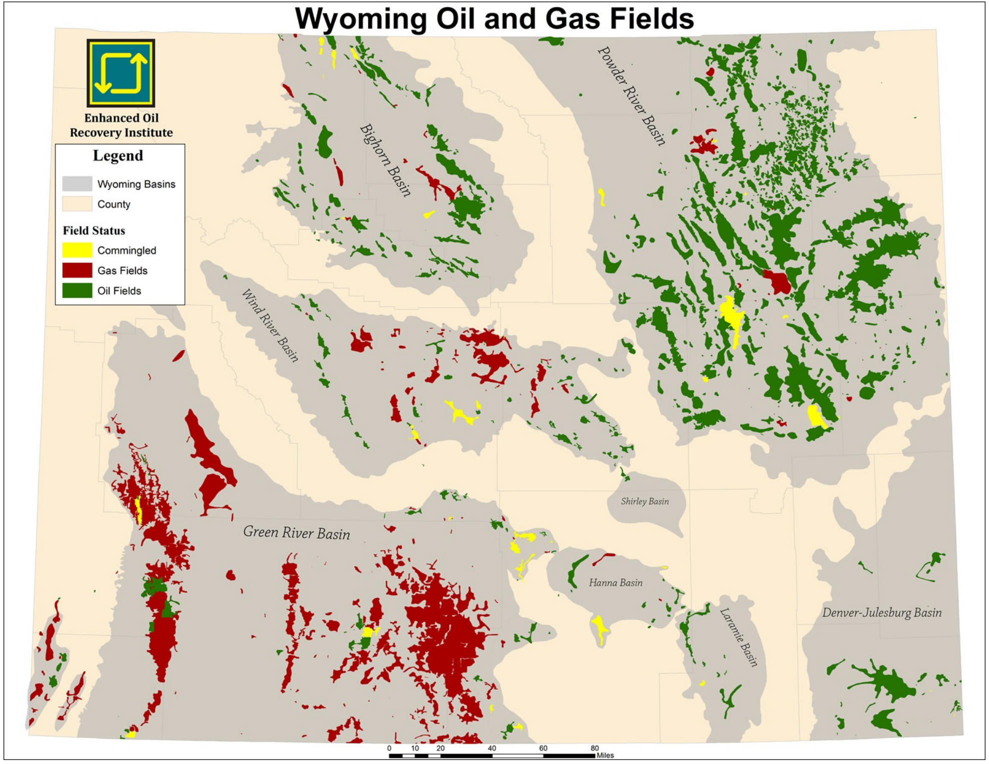
and secondary territory will warrant inclusion for protection. I include a map of core and secondary territory provided by the WG&FD. In this map, ‘core areas are shaded blue, yellow, purple and gold, and ‘secondary’ territory is shaded gray. Note that all ‘core’ territory is a proper subset of ‘secondary’ territory.

Figure 3: Map of Sage-Grouse Habitat



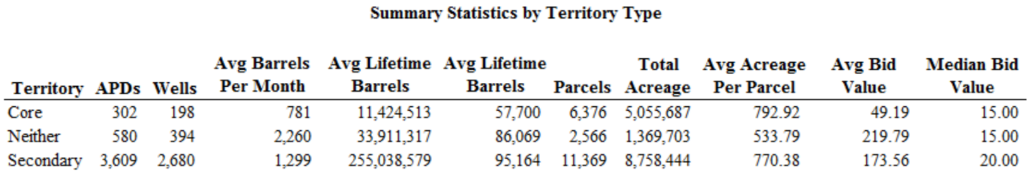
Also of interest is a map of the oil and gas plays in Wyoming, which plots where recoverable minerals can be found:

Figure 4: Map of Wyoming Oil & Gas Fields



There is a high degree of overlap between the sage-grouse territory and the oil & gas plays in Wyoming. This is because the sage-grouse are found in the more hospitable, prairie-like basins of Wyoming, rather than in heavily forested and mountainous areas like Yellowstone Park and Bighorn National Forest. These are also the same areas dominated by oil and gas developers, as they contain more accessible mineral deposits and are afforded fewer protections by the government. This overlap underscores the dire threat to the industry posed by the sage-grouse but does raise the possibility that any analysis will be confounded by the fact that there is virtually no territory that is not sage-grouse habitat but also an oil or gas play. This is the primary reason why my analysis compares core territory to other territory, rather than all sage-grouse habitat to non-habitat.

Table 6: Core, Secondary, and Other Territory



Summary Statistics by Territory Type

Territory	APDs	Wells	Avg Barrels Per Month	Avg Lifetime Barrels	Avg Lifetime Barrels	Parcels	Total Acreage	Avg Acreage Per Parcel	Avg Bid Value	Median Bid Value
Core	302	198	781	11,424,513	57,700	6,376	5,055,687	792.92	49.19	15.00
Neither	580	394	2,260	33,911,317	86,069	2,566	1,369,703	533.79	219.79	15.00
Secondary	3,609	2,680	1,299	255,038,579	95,164	11,369	8,758,444	770.38	173.56	20.00

Table 6 includes APD, production, and leasing data by territory. The relatively low number of monthly and lifetime barrels extracted in core territory does not necessarily suggest that core territory is of lower quality relative to secondary territory. It also reflects a lack of investment in core territory due to uncertainty, leaving a disproportionate number of older and past peak wells. Additionally, there are some drilling restrictions exclusively in core territory, such as extraction being limited in mating season.

5 Well Location

5.1 Conditional Logit Discrete Choice Well Location Model

The similarities in the research setting between Melstrom and I are obvious. Both his study and this paper investigate the effect of the 'pre-listing' uncertainty of a candidate for the ESA on the local energy industry. The central finding of Melstrom (2017)[46] is that energy developers avoided habitat of the prairie chicken in western Kansas and Oklahoma as the likelihood of listing under the ESA became high.

Given the similarity of our research contexts, I replicate Melstrom's work for the setting of the sage-grouse in Wyoming. Melstrom uses a conditional logit discrete choice model of well location, interacting pre-listing time periods with core territory and set of controls. His set of controls includes:

- Population density
- Soil type
- Distance to nearest oil refinery
- Density of natural gas plants
- Whether the parcel is located in a sedimentary basin
- Whether the spudding was during the uncertainty period, which is split into 3 parts based on the updating of the prairie-chicken's LPN

Like Melstrom, I first sample the section (a 1x1 mile square, and 1/36th of a township-range) of all wells drilled in the Wyoming APD data spanning April 2001-2019. Because my research questions concern the oil industry only, I limit the drilled wells to the 4,790 oil wells drilled during my research period. Following Melstrom's methodology, using simple random sampling without replacement I sample 500 sections from Wyoming that are *not* the section selected for drilling to form the alternative options in the discrete choice model. The sampling frame of the alternative options excludes sections from federally managed land that is ineligible for development due to conservation protections[44]. I repeat this process for all 4,790 wells to construct my regression dataset.

I use the same or similar controls as Melstrom to control for factors determining well placement location other than the threat of listing on the ESA. Like Melstrom, I control for whether a section already has seen drilling before the observed spudding,

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[44] Specifically, I exclude sections located in Yellowstone National Park, Grand Teton National Park, Bridger-Teton National Forest, Bighorn National Forest, and Shoshone National Forest.

control for county population density and use county fixed-effects to control for the time-invariant land quality of the section, control for year-quarter to account for contemporary market conditions including oil price, measure the distance from the section to the nearest oil refinery, and I use a map of sedimentary basins to control for whether the well was placed in an oil & gas basin. While Melstrom controls for the land-cover type of the section to compare the agricultural value of the section, I control for the Wyoming soil moisture and temperature regime of the section, which is another stand-in for the agricultural value of a given section. Because I am considering only oil wells, I do not control for the number of gas plants in the section's county like Melstrom does. One significant difference between Melstrom's model and my own is that I cluster my standard errors on season, while he uses lease. As described in detail in Section 6, I do not have access to the lease number of nearly all observed wells.

As provided in Equation 1 of Melstrom (2017), the expected return of choosing section j for a new well drawn from $j = 1...A$alternative sections in my discrete choice model is:

$E[\Pi_{jt}] = x_{jt}\beta + \delta_1 review_t * habitat_j + \epsilon_{jt} = w_{jt} + \epsilon_{jt}$

A developer will select section j for their well for which $\Pi_{jt} \geq \Pi_{kt}$ for all sections $j \neq k$. Assuming IID extreme error values provides a conditional logit model for the probability of selecting any section j for drilling:

$P_{jt} = \frac{e^{W_{jt}}}{\Sigma_{k=1}^{A} e^{w_{kt}}}$

Π_{jt} represents the profit of drilling in section j in quarter t. $Review_t$ is a binary indicating whether spudding occurred during the review period from December 2007-September 2015 and $habitat_j$ is a binary indicating whether the section falls within core sage-grouse habitat. The interaction of these terms forms the key variable in the discrete choice model. A positive coefficient on the interaction term indicates that developers are *more* likely to drill in core habitat during the uncertainty period, perhaps to pre-empt a decision by USFWS or to intentionally engage in habitat destruction to such a low level that preservation of the sage-grouse is not warranted, while a negative cofficient indicates they avoid the core habitat out of fear of losing drilling rights. The vector of controls X_{jt} include the contemporaneous population density of the county section j is located in, whether section j is located in a sedimentary basin, distance in miles from the section to the nearest oil refinery, fixed-effects for the predominant soil type of section j, and county and season fixed-effects.

My primary model excludes wells that are not in sage-grouse breeding habitat but are nearby the habitat. If a firm wanted to drill on sage-grouse territory but was concerned of running into regulatory issues, the firm may simply relocate drilling to just over the border. If that were the case, the difference in treatment effect observed in the model may not be generalizable to the whole state, but could be limited to just the area around the sage-grouse territory. To prevent this possibility, my model is run with a 5-mile buffer. The 5-mile buffer was selected for the base model because it is just wide enough to ensure that any signals gleaned from one well could not be applied to wells outside the buffer distance (see Lewis (2015)[40]].

The primary model is run with several robustness checks in the discrete choice model as well as models used later in the paper:

1. An alternative time period, with the 'uncertainty period' running when the review actually began (March 23, 2010), rather than when the Idaho District

Court mandated a review (December 4, 2007).

2. All data included (removes the 5 mile buffer). I also checked the effect of using 3 and 10-mile buffer zones for the primary specification and received similar results.

3. A 'spatial discontinuity' regression model, including only parcels within 10-miles of the core territory border. This model has the advantage of limiting analysis to reasonably similar plots of land. A 'spatial discontinuity' model is not my main model, because I anticipated it would overstate the effects of the uncertainty for the reason just described: a developer could reasonably expect to have the same chance of hitting oil on a parcel *just* over the sage-grouse border and would activity to that territory.
    (a) Please see Appendix C.2 for an explanation of why I often see *smaller* effect sizes in the spatial regression discontinuity model than the primary model.

While other analyses also provide an alternative with developer controls, the location selection analysis did not converge for that specification.

One weakness of difference in differences analysis is the possibility that results are driven by outlier observations. The reliance of a regression's outcome based on specific observations is called its 'leverage', and difference in differences is particularly susceptible to high leverage observations when treatment effects are heterogeneous across the treated. Young (2019)[62] shows that this effect is pervasive across many DiD analyses in major economics journals by removing one observation and then re-running experimental economics regressions. As Chapters 2 and 4 use difference in differences, an extension of this dissertation would be to use a jackknife procedure to determine how much my analyses are impacted by leverage.

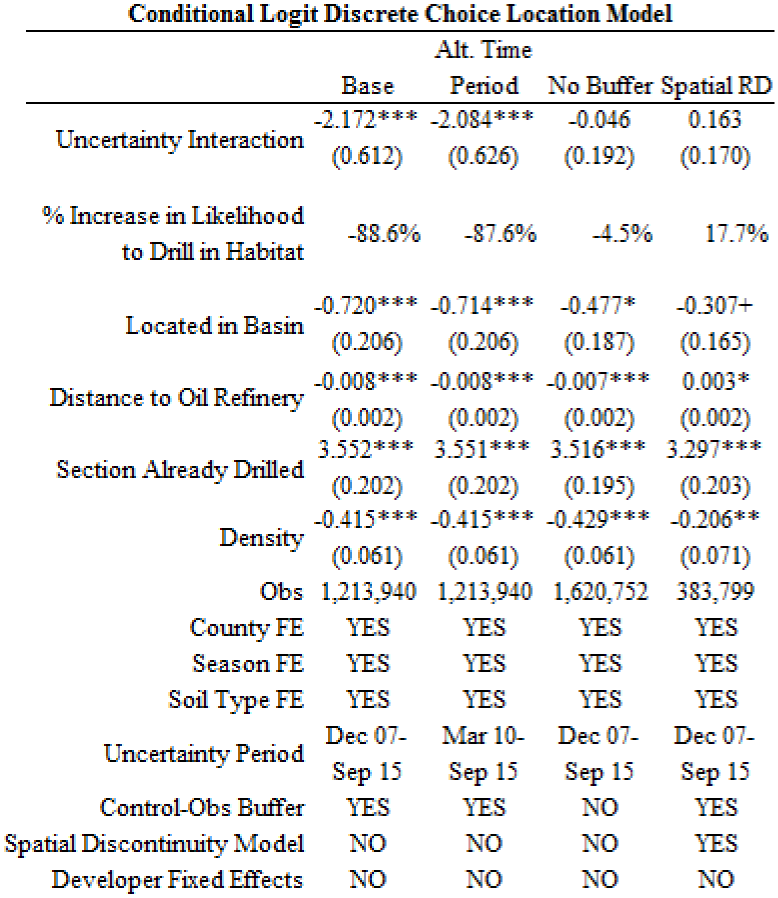
5.2 Results

Melstrom's paper found differing effects of potential listing dependent on time period. During the time period when the prairie chicken was first announced as a candidate for review, USFWS designated the prairie chicken as an LPN of 8, meaning the threat to the prairie chicken was imminent but not gravely serious. This is the same designation received by the sage-grouse through its entire candidacy period. During this period, Melstrom finds weak evidence that developers were actually *more* likely to drill in prairie chicken territory and engage in habitat destruction. Unlike the sage-grouse, the prairie chicken saw a change in LPN in December 2008, when the bird received an elevated LPN of 2, meaning that the prairie chicken was experiencing an imminent *and* grave threat to its existence as a species. Melstrom finds that developers avoided core habitat during this period.

Like Melstrom, I find somewhat ambiguous results from the location discrete choice model. My results differ based on what iteration of the model (base, alternative time period, no buffer, regression discontinuity) is considered.

The primary base model, along with the alternative time period model, provide strong evidence that developers avoided sage-grouse habitat during the uncertainty period. The expropriation uncertainty makes developers nearly 90% less likely to drill in sage-grouse habitat versus other land across the state. Firm conclusions are tough to draw due to the fluctuating ratio of the coefficients to the standard errors,

Table 7: Location Selection Results



Conditional Logit Discrete Choice Location Model

	Base	Alt. Time Period	No Buffer	Spatial RD
Uncertainty Interaction	-2.172*** (0.612)	-2.084*** (0.626)	-0.046 (0.192)	0.163 (0.170)
% Increase in Likelihood to Drill in Habitat	-88.6%	-87.6%	-4.5%	17.7%
Located in Basin	-0.720*** (0.206)	-0.714*** (0.206)	-0.477* (0.187)	-0.307+ (0.165)
Distance to Oil Refinery	-0.008*** (0.002)	-0.008*** (0.002)	-0.007*** (0.002)	0.003* (0.002)
Section Already Drilled	3.552*** (0.202)	3.551*** (0.202)	3.516*** (0.195)	3.297*** (0.203)
Density	-0.415*** (0.061)	-0.415*** (0.061)	-0.429*** (0.061)	-0.206** (0.071)
Obs	1,213,940	1,213,940	1,620,752	383,799
County FE	YES	YES	YES	YES
Season FE	YES	YES	YES	YES
Soil Type FE	YES	YES	YES	YES
Uncertainty Period	Dec 07-Sep 15	Mar 10-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15
Control-Obs Buffer	YES	YES	NO	YES
Spatial Discontinuity Model	NO	NO	NO	YES
Developer Fixed Effects	NO	NO	NO	NO

although the data weakly suggests that firms avoided locating wells in sage-grouse habitat when faced with uncertainty. When compared with the Melstrom results, the case of the sage-grouse provides further evidence that developers rationally respond to the possible loss of extraction ability and pre-emptively avoid drilling in the habitat of potentially endangered species.

Other variables mostly behave as expected. Being located in a section that's already been drilled is a consistent and strong predictor of drilling likelihood, indicating that drilling is spatially correlated due to the high probability that land nearby other drilled parcels also contains oil reserves. Not surprisingly, population density and distance to the nearest refinery are negatively correlated with energy development. There is an unexpected sign on being located in a sedimentary basin, which should be correlated with development as per Melstrom. However, I see a negative relationship between a section being located in a sedimentary basin and oil development in all models[45].

5.3 Parallel Trends

Figure 5 provides the seasonal rate of drilling likelihood by core vs. non-core territory. I have averaged the percent of observations in each season (quarter) and run a LOESS smoothing function through the scatterplot to evaluate a trend. This is not a traditional parallel trends chart because by construction when one group (core or non-core) experiences a higher percentage of sections drilled, the other territory sees a decline. This is why there is a strictly negative correlation between the two lines. However, the lines are not mirror images of one another because there

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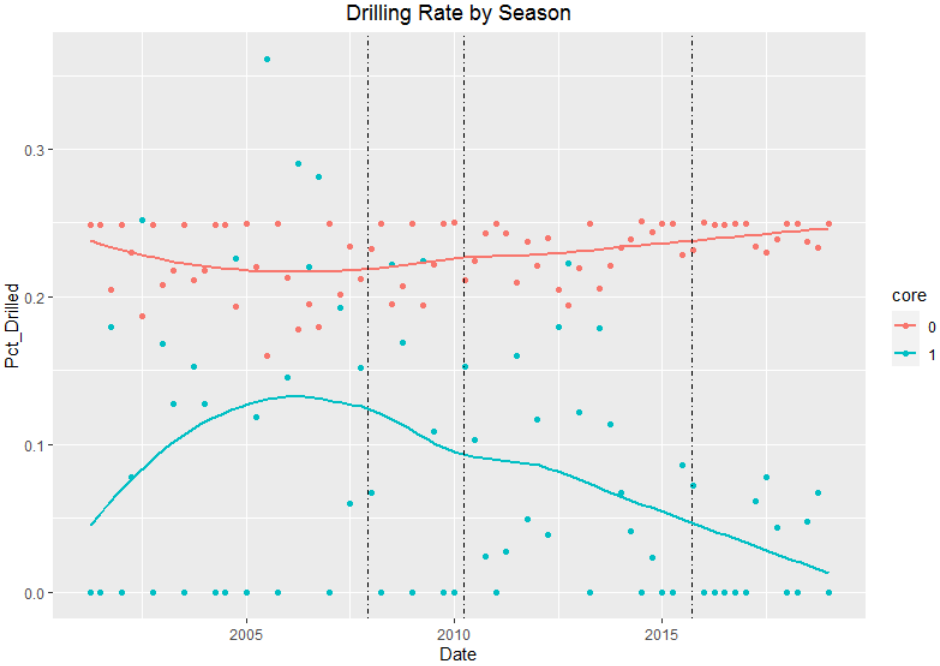
[45] Because of the high number of observations and the high number of sections on which I cluster errors, I was not able to complete this model with an alternative in which developer characteristics are controlled for.

are many more non-core observations than core observations.

Figure 5: Parallel Trends - Location Selection



The codependent determination of the drilling rates complicates a parallel trends story, because by definition the trends cause one another. However, the visual is so stark that there is no doubt that the assumptions of parallel trends does not hold in the *opposite* direction, meaning that if anything the effect in the regressions is understating the true effect. Before treatment in 2007, the rate of drilling in core habitat was climbing while drilling outside of the habitat was declining, and the rates were converging to each other. After treatment, these rates are reversed, and drilling in core habitat collapses. This story is consistent with the regression results.

6 Timing and Speed of Drilling

6.1 Timing of Drilling - Duration Model

To evaluate whether the sage-grouse caused firms to either delay their drilling decisions (the 'wait-and-see' approach) or speed up their plans (the 'hurry-up-and-drill' approach), I utilize a Cox proportional-hazards model to estimate the different hazard rates between core sage-grouse territory and other territory as firms decide when to drill their well. In this section, I evaluate the entire drilling process, which includes both the 'spudding' phase and the initial production phase. 'Spudding' refers to the first moment a drill bit touches the ground, and the intial production of oil is referred to as the 'completion' of the well. Since 'spudding' the well initiates the completion stage, it is the primary choice variable developers adjust in response to price or regulatory uncertainty. Developers optimizing when to spud the well, which represents committing to an investment of several million dollars, must balance the goal of extracting before the regulatory makes a potentially unfavorable decision with the possibility of waiting out the uncertainty to avoid an enormous financial loss.

As Newell, Prest, and Vissig (2016)[48] make clear, the developer could adjust behavior on both the spudding and completion dimensions in response to a price change, making both elements worthy of consideration on their own as well as in tandem. While the primary choice variable is the spudding time, there is also considerable variation in the initial production stage of drilling. Newell, Prest, and Vissig (2016)[48] note that well characteristics like depth and horizontal length are prime determinants of the time from spudding to well completion. Their paper also notes that there are characteristics that can be changed, which would speed or delay the completion. For example, fracking the well increases time between spudding and completing the well. Market conditions also play a factor, with high prices incentivizing operators to spend extra to speed production, while a lack of available rigs or labor will impede completion.

In this sense, uncertainty plays the same role as the ‘high-price’ state, though for different reasons. Developers have an incentive to beat the regulator’s decision, either because they may believe an already-producing well will evade regulation, or to take advantage of a more favorable regulatory regime that could change at a moment’s notice. However, the uncertainty provides another opposing aspect to the optimal completion decision - the ‘storage’ value property of deciding when to spud a well also pertains to the timing between spudding and completion. Slowing completion - for example, by waiting for rig prices to fall and not spending extra to rush production - are ways developers could try to wait out the uncertainty.

Hazard modeling is the same strategy Newell, Prest, and Vissig (2016)[48] used to determine whether firms speed or slow the completion of wells to take advantage of favorable gas price regimes, and is often used in survival analysis modeling. The Cox proportional hazards model provides estimates of what contributes to the ‘failure’ or ‘death’ of a process. In my model, the completion of a well represents this ‘failure’. As mentioned above, there could be a ‘wait-and-see’ or ‘hurry-up-and-drill’ story for both the spudding and/or the completion stages of the process, and my main results represent the entire life-span of the decision from APD submission to completion. In Appendix C I provide the breakout of these decisions separately, rather than the joint process.

The full Cox hazards model equation being estimated is:

$$CompletionDays_w = Season_s + Field_i + Interaction_{w,s} + WellControls_w$$

The well characteristics of well w include:

1. Depth of the well, as well as a quadratic term $Depth^2$
2. Topological elevation of the well, as well as a quadratic term $Elevation^2$
3. A binary indicating whether the well is drilled horizontally
4. The land type of the well

This equation will uncover the hazard rate of completing a well in sage-grouse territory under uncertainty versus the same well being located elsewhere or in a different time period. Because of this structure, the hazard rate represents the chance that a well subject to expropriation threat is completed in the next period (in this case, day) relative to the same well not facing uncertainty, controlling for all other factors.

Dependent variable $CompletionDays_w$ is the number of days between APD submission and well completion. Field fixed-effect i represents a vector of binaries indicating the oil field i containing well w. This fixed-effect controls for the inherent, time-invariant production potential of the area the well is located. Errors are clustered at the field level[46]. The Season fixed-effect controls for market conditions in the oil & gas industries at the time the application to drill was submitted. They are at the quarter-annual level, although yearly and monthly controls produce similar results[47]. The interaction term is the primary variable of interest, and takes

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[46] There is an argument to be made that errors should not be clustered at all, since the 'treatment' of being in sage-grouse territory is not dependent on any specific geography like an oil field. I selected field as my level of clustering to follow Kellogg (2014), who clusters at the field level when performing survival analyses in his study of the Texas oil well market.

[47] Seasons are selected as the primary time controls to better match with the price regressions (Section 6), which have to be at the quarterly level.

a value of 1 when the well w is located within core sage-grouse habitat and the APD is received during the uncertainty period (December 4, 2007 to September 22, 2015). A negative value on this variable indicates there is slower 'failure', and hence less drilling, due to the uncertainty, lending credence to a 'wait-and-see' effect. Conversely, a positive coefficient indicates that firms speed up drilling in order to 'hurry-up-and-drill'.

Ideally, I would measure the amount of time from when a developer obtained a lease through when it spuds the well. This is the complete time between when testing for mineral deposits can commence and when the firm makes the large fixed investment of about $3 million. All APDs in Wyoming are required to submit the lease number the potential well was leased under, but in practice this information is rarely provided and never enforced. Of the APDs the state of Wyoming received, 23.0% were submitted with no lease number whatsoever, and overall I could only connect 7.7% of APDs to a specific lease[48]. Because of the large amount of apparent missingness in the APD and spudding data, my 'wait-and-see' analyses are based on the time between APD submission compared to completion time, as those events do not require joining to the lease data.

While this does create some measurement error in the dependent variable, the error should be limited for several reasons. Because Wyoming is a 'first-to-file state'[49], there is an enormous backlog of APDs[50]. Moreover, due to the the trivial cost of the APD ($500)[51], firms will usually submit an APD immediately upon

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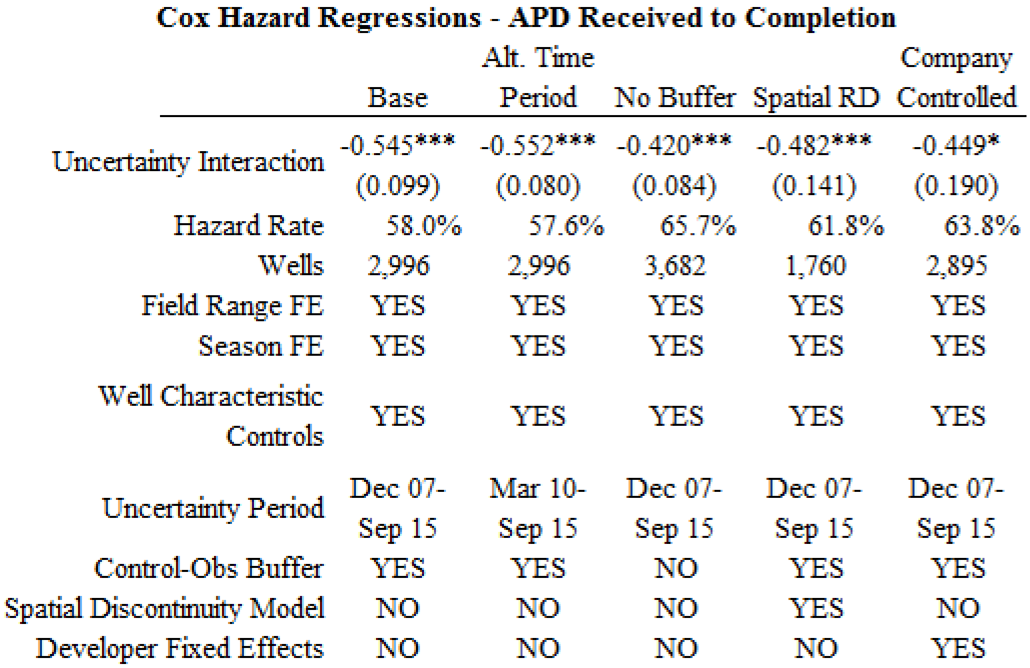
[48] I discussed this issue with Robert Meyer of the WOGC. He confirmed that the lease number is required, but that it is not enforced and sometimes applications do not list which lease number to which the parcel applies.

[49] The first applicant to submit an APD becomes the "operator" of the surrounding drilling and spacing unit (DSU), allowing that individual or company to dictate drilling in the immediate area, see https://trib.com/business/energy/energy-journal-state-regulators-establish-new-drilling-rules/article_b922d8c7-5244-5997-a497-5469bbec2b1a.html

[50] There is a similar APD backlog for the BLM. See https://www.eenews.net/greenwire/stories/1059946951/

[51] https://www.wyomingbar.org/wp-content/uploads/Intro-to-Wyomings-Air-Quality-Division.pdf

Table 8: Drilling Timing Results



Cox Hazard Regressions - APD Received to Completion

	Base	Alt. Time Period	No Buffer	Spatial RD	Company Controlled
Uncertainty Interaction	-0.545***	-0.552***	-0.420***	-0.482***	-0.449*
	(0.099)	(0.080)	(0.084)	(0.141)	(0.190)
Hazard Rate	58.0%	57.6%	65.7%	61.8%	63.8%
Wells	2,996	2,996	3,682	1,760	2,895
Field Range FE	YES	YES	YES	YES	YES
Season FE	YES	YES	YES	YES	YES
Well Characteristic Controls	YES	YES	YES	YES	YES
Uncertainty Period	Dec 07-Sep 15	Mar 10-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15
Control-Obs Buffer	YES	YES	NO	YES	YES
Spatial Discontinuity Model	NO	NO	NO	YES	NO
Developer Fixed Effects	NO	NO	NO	NO	YES

acquiring a lease. No firm wants to be in the position to not be able to drill because they are last in the list of thousands of APDs to review, especially while they are on a 5 or 10 year ‘use it or lose it’ primary term (see: Hernstadt, Kellog, & Lewis 2020 [27]). Wyoming legislators are considering legislation to vastly increase the cost of APDs to disincentivize stockpiling and incentivize firms to focus only on promising wells[52], and in 2019 (beyond the end of my data) Wyoming passed a new directive that nearby potential operators can challenge unused APDs[53]. Because firms submit an APD for a parcel as a matter of routine I consider the *submission* date to be a good proxy for the date the parcel was acquired.

6.2 Results

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[52] https://trib.com/business/energy/wyoming-s-oil-and-gas-permitting-war-sparks-legislation/article_e25886f8-1015-56c9-9121-151a4645e8b8.html

[53] https://trib.com/business/energy/energy-journal-state-regulators-establish-new-drilling-rules/article_b922d8c7-5244-5997-a497-5469bbec2b1a.html

Results from Kellogg (2014) [35], Stokey (2016)[58], and Dorsey (2019)[15] indicate that the ‘wait-and-see’ effect can be significant, and my results lend further support to their conclusion. Results indicate that firms do indeed ‘wait-and-see’ when considering when to drill, rather than ‘hurry-up-and-drill’ to get in as quickly as possible. The hazard rate is consistently negative and statistically significant at the 0.1% level, indicating longer waits to complete a well under sage-grouse uncertainty even after controlling for other factors like land type, oil field, and time period effects. The hazard rate of 58% indicates that at any period, a firm in the uncertainty area is only slightly more than half as likely to drill in the next period as an identical firm outside the uncertainty region. At its face the 58% hazard rate is significantly larger than the 7.8% increase in wait times as predicted by the simulation, but a hazard rate is not a perfect comparison to a levels difference as the measurements are qualitatively different values. Importantly, the differences in both the simulation and the Cox regressions measuring the difference in time between submission and spudding show a statistically significant increase in wait times at least at the 5% level. Additionally, all robustness checks are negative and significant as well, and are similar in magnitude to the baseline model.

A breakdown of this process into its two component parts (APD submission to spudding & spudding to completion), as well as the parallel trend charts, are presented in Appendix C. Also presented in Appendix C are analyses investigating whether firms adjust the design of their wells to account for uncertainty. For example, drilling a horizontal well allows for more flexibility under different future regulatory regimes, but is significantly pricier, exposing the firm to higher potential losses. In another test, I test for whether firms adjust the extensive margin as well

- whether they drill at all. Lastly, I perform a check by splitting developers into large and small categories. If small firms are driving the delay, the 'wait-and-see' may be due to risk aversion, which is not an aspect in either Kellogg (2014)[35] or Stokey (2016)[58]'s models. In the Appendix analyses, I find that:

1. Firms delay *both* component parts of drilling (APD submission to spudding & spudding to completion) by a statistically significant margin, rather than just 1 component.
2. Firms are less likely to drill horizontally/unconventionally under uncertainty (conversely, they are more likely to drill conventionally/vertically).
3. There is no effect on well depth due to uncertainty.
4. Most specifications find that firms are *more* likely to drill under uncertainty. This is an unexpected result.
5. The 'wait-and-see' effect does not appear to be due to risk aversion.

Of these conclusions, the first, that firms delay *both* component parts of drilling (APD submission to spudding & spudding to completion), is particularly important. If only the first component (APD submission to spudding) saw delays, the relationship could be due to the state government holding up approval on core territory or developers undergoing more rigorous environmental reviews[54], rather than representing developers intentionally delaying spudding. Since I see a strong delay in both parts, and in fact the delay between spudding and completion is the more robust and stronger relationship, it is clear that operators are delaying development even beyond what is required of them by regulators.

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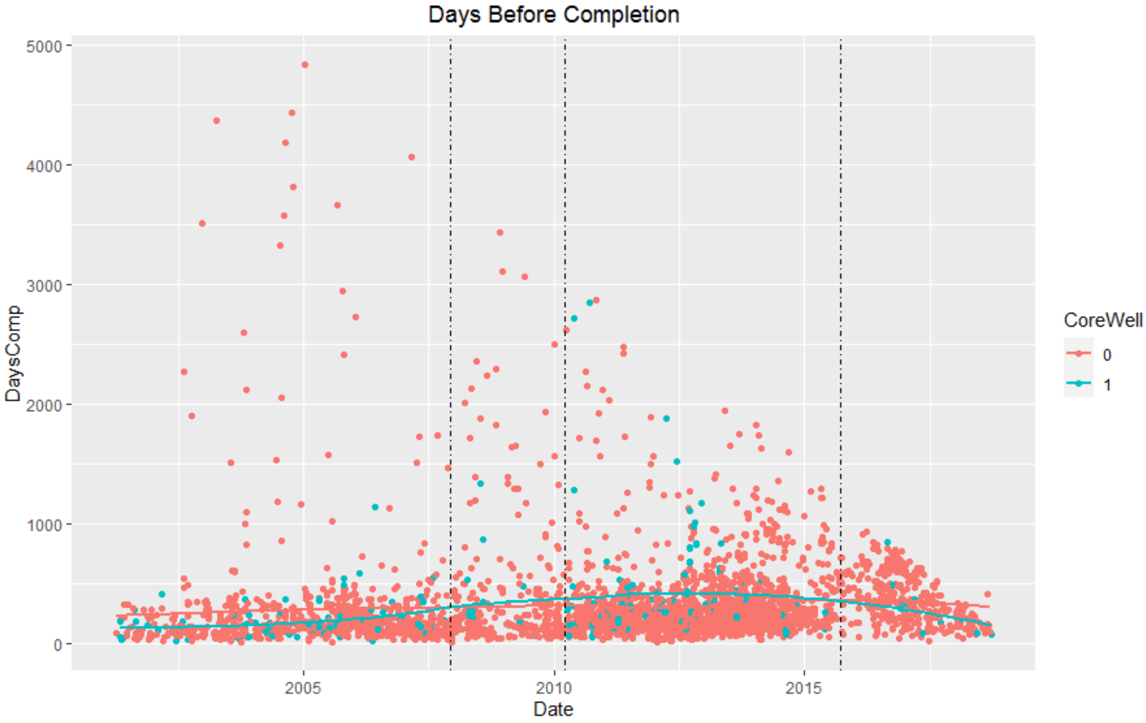
[54] https://www.nrc.gov/docs/ML1108/ML110830533.pdf

6.3 Parallel Trends

The parallel trends charts of the drilling timing models show relatively constant wait times for control observations (non-sage-grouse habitat) and see an increase in wait times for treatment observations (sage-grouse habitat). The drilling timing parallel trends chart is consistent with a story in which the effect of the uncertainty is seen only in the treatment group.

Figure 6: Parallel Trends - Drilling Timing



6.4 Speed of Extraction - Methodology

But what about the rate of extraction itself? While the drilling timing decision is perhaps the most important decision a developer will make, it is not the only dimension the developer could adjust.

To evaluate whether firms 'speed up' extraction, I analyzed wells that were already drilled before the end of 2007 when the expropriation uncertainty began.

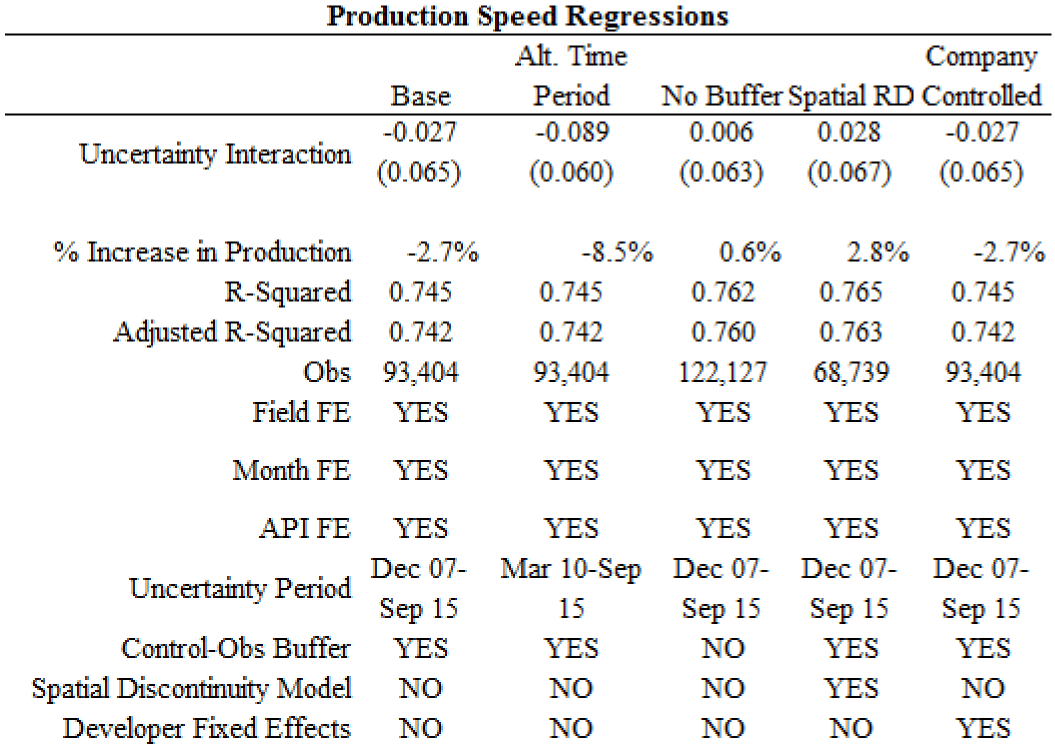
These are wells which are sunk-costs from a drilling standpoint - since they already have incurred the large upfront cost of drilling, the only costs are the (relatively) trivial costs of maintaining a well. They present the ideal environment in which to test the results of 'Hotelling Under Pressure' versus the original Hotelling model, because extraction costs are negligible and developers are faced with an unexpected uncertainty shock.

Controlling for time since original spudding is critically important because regardless of whether firms have any behavioral response or even ability to change extraction rates, the age of the well will be a primary determinant in extraction rates. Since this data series is a panel dataset made of wells w across months m, I control for the inherent productivity of every well through API number fixed-effects. These fixed-effects also control for well characteristics like depth, elevation, and land type. Errors are clustered at the API level. I also include month and field fixed-effects. Month fixed-effects control for oil and gas prices, which will impact production decisions if firms actually have the ability to alter extraction rates (see Newell, Prest, and Vissig (2016)[48]). If developers are able to adjust extraction rates, a high oil price should speed extraction, and a high gas price should slow extraction as they are substitutes. Depth, elevation, and land type are not directly included in this equation because they do not vary along the same API.

$ln(BarrelsExtracted_{i,m,w}) = Age_{w,m} + Age^2_{w,m} + API_w + Interaction_{w,m} + Month_m + Field_i + \epsilon_{i,m,w}$

6.5 Speed of Extraction - Results

Table 9: Production Results

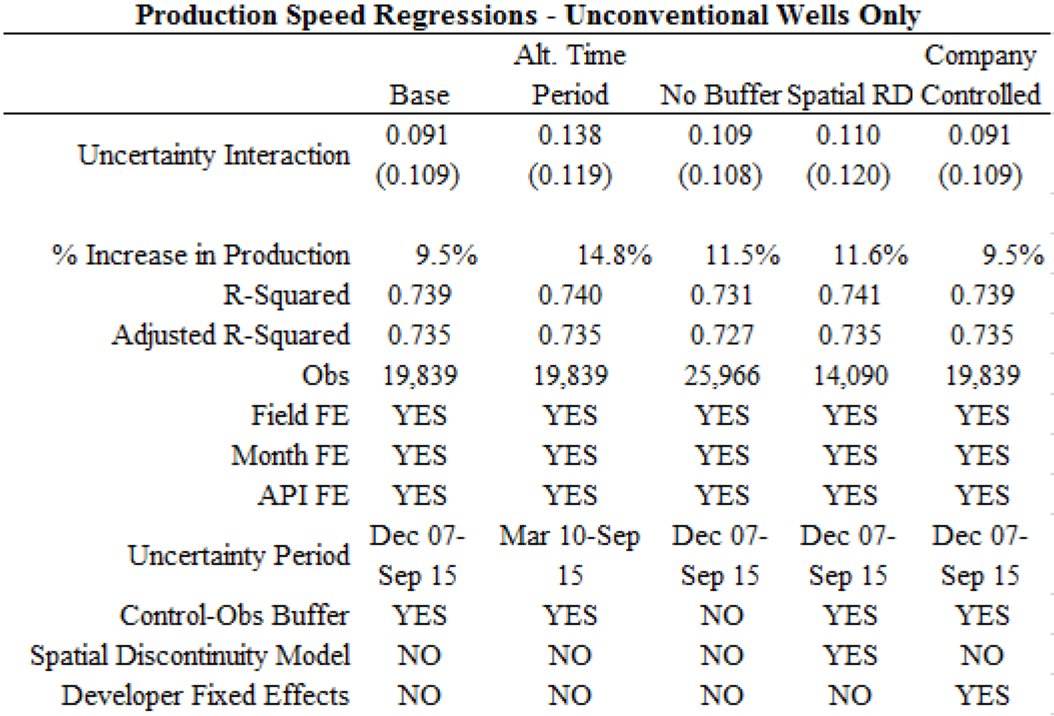


Production Speed Regressions

	Base	Alt. Time Period	No Buffer	Spatial RD	Company Controlled
Uncertainty Interaction	-0.027 (0.065)	-0.089 (0.060)	0.006 (0.063)	0.028 (0.067)	-0.027 (0.065)
% Increase in Production	-2.7%	-8.5%	0.6%	2.8%	-2.7%
R-Squared	0.745	0.745	0.762	0.765	0.745
Adjusted R-Squared	0.742	0.742	0.760	0.763	0.742
Obs	93,404	93,404	122,127	68,739	93,404
Field FE	YES	YES	YES	YES	YES
Month FE	YES	YES	YES	YES	YES
API FE	YES	YES	YES	YES	YES
Uncertainty Period	Dec 07-Sep 15	Mar 10-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15
Control-Obs Buffer	YES	YES	NO	YES	YES
Spatial Discontinuity Model	NO	NO	NO	YES	NO
Developer Fixed Effects	NO	NO	NO	NO	YES

Regression coefficients on the uncertainty interaction variable never approach statistical significance, and fluctuate around zero, indicating no relationship between uncertainty and production. My work corroborates Anderson, Kellogg, and Salant (2018)[1] and Newell, Prest, and Vissig (2016)[48], refuting the theoretical implications of Hotelling (1931)[30] and Long (1975)[42], as well as Melek (2018)[45] and Portillo's (2016)[49] conclusion that extraction rates increase (see Section 6.5.1 below for a discussion). I find that firms do not adjust the intensive margin, as I find no evidence that extraction rates of already completed wells climb in the face of regulatory uncertainty nor is completion of the well sped up under uncertainty. While the theoretical models may approximate the oil industry in a world not bound by geological physics, the inability of operators to control the pressure of their well seems to render them incapable of responding to changing market conditions by

Table 10: Production Results - Unconventional Wells



Production Speed Regressions - Unconventional Wells Only

	Base	Alt. Time Period	No Buffer	Spatial RD	Company Controlled
Uncertainty Interaction	0.091 (0.109)	0.138 (0.119)	0.109 (0.108)	0.110 (0.120)	0.091 (0.109)
% Increase in Production	9.5%	14.8%	11.5%	11.6%	9.5%
R-Squared	0.739	0.740	0.731	0.741	0.739
Adjusted R-Squared	0.735	0.735	0.727	0.735	0.735
Obs	19,839	19,839	25,966	14,090	19,839
Field FE	YES	YES	YES	YES	YES
Month FE	YES	YES	YES	YES	YES
API FE	YES	YES	YES	YES	YES
Uncertainty Period	Dec 07-Sep 15	Mar 10-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15
Control-Obs Buffer	YES	YES	NO	YES	YES
Spatial Discontinuity Model	NO	NO	NO	YES	NO
Developer Fixed Effects	NO	NO	NO	NO	YES

varying the rate of output of their wells. Instead, as shown in my drilling analyses, firms adjust the timing of their drilling to match market environments.

These results also compare favorably to the simulated results. My simulation produced a 42.5% *decrease* in *average* extraction under uncertainty. However, this effect is purely due to unfavorable regulatory decisions in the simulation that did not occur in Wyoming. Simulations without a possible unfavorable decision indicated no difference in production. See Appendix A for these simulation runs.

Unconventional wells drilled directionally are generally considered to be more flexible in production (see Newell, Prest, and Vissig (2016)[48]), and would be more likely to exhibit increased production under uncertainty. Given the extra control developers have in unconventional wells, it is possible an effect could be observed limiting observations to only unconventional wells. I present results limited to unconventional wells in Table 10.

Although coefficients are now consistently positive (indicating quicker withdrawal of liquid reserves), none are significantly different from 0, further supporting the notion firms are unable to adjust production rates at will.

As a robustness check, I also evaluated whether firms cease production quicker under uncertainty. This effectively tests the same question in another way - if otherwise identical wells are drained faster (timed from initial production to final production), this may represent operators successfully speeding up production to beat the regulator. I find no evidence that wells under uncertainty are exhausted quicker. For results, see Appendix C. The Appendix C contains one more test related to production - the likelihood to 're-frack' a well. Wells can be refracked in order to spur production quickly, and thus could be one instrument developers use to beat the regulator to the punch on wells they have already completed. I find strong and consistent evidence that developers refrack wells more often due to uncertainty in horizontal wells only.

6.5.1 Discrepancy between prior expropriation work and this study + energy uncertainty papers

Melek (2018)[45] and Portillo (2016)[49] both conclude that extraction rates of oil increase during the 'pre-announcement' uncertainty period before the 1975 Venezuelan oil nationalization. This result matches their theoretical and simulated results, but conflicts with with my empirical results as well as those by Anderson, Kellogg, and Salant (2018)[1] and Newell, Prest, and Vissig (2016)[48] that show no change in extraction rates.

Melek (2018)[45] presents a theoretical framework to evaluate oil developers' incentives before the expropriation. Using a simulation and compilation of annual nationwide data, Melek finds that the push for nationalization of the Venezuelan oil industry in 1975 caused multinational firms to invest less in oil exploration, shed workers (especially skilled foreign labor), and increase implied extraction rates of oil in the 'pre-announcement' period, or the years before the nationalization when firms suspected expropriation could be imminent. Melek also finds that the industry becomes 65% less profitable due to the combined effects of expropriation uncertainty as well as the nationalization itself.

Stressing the importance of considering expropriation as a protracted rather than sudden event when considering causality, Portillo (2016)[49] also studies multinational oil companies' behavior in the 'pre-announcement' period. Portilli's theoretical and empirical results match Melek (2018)[45]: developers adjust the expected time-horizon of their mineral assets and raise the marginal extraction cost by speeding extraction, even as they invest less in new exploration and development of reserves.

The most likely explanation[55] is that the apparent discrepancy between prior work is that the studies focus on fundamentally different questions. Melek and Portillo assume that oil companies in Venezuela knew with near or full certainty what date nationalization would occur. Indeed, this assumption is built into both

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[55] A second explanation is simply that Melek and Portillo's extraction data do not actually show a consistent increase in extraction rates. Rates peak in 1970, five years before the oil nationalization of 1975. Both authors latch onto the earlier increasing rate of extraction as evidence that future expropriation is driving over-extraction and appeal to the Reversion Law passed in 1971. This law dictated that control of reserves would revert back to the government at the termination of the lease, reverting at the latest by 1983. This law implies that the expropriation actually occurred before 1975. It is also important to note that the increase in extraction rates prior to 1970 may not be causal, as there is no control territory to compare against Venezuelan extraction. Perhaps in the absence of nationalization chatter extraction rates would have been even higher. Indeed, the growth rate of extraction rates slows starting around 1960. The authors also interpret their data differently than may be expected. Melek claims that extraction is speeding because extraction falls at a slower rate than the plunge seen in proven reserves - the ratio of production to reserves increases through the entire time period. Portillo presents only years *through* 1970 when extraction rates peaked, claiming that developers always expected nationalization to happen by 1971 .

of their theoretical and simulated models, while it is not assumed in my simulation or empirics or other work on investment under regulatory uncertainty like Dorsey (2019)[15] and Stokey (2016)[58]. This is important because Melek and Portillo note that developers drill fewer *exploratory* wells under pending expropriation. Exploratory wells are meant to prove liquid reserves exist for future extraction, while a developer drills developed wells on a pool it is already certain will provide a return. If we are to assume that developers know with near or full certainty when expropriation occurs, it makes sense that extraction will increase, but not because developers are spurring any given well to increase faster. Instead, they construct more developed wells to deplete their pools before expropriation, and already drilled wells will maintain their production path.

This is why it is important to note that Melek and Portillo are using aggregated, nationwide production data. The production data source for both Melek and Portillo is the Venezuelan Ministry of Mines and Hydrocarbons, Oil and Other Statistical Databooks, and it provides nationwide data at annual levels. What is happening at a macro-level may mask micro-level individual behavior. My work, along with other work showing steady production, is at the well-month level, allowing me to conclude that a given well does not adjust production rates. This is why it is critical to have well-specific data when considering questions like rates of extraction and drilling timing. Both Anderson, Kellogg, and Salant (2018)[1] and Newell, Prest, and Vissig (2016)[48] also use well-level data and see no increase in extraction rates. The only prior paper that has found adjustable extraction rates using well-specific data is Rao (2018)[51]. She investigates developer response to a windfall tax increase in California, and finds that developers can limit production to time periods of low-taxation.

6.5.2 Parallel Trends

Although I did not find a significant increase in extraction in response to the listing threats, the parallel trends test is shown in Figure 7. In this parallel trends chart, the horizontal axis is again time and the vertical axis is the log of barrels extracted per month. There are significantly more observations in this chart than the prior parallel trends chart Because there are so many observations plotted in these charts and the large majority of wells are 'non-core', I have presented the data in two charts. The first uses all the data of the production regressions, causing the trend of the non-core territory to be tough to decipher. The second chart is the same data with 90% of the non-core wells removed. The removed wells were selected randomly.

In both charts, both the core and non-core wells exhibit a monotonically decreasing trendline through the data, suggesting that either extraction rates are decreasing, old wells are not being replaced with new wells, or some combination of the two. Additionally, the decrease in the trendline is steeper for core territory than non-core territory throughout the time range, meaning that core territory is generally seeing a quicker reduction in extraction rates than non-core territory. From a causal perspective, the charts are consistent with the regressions. Because there is somewhat of a 'flattening' in the trendline for core territory during the uncertainty period relative to the certainty period and the non-core territory, the trendline suggests that there may be a causal increase in extraction rates of a small magnitude that cannot be differentiated from 0.

Figure 7: Parallel Trends - Production

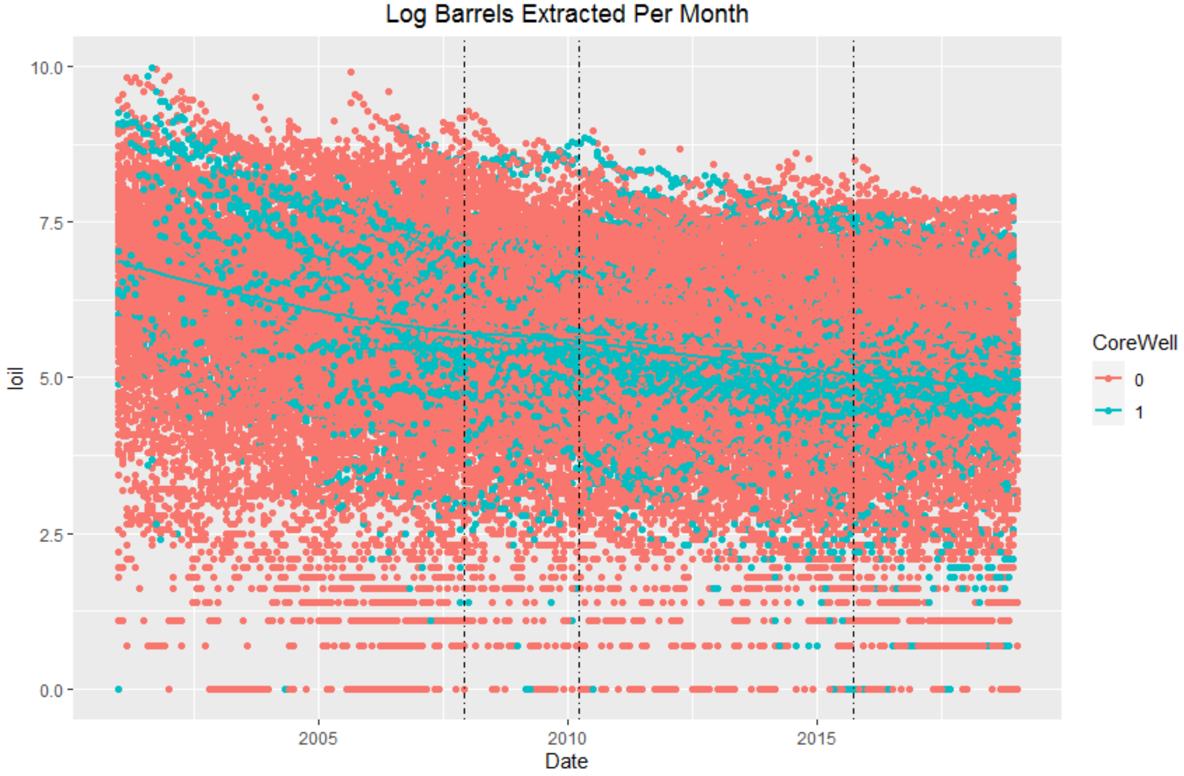
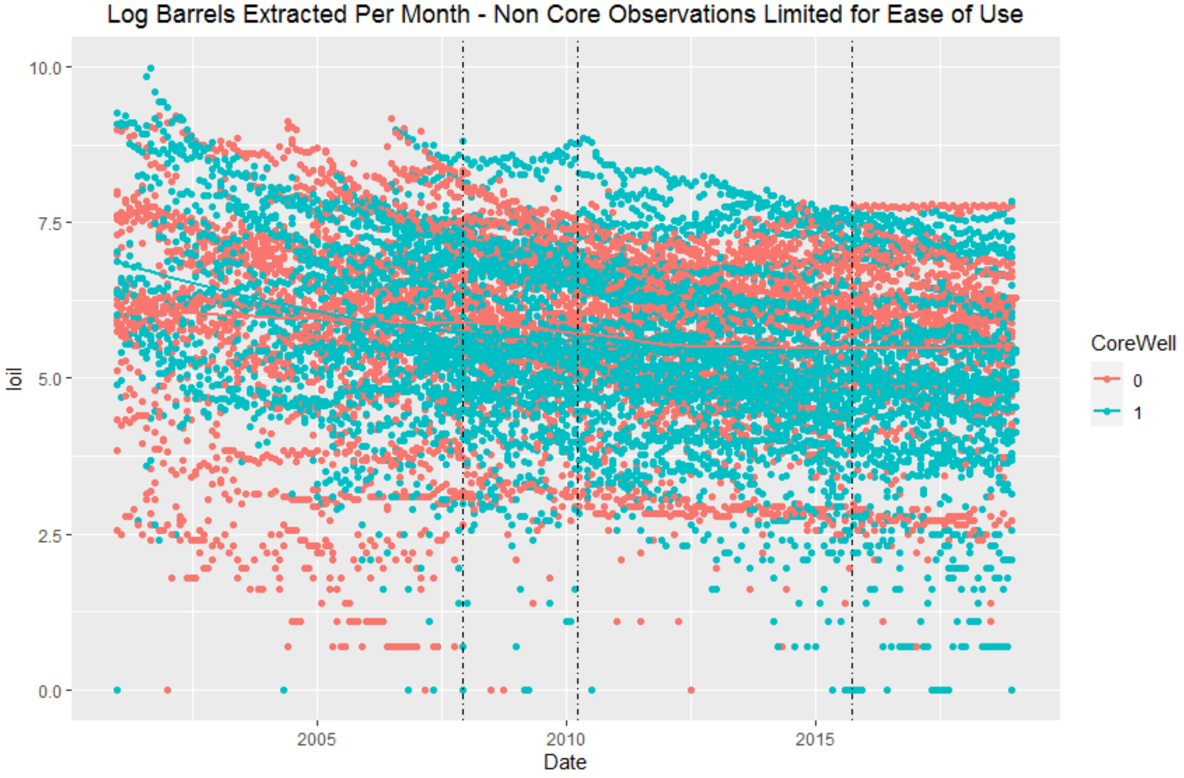


Figure 8: Parallel Trends - Random Sample of Production



7 Does uncertainty affect bidding?

Expropriation uncertainty doesn't just impact developers who already hold mineral leases - it also affects future lease sales. This is because leases (the exclusive right to drill on a parcel) represent the discounted expected value of extracted minerals less the cost of extraction. As shown in Section 3, my simulation results in a 30.1% decrease in well profitability due to expropriation threat. There are three possible avenues for the reduced value of a parcel, and the simulation has the ability to parse out what share of the total average loss of $165,805 attributable to each method of loss:

1. Some wells are never drilled (4.40%)
2. Some wells are drilled later than they otherwise would have been drilled (4.25%)
3. The regulator disallows drilling, causing loss of all revenues post-decision (91.35%)[56][57]

The overwhelming majority of lost value is due to method (3), that the regulator produces a decision unfavorable to the driller. This causes the developer to suffer large losses, especially if the decision is made soon after drilling, because the developer does not recoup the value of the lost investment. As firms are considered to be risk-neutral in my model, firms do not weigh these negative outcomes with special consideration.

The upside of this breakout is that it implies little social welfare was lost in the case of the sage-grouse. Since the sage-grouse was never listed under the ESA,

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[56] These percentages are calculated for all holes. If only non-dry holes are considered, the percentages are effectively the same (4.37%, 4.86, and 90.77%, respectively).

[57] Note that method (2) and (3) could conceivably occur on the same well, as well as methods (1) and (3) (in that situation, the regulator disallows drilling, but if the regulator had not made this decision, the firm would have drilled in some later time period). When methods (2) and (3) intersect, I consider lost revenue post-decision attributable to method (3) and lost revenue prior to the decision due to later drilling attributable to method (2). When methods (1) and (3) intersect, I attribute lost revenue to method (1).

draconian regulations were never imposed and developers were mostly free to extract at will. As there were no developers left holding a worthless multimillion dollar investment, the impact of the sage-grouse uncertainty on producer welfare was limited. Of course, the converse story is that had the sage-grouse been listed as endangered and drilling halted, firms would have lost millions in well investments.

The decrease in expected value of a well deprives the state and BLM of revenue, as the marginal bidder will have a lower willingness-to-pay for a parcel under uncertainty. In this section of the paper, I determine the real-world impact of the expropriation thereat by comparing sage-grouse habitat to non-habitat in a DiD framework.

7.1 Methodology

This section utilizes a reduced-form standard difference in differences (DiD) strategy to evaluate whether extractive firms discount the value of sage-grouse review territory. DiD analysis evaluates the impact of a treatment (in this case, the uncertainty caused by the candidate listing) on an outcome (bid value) across a treatment and control group over multiple periods, in which the treatment is only active for some of the periods. The regression equation is:

$$ln(Bid_{i,s}) = Sale_s + TownshipRangeFE_i + Interaction_{i,s} + \gamma Royalty_{i,s} + \epsilon_{i,s} \quad (7)$$

[58][59] where $Bid_{i,s}$ is the bid of a parcel located in township-range i during sale s, $Sale_s$ is a categorical fixed-effect for sale s. There are 103 distinct sales in the data, with one occurring approximately each quarter. As every observation is a bid result, controlling for the sale controls for common oil market conditions during the auction. $TownshipRange_i$ is a categorical fixed-effect for township-range i, $Interaction_{i,s}$ is a binary equal to 1 if the observed parcel is in sage-grouse habitat during the uncertainty period (Dec. 2007 - Sep.2015), and $Royalty_{i,s}$ represents whether the parcel has a royalty rate of 12.5% or 16.7%. The model includes a buffer around sage-grouse territory of 5 miles, as used in prior analyses. Observations found within this buffer are not included in analyses. Errors are clustered at the township-range level[60]. Using township-range fixed-effects allows me to control for innate differences in production capacity and land quality between township-ranges will be controlled for. Otherwise, it would be possible that significant findings are due to differing levels of expected oil & gas well production. This eliminates the possibility that results are driven simply by the non-sage-grouse territory parcels sold in the uncertainty period being of higher quality than those sold in other periods. I assume that the bidders are risk-neutral and the bidding market is competitive.

The uncertainty concerning expropriation may cause developers that are constrained by the minimum $1 per-acre bid to drop out of bidding entirely. Any

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[58] The regression equation is similar to Fitzgerald (2010), in that he also regresses bids on sale and geographic fixed-effects. However, Fitzgerald's geographic fixed-effect is less precise than mine (he uses county) and he regresses the entire bid value rather than per-acre bid, meaning he also must control for lease size. Fitzgerald does not control for royalty rates because he only looks at federal leases.

[59] I did not control for whether a given lease is controlled by the federal government or the state of Wyoming because all federal leases have a royalty rate of 12.5%, making it impossible to control for the effect along with a royalty fixed effect. However, analyses controlling for land ownership indicate that land owned by the federal government earns less-valuable bids than comparable land controlled by the state government. This corroborates the finding of Lewis (2015), which finds that companies prefer to develop on state land because of fewer restrictions than federal land.

[60] Parcels are auctioned using the township-range as the primary geographic identifier.

parcel that would have been valued at least at \$1 per acre (\$2 for the BLM) but is considered less valuable under uncertainty will not appear in my regressions. In this sense, the coefficient on the interaction term in Equation 7 may understate the true effect of the regulatory uncertainty, because it is not taking into account a drop in bids below the \$1 per acre minimum.

I also added two extra robustness checks for this model:

1. Prior regressions have only used oil wells. However, when parcels are auctioned, the developer does not need to commit to producing oil or gas on a given parcel. In fact, many developers will produce both oil and gas on the same parcel[61] A key identifying assumption of my DiD model is that treatment and control geographic areas were impacted the same by world oil & gas markets (see my discussion in Section 7). The alternative story is that certain territory could become more desirable relative to others as market conditions change. It is conceivable that as oil markets were strong in the uncertainty time period (2010-2015) relative to the beginning of the first certainty period and the entire second certainty period (post September 2015), bid prices could be inflated on leases with more easily accessible oil than nonproductive leases. It could be the elasticity of lease prices to world oil prices that is driving the differing results by region. However, this does not appear to be the case. There is an opposing narrative with respect to natural gas. Natural gas prices were *lower* during the uncertainty period relative to the certainty periods, and so this 'inflationary' effect would be 'deflationary' for regions that primarily produce natural gas instead of oil. Using the production data, I ran the base model using only

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[61] In fact, the same *well* can even produce both oil and gas. In all prior analyses, I have limited my work to wells that are labeled as oil wells rather than gas wells in the Wyoming application and production data.

township/ranges that produce more natural gas than oil. Model results did not meaningfully change.

2. Like any regression minimizing the sum of squares, the model is susceptible to outliers. The variance between observations is large, given that many parcels are leased with no testing indicating that recoverable minerals are present. These low-bid leases selling near the minimum $1 per acre may either be purely speculative, or may be defensive to prevent a competing firm from gaining a foothold in the local market. The low-bid leases stand in contrast to leases with proven recoverable reserves, which often go for hundreds or even thousands of dollars per acre. The lease data spans bids ranging from $1 - $16,851 per acre with a standard deviation of $76.40. To ensure results were not driven by high-value outliers, the model was re-run with the top 1% most valuable parcels excluded. Results did not meaningfully change.

7.2 Results

7.2.1 Regression results - Base Model

There is strong evidence that the threatened listing of the sage-grouse decreased bids in both state and federal auctions. The interaction term is consistently negative at the 0.1% level, indicating that regulatory uncertainty makes the core territory less appealing to developers than other parts of the state. The magnitude of the coefficient is large relative to the average bid value: the base model indicates that core habitat causes prices fall by 48.4%. This 48.4% almost perfectly matches the 52.6% estimated probability of activated listing I found in Section 2.3, and

Table 11: Bidding Results

Bidding Price Regressions

	Base	Alt. Time Period	No Buffer	Spatial RD	Company Controlled	Gas Wells Only	Outliers Removed
Uncertainty Interaction	-0.662***	-0.593***	-0.513***	-0.255*	-0.414***	-0.649**	-0.610***
	(0.113)	(0.134)	(0.104)	(0.117)	(0.110)	(0.210)	(0.111)
Royalty Rate	0.102**	0.103**	0.093**	0.105**	0.051	0.410***	0.106**
	(0.350)	(0.036)	(0.030)	(0.035)	(0.038)	(0.103)	(0.033)
% Decrease in Bids	-48.4%	-44.7%	-40.1%	-22.5%	-33.9%	-47.7%	-45.7%
R-Squared	0.633	0.633	0.612	0.564	0.745	0.626	0.616
Adjusted R-Squared	0.586	0.585	0.563	0.508	0.689	0.566	0.566
Obs	12,392	12,392	16,568	11,461	12,311	3,317	12,236
Township-Range FE	YES	YES	YES	YES	YES	YES	YES
Sale FE	YES	YES	YES	YES	YES	YES	YES
Uncertainty Period	Dec 07- Sep 15	Mar 10- Sep 15	Dec 07- Sep 15	Dec 07- Sep 15	Dec 07- Sep 15	Dec 07- Sep 15	Dec 07- Sep 15
Control-Obs Buffer	YES	YES	NO	YES	YES	YES	YES
Spatial Discontinuity Model	NO	NO	NO	YES	NO	NO	NO
Developer Fixed Effects	NO	NO	NO	NO	YES	NO	NO
Oil & Gas Wells	BOTH	BOTH	BOTH	BOTH	BOTH	GAS	BOTH
Top 1% Censor	NO	NO	NO	NO	NO	NO	YES

compares favorably to the 30.1% decrease in expected value of the well, and almost exactly matches the 48.0% loss if only non-dry holes are considered. As shown in Appendix A, the vast majority of this lost profitability is due to the possibility of an unfavorable regulatory decision, rather than delayed or lost drilling.

The bidding reductions also compare favorably to the simulated valuation results. In my simulation, developers under uncertainty lost 30.1% of the value of their well. Additionally, if only non-dry wells are considered, the 48.4% decrease found in the base model matches the simulated loss of 48.0% almost exactly. Taken in combination with the robustness checks which report consistent results spanning a 22.5% decrease up through the 48.4% found in the base model, it is clear that developers significantly discount parcels under uncertainty of expropriation, and discount them in line with expected reduced profit.

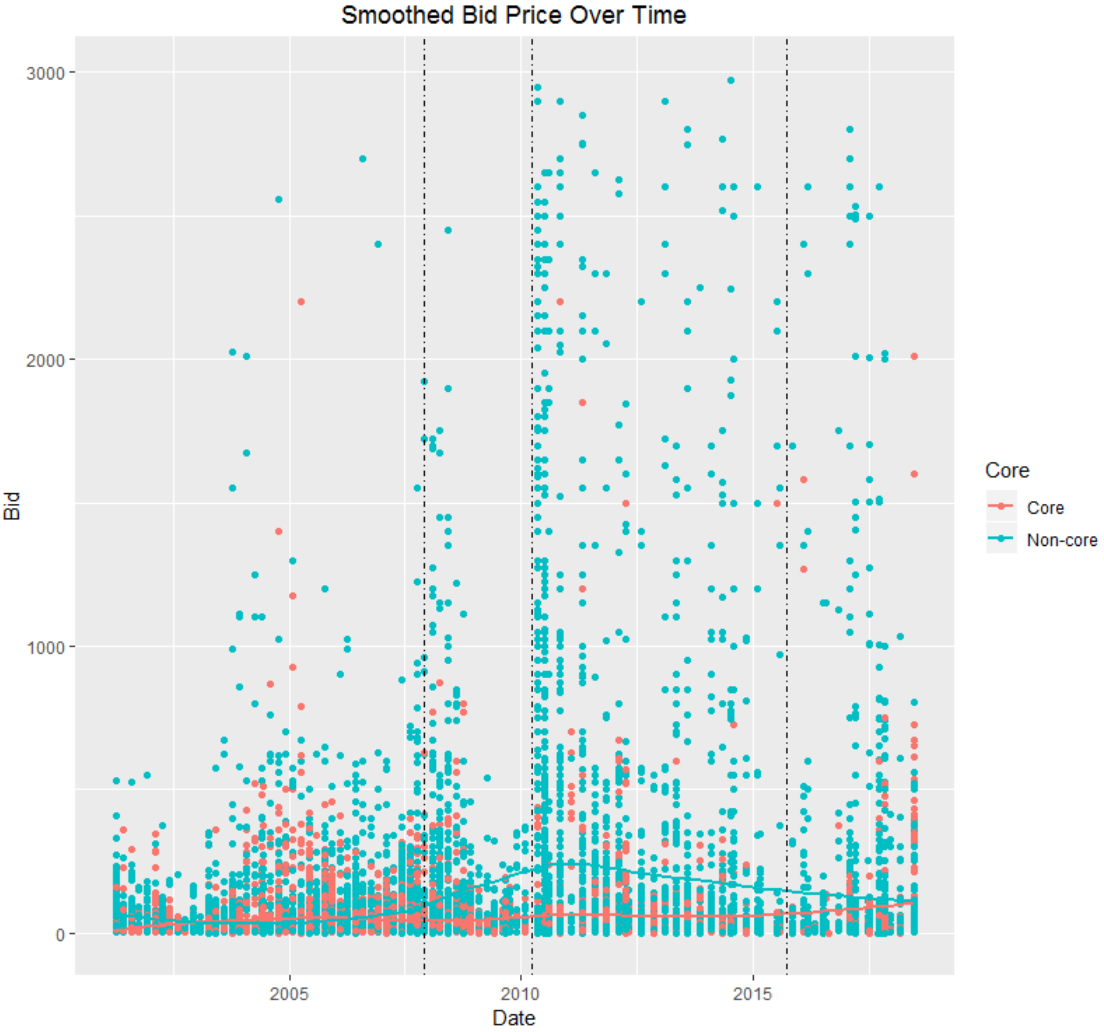
A consistent and positive value ascribed to royalty rates may seem surprising, as a higher royalty rate means more of the value of production is forfeited to the lessor, but is this due to Wyoming state lands generally although not exclusively having a higher royalty rate than federal lands (16.7% vs. 12.5%). Firms prefer to operate on state lands due to less regulation, as found by Lewis (2015)[40].

7.2.2 Parallel trends check & 'constrained response'

DiD analyses rest upon the assumption of 'parallel trends', or that a given policy only impacted the treated observations and did not affect the control observations. This is usually shown by displaying running trends of the data with no discernible change in slope of the control observations when the policy in question begins, but a noticeable change in slope for the treated observations.

What is interesting and potentially problematic about this case is that the parallel trends charts show a response *only in the 'control' population* - that is, the depression in sage-grouse habitat bids compared to other territory consistently found in almost every variation on the regression is caused by an *increase* in bid values from the non-sage-grouse territory, rather than a decrease in bids in the sage-grouse territory. It is remarkable that there is a visible response only in the non-sage-grouse parcels that almost completely matches the uncertainty period, especially if the uncertainty period is considered to begin when the Federal District Court of Idaho (12/4/07) ordered a reconsideration of the decision not to list the sage-grouse. There is no such response in the 'treatment' group - the trend line is perfectly flat through the entire dataset. See the parallel-trend chart in Figure 9 that includes a loess-smoothed curve connecting points within and outside core territory for a visual representation.

Figure 9: Parallel Trends- Bids



For a discussion of why I only see a change in the non-core territory, please see Appendix C.3.1. The most likely explanation appears to be a 'flight-to-certainty', a phenomenon described by Falk and Shelton (2018)[19], in which developers are shifting planned future production to areas of political uncertainty. If this is the case, it is possible the coefficients in this section are biased upwards.

8 Conclusion

This paper shows that the uncertainty created by the candidate review of the sage-grouse in which the species had a plausibly 50/50 chance of being listed on the Endangered Species List engendered changes in oil developer behavior fitting with both a 'wait-and-see' story as well as commensurate with the expected loss in parcel profitability. Adopting the conditional logit discrete choice model of Melstrom (2017)[46], results show that developers avoid sage-grouse habitat during regulatory uncertainty. Using Wyoming state drilling data fitted into a Cox proportional hazards model of survival along with a structural drilling simulation, I find that firms delay spudding *and* completing wells in an attempt to wait out uncertainty. Developers are only about 60% as likely to spud or complete the well each period under an uncertain regime, and this delay is not due to risk aversion. Using state and federal competitive leasing data in a difference in differences model, I also found that developers discount uncertainty at a level virtually identical with the expected loss of profitability of their parcels due to the possibility of an unfavorable regulatory decision to restrict drilling. Simulation results imply that the overwhelming majority of lost profitability (over 90% of the 48% loss in value) is due to the threat of regulation, rather than delayed drilling or wells that are not spudded at all due to uncertainty.

Using state monthly oil production data, I find no indication that developers speed up extraction rates of already drilled wells in an effort to extract liquid reserves before a switch to an unfavorable regulatory regime. Although this finding runs counter to economic logic and prior theoretical work, it matches recent landmark empirical papers in the oil & gas literature showing that firms have no ability to adjust extraction rates. I also tested whether firms can change the well design in order to accommodate for the uncertainty, finding that developers drill vertically more often than in the certain regime, and unconventionally drilled horizontal wells are refracked more often in an effort to spur production in the short term. Thus, firms facing an existential threat due to regulation or appropriation are mostly devoid of available tools to mitigate the damage to their business once the well has been completed, and their bidding behavior for future development reflects their inability to adapt to existential threats like expropriation after the drilling process finishes.

The policy takeaways from this paper are the following:

1. Expropriation of development rights would incur a large loss of welfare for oil developers.
2. Uncertainty regarding drilling ability causes firms to pre-emptively leave core habitat.
3. Uncertainty regarding drilling ability causes firms to 'wait-and-see' when determining when to drill.
4. Developers incorporate this uncertainty in their bidding functions.
5. Mineral developers prefer to operate in more certain regimes and will prioritize drilling in areas with a more certain environment.
6. Oil companies do not 'speed up' drilling of already-spudded wells in the face of uncertainty, but they may respond to uncertainty in other ways like re-fracking and drilling conventionally rather than unconventionally.

Chapter III

Ozone in the Uinta Basin

1 Introduction

In early 2010, Bureau of Land Management (BLM) regulators made an unexpected and disconcerting discovery. Readings from recently installed ozone monitors in the Uinta Basin of Utah[62] indicated that wintertime "measured ozone concentrations exceed[ed] federal health standards more than 68 times in the first three months of 2010...The winter ozone phenomenon surprised BLM[63], which this week issued a draft environmental impact statement (EIS) identifying hundreds of existing oil and gas wells in the basin as the primary cause of the ozone pollution"[64]. After the discovery of these high ozone readings, state and federal regulators reconsidered future drilling in the Uinta Basin, which was set to become one of the most important plays in the nation.

The unsafe ozone readings were a dire threat to the energy industry because the EPA might declare the Uinta Basin a violator of ozone pollution standards under the National Ambient Air Quality Standards[65]. Being deemed a 'non-attainment' area for ozone requires the state to reduce ozone pollution to below non-attainment levels[66] under a State Implementation Plan (SIP). This plan would include limiting new development, essentially freezing drilling at the current level. Additionally,

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[62] There is considerable debate on whether the name of the Basin - and several surrounding natural amenities and manmade structures - is spelled 'Uinta' or 'Uintah'. I keep the 'h' out in this paper, following the instructions on this website: http://theedgemagazine.blogspot.com/2010/11/uinta-vs-uintah.html

[63] the Bureau of Land Management, which administers most of the Uinta Basin

[64] https://www.eenews.net/stories/1059940555

[65] Ozone is one of the 6 air pollutants monitored by the EPA to designate areas being 'in attainment'. The others are carbon monoxide, lead, nitrogen oxides, particulate matter (both 10 and 2.5), and sulfur dioxide

[66] http://ohioepa.custhelp.com/app/answers/detail/a_id/905/~/definition-of-air-quality-nonattainment

drilling could be banned during winter months, when the ozone pollution in the Uinta Basin is most acute[67]. Ultimately, the Uinta Basin was determined to be in non-attainment in 2018, and the state is attempting to thwart crippling restrictions on drilling by instituting minor restrictions on drilling in low-elevation areas, which are most susceptible to the collection of ground-level ozone.

Because the EPA requires a three-year moving average of elevated ozone levels before non-attainment is officially declared, there was an 'announcement period' in which developers were acting without restriction but under the assumption that future restrictions on drilling and/or extraction were likely. This depresses the expected future value of their parcel holdings while keeping the present value of liquid reserves constant, reducing the 'option value' of waiting to drill in the hopes of more favorable future market conditions, as discussed by Kellogg (2014)[35]. The reduction of the option value means that while less parcels will be developed overall, some portion of parcels are developed earlier than they would have been developed without the EPA regulation. This could lead to a case of the 'green paradox' coined by Sinn (2008)[55], in which regulation meant to improve the environment actually worsens the problem, at least in the short-term.

My paper uses a computer simulation of agent-based modeling (ABM) to determine whether a green paradox exists. The advantage of the simulation is that I can game out different factors that would make breaching the threshold more or less likely, repeating the simulation hundreds of times while also adjusting different parameters. Demonstrating the effect of the level of the threshold is especially pertinent to the Uinta Basin because during the period of uncertainty, the thresh-

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[67] https://www-eenews-net.proxy-um.researchport.umd.edu/landletter/stories/1059940555/

old changed to become stricter based on better available evidence of the harmful effect of ozone. In 2015, the EPA reduced the threshold of being in 'marginal' non-attainment to ozone to 71 parts-per-billion from 76 (which was itself a 2008 reduction from 86 parts-per-billion)[68], and thresholds as low as 66 were considered before the final rule was announced[69].

The simulation results indicate that developers expected there was a 73.0% chance that the Uinta Basin would at some point fall into non-attainment from 2010-2018. Of course, the Basin did indeed fall into non-attainment, which is implemented in every iteration of the model. The base model does not exhibit a green paradox, because there are no periods in which ozone emissions are higher under EPA regulation than without regulation. However, several wells are spudded earlier under regulation than without regulation, making the difference between no green paradox and the existence of a weak green paradox in early periods a marginal call.

This paper considers which elements of the developer's production decision are critical in determining whether a green paradox exists. Guided by the literature, I find that the cost of spudding is a key factor in creating the environment ripe for a green paradox. The very same model, input parameters, and random seed initiation predicts a small-magnitude weak green paradox for the first period if there are no costs to production. Likewise, the same model implies that varying the level of regulatory standards while maintaining some form of regulation also produces a weak green paradox.

The rest of the paper is organized as follows. Section 1.1 contextualizes my work within the green paradox literature. The introduction concludes in Section 1.2,

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[68] https://www.epa.gov/green-book/ozone-designation-and-classification-information . Note that the threshold of 76 ppb means that 75 ppb is acceptable, while 76 ppb is not.

[69] https://www.epa.gov/sites/production/files/2015-10/documents/20151001_air_quality_index_updates.pdf

which provides an overview of the energy development industry in the Uinta Basin of Utah. Section 2 describes the data I am using, along with a brief introduction to the mechanics of my simulation. Results of the simulation along with several alternatives pertinent to the green paradox are presented in Section 3. Section 4 provides brief concluding remarks. The specific transition equations and justifications for all parameters of my model are presented in an appendix to this paper.

1.1 The 'Green Paradox'

1.1.1 Introduction

Counterintuitively, it is possible for regulation of scarce & exhaustible dirty resource to worsen the problem of pollution or other externalities associated with the use of the resource. When regulation decreases the future profitability of the resource (say, through future taxation like a rising carbon tax, or through restrictions on extraction like EPA non-attainment regulation, or through reducing future demand for the resource by limiting its use or subsidizing green alternatives), owners of the resource may speed extraction, causing higher emissions of whatever dirty negative externality is being regulated, at least in the short run. This is called the 'weak' green paradox, in contrast with the 'strong' green paradox, in which total *damages* from the externality are higher in the long run under the regulation than without regulation[70]. To have a strong green paradox, there generally must be some feedback loop, nonlinearity in damages, or tipping points. For example, when considering global warming, warming beyond 1.5° C will unlock methane held in the ground and melt sunlight reflecting-ice, causing further warming even without

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[70] For a logical narrative introduction to the green paradox, I recommend Jensen et al. (2015)[33]. For a clear theoretical background to the producer's optimization problem that causes the weak and strong green paradox, I recommend Hoel (2013)[29].

more emissions. If exposure to ozone exhibits nonlinearity in damages - say, if a day at 100 ppb is more than twice as damaging to the human body than a day at 50 ppb - then ozone regulation may be a strong green paradox example, even if total cumulative ozone emissions are lower. This could happen if the damages associated with the concentration of emissions within a smaller timeframe exceed damages associated with higher total emissions with a lower ‘peak’ over a longer time frame.

While there have been several papers concerning the green paradox since the original paper by Sinn (2008)[55], the theory backing the green paradox lies in the classic Hotelling (1931)[30] model. In this model, owners of a scarce resource extract the resource with the goal of maximizing the net present value of their stock. As Sinclair (1992)[54] writes, "the key decision of those lucky enough to own oil wells is not so much *how much* to produce as *when* to extract it[71].” Broadly speaking the owner will extract when the price of the resource is high and costs are low. In the case of oil drilling, the resource owner faces the drilling timing decision detailed by Kellogg (2014)[35], described in detail in the prior chapter of this dissertation. In this model based on the real-options finance literature, in each period the resource owner considers current and expected future market conditions when deciding whether to drill now or to keep the option to drill later and wait. If a risk-neutral owner expects any future period to provide higher discounted profits than the current period, the resource owner will wait to drill and revisit the drilling question again in the next period.

The green paradox is most often studied from either a purely theoretical per-

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[71] Emphasis my own.

spective [see: Kollenbach (2019)[37], Gerlagh (2011)[22], Grafton, Kompas, & Long (2012)[50], Hoel (2013)[29], Eichner and Pethig (2011)[18], Hoel (2011)[28], Ryszka & Withagen (2014)[52]] or using simulation modeling [see: Jensen et al. (2015)[33], Cairns & Smith (2016)[8], Ryszka & Withagen (2014)[52], Michielsen (2014)[47], Fischer & Salant (2012)[20]] due to the difficulty of locating a convincing counterfactual narrative or a strong casaul identification strategy. To date, there have been only two empirical analyses of the green paradox. Di Maria et al. (2013)[13] find no evidence that the announcement of future caps on sulfur dioxide emissions (the Acid Rain program of the 1990s) led to increased burning of coal in the early 90s, but they do find strong evidence of a reduced price for coal and speculate the reason they do not find increased consumption of coal is becaues of industry-specific constraints on the short-term fungibility of inputs to energy production. Their results are contrasted with Lemoine (2016)[39], who finds increased use of coal and increased emissions due to legislation in 2010 that ultimately failed to pass that would have instituted a cap-and-trade system for carbon emissions in the United States.

Regardless of whether there is a green paradox at all, or even whether regulation has any impact whatsoever on drilling timing or rates, it is important to remember that these local effects are offset by behavior elsewhere because oil & gas is a commodity good with supply chains all over the world. If developers in the Uinta Basin speed up drilling creating a green paradox and higher ozone emissions in the Basin, there will be less drilling elsewhere in those periods. Likewise, if regulations are so onerous that drilling in the Basin were to effectively stop, there would be offsetting additional drilling somewhere else in the world.

1.1.2 Ozone and the Green Paradox

The determination of whether ozone regulation is a *meaningful* weak or strong example of the green paradox or even a paradox at all depends on assumptions of damages associated with different ozone levels and the relative response of drilling timing and overall spudding rates to the regulation. For example, if the median spudded well is indeed drilled earlier but a large percentage of parcels are simply not drilled at all due to the regulation, then there will be no paradox. Ozone emissions will be lower in all periods including the short term because so few wells are spudded. However, if the number of wells spudded in the short term rises due to the relatively higher profits from drilling soon due to the regulation, then the weak green paradox will be satisfied. If the emissions associated with these wells exhibit nonlinear damages and cumulative ozone damages under regulation exceed damages with no regulation due to the 'clumping' of spudding, then the strong green paradox is also satisfied.

Factors that differentiate current and future profitability are critical to determining whether the threat of regulation perversely increases pollution in the short run, especially when coupled with other factors that make drilling more profitable overall. Thus, model factors that make a green paradox more likely are:

1. Higher price volatility (increasing the likelihood that some future period has a high enough price to cover the lost discounted revenue from a delayed spudding)
2. Higher discount rate (future revenues are relatively more valuable)
3. Higher future prices relative to current prices (increasing the value of drilling later)

4. Lower drilling costs or higher current prices (higher profitabiliy of wells means more will be drilled overall)

1.2 Drilling & Ozone in Utah

Utah is a relatively large energy developer. The state ranks as the 10th-largest crude oil producer and 13th-largest natural gas producer in the country[72]. Most of that development is centered around the Uinta Basin, an area to the east of the Wasatch Front (which is home to the vast majority of Utah's population) and just to the west of the state border with Colorado. Gas and oil drilling gradually expanded in the Basin before 2010 in response to better technology. Just as these ozone findings were released, developers were readying four new large-scale gas projects that were projected to be the largest in the history of the Basin by a wide margin[73]. It is estimated that these oil shale formations contain over a trillion barrels of oil and the area has over 7 trillion cubic feet of natural gas reserves[74]. By comparison, the US as a whole produces about 4.6 billion barrels of oil and 36 trillion cubic feet of gas per year[75]. See Figure 10 for a map of all Utah development.

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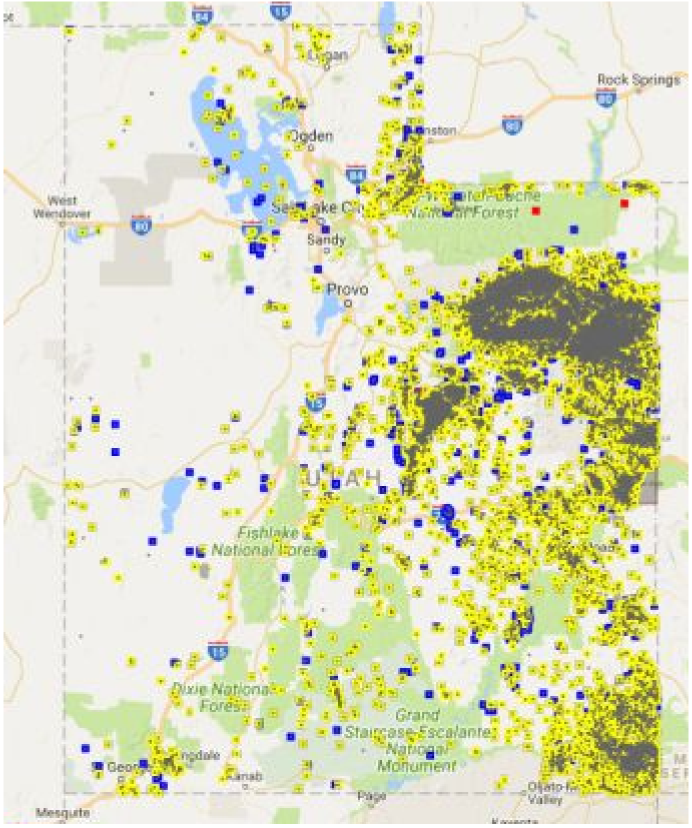
[72] https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_a.htm

[73] Had all the expected wells been spudded, natural gas output in the Uinta Basin would have more than doubled

[74] https://www-eenews-net.proxy-um.researchport.umd.edu/energywire/stories/1059976330/

[75] https://www.eia.gov/todayinenergy/detail.php?id=38692

Figure 10: Utah Oil & Gas Map



Air quality is a well-known issue in the state of Utah, due to a unique wintertime process known as 'inversion'[76]. In Utah's valleys and basins, wintertime ground-level air is colder than warmer, higher-elevation air (hence the 'inversion'), which causes that cold air to become trapped in the lower elevation regions. This trapped air contains particulate matter (PM) chemicals (particularly NOx, volatile organic compounds (VOCs), sulfur dioxide and ammonia) are emitted at the ground-level or are created through regular chemical reactions in the atmosphere, and the lack of mixing with higher air prevents the pollutants from moving to higher elevations, away from the local population. Because of this well-known inversion process, the state of Utah monitors air quality carefully through the year, and daily television and newspaper reports in the winter will always specially mention the current air

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[76] https://deq.utah.gov/air-quality/inversions

quality projection.

Ozone was not a chemical identified by the state as a pollutant caused by this 'inversion' process, nor was ozone considered a by-product of drilling before 2011 at the earliest, and thus it was not specially monitored or considered a risk until recently[77]. While lauded for its protection from ultraviolet radiation when it is found miles up in the atmosphere, 'ground-level' ozone is considered pollution. Ozone can cause respiratory problems, including asthma. It is particularly dangerous for the young, sick, or elderly[78]. Ozone is traditionally considered to be a problem in areas with heavy traffic, but it is also one of several pollutants formed in oil and natural gas drilling. It results from the nitrogen oxide and volatile organic compounds released in drilling, especially from deeper wells that can be accessed with new technology[79].

Ozone is broadly considered a 'summertime' problem because in other areas of the country it primarily collects in the summer[80]. However, ozone was identified as a 'wintertime' problem in the Uinta Basin starting in late 2009, when the state of Utah and private operators installed several ozone monitors in the Basin, an area that was previously unmonitored[81]. State regulators were concerned that ozone levels would be dangerously high because of troubling evidence from Wyoming, in which elevated ozone levels were detected near natural gas wells in the Upper Green River Basin. Indeed, the officials found unsafe ozone levels in these preliminary tests[82].

Contemporaneous news articles confirm that the ozone problem was a surprise

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[77] https://www.sltrib.com/news/environment/2018/01/04/feds-say-utah-has-another-serious-air-quality-problem-ozone/ , https://www.ksl.com/article/46557883/study-shows-rise-in-ozone-related-deaths-in-salt-lake-city

[78] https://www.epa.gov/ground-level-ozone-pollution

[79] https://www-eenews-net.proxy-um.researchport.umd.edu/landletter/stories/1059940555/

[80] https://www.nationaljewish.org/conditions/health-information/air-pollution-and-healthy-homes/outdoor-air-pollution/summer-ozone-dangers

[81] https://www-eenews-net.proxy-um.researchport.umd.edu/energywire/stories/1059976330/

[82] https://binghamresearch.usu.edu/files/edl_2010-11_report_ozone_final.pdf

that caught developers and regulators off-guard. An April 2011 article reads, "In Utah, where the wintertime ozone was identified as a problem just last year, regulators say they are addressing the problem. But it remains unclear what strategies will be most effective in bringing ozone back into compliance with the federal health standard...The nagging questions around wintertime ozone stem in part from the fact that ozone is traditionally a summer problem, when emissions from industry smokestacks and automobile tailpipes mix in sunlight and heat to form the odorless gas. Regulators are also puzzled by the inconsistency of wintertime ozone. For example, the phenomenon was first discovered in Wyoming's Upper Green River Basin in 2008, Guille said, then dropped off in 2009 and 2010 before making a resurgence in 2011."[83].

Moreover, the uncertainty was driven not just by the data, but by the science. Even today, the science on ozone formation is very much up in the air[84]. Utah State University's current Uinta Basin website currently says that "[M]any aspects of the meteorology, chemistry, and emissions that allow ozone to form during winter are still poorly understood"[85]. A recent atmospheric study by Mansfield and Hall (2018)[44] trying to isolate the specific reasons why the Uinta and Upper Green River (WY) Basins have such high ozone concentrations concluded that "The single strongest predictor of high winter ozone is the level of oil or natural gas extraction in a basin".

There were not any scientific studies on the correlation until a 2013 white paper by Utah State University researchers[86]. This paper was supported by a 2014

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[83] https://www-eenews-net.proxy-um.researchport.umd.edu/landletter/stories/1059948108/

[84] Pun intended.

[85] https://binghamresearch.usu.edu/files/2-pagehandoutUBairquality.pdf

[86] https://binghamresearch.usu.edu/files/2013%20final%20report%20uimssd%20R.pdf

academic article also studying the Basin in the journal *Nature,* which definitively concluded that gas drilling caused elevated ozone concentrations[87] [Edwards et al (2014)[16]]. Because of the lack of science backing up the 2010 ozone measurements, industry representatives questioned the data, calling it "[F]aulty...that data cannot be used in determining the attainment status" of the Uinta Basin[88]. A year later, the same spokeswoman said that "The EPA maps show data that are extrapolated from a limited number of monitors"[89].

Any initial reading of excess levels must be confirmed through three years of data before a region is officially deemed to be in 'non-attainment'. This was no idle threat: the problematic measurements from Wyoming that originally spurred Utah to install its own monitors were confirmed through further testing and the EPA deemed the Upper Green River Basin of Wyoming to be in 'non-attainment' for ozone in 2012[90].

On May 21, 2012, the EPA designated the Uinta Basin (Duchesne County, Uintah County, and the Ute Indian Tribal land) as being 'unclassifiable' for attainment status regarding ozone. The Federal Register released that day says, "The EPA is designating one area, Uinta Basin, WY [sic][91], as unclassifiable because there is existing non-regulatory monitoring in the area that detected levels of ozone that exceed the NAAQS. Regulatory monitoring has been conducted in that area since April 2011, and thus there are not yet three consecutive years of certified ozone monitoring data available that can be used to determine the area's attainment

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[87] https://www-eenews-net.proxy-um.researchport.umd.edu/greenwire/stories/1060006726/

[88] https://www-eenews-net.proxy-um.researchport.umd.edu/landletter/stories/1059940555/

[89] https://www-eenews-net.proxy-um.researchport.umd.edu/landletter/stories/1059945402/

[90] https://www-eenews-net.proxy-um.researchport.umd.edu/energywire/stories/1059963950

[91] This is a typo on the part of the Department of the Interior. The Uinta Basin is located in Utah (plus some in Colorado), not Wyoming. Moreover, the detailed attainment/non-attainment/unclassifiable notes located further down this specific Register only provide findings for the Uinta Basin Utah, not the Uinta Basin Wyoming. Indeed, the Uinta Basin, Utah is labeled as 'unclassifiable'. News articles of the time also make clear this finding is for the Uinta Basin, Utah.

status”[92]. An ‘unclassifiable’ finding is distinct from an the ‘non-attainment’ and ‘attainment’ findings in that it represents an uncertain finding pending more information. Specifically, the May 2012 Federal Register reads “[T]he EPA cannot designate on the basis of available information as meeting or not meeting the standards should be designated as ‘unclassifiable.’” Although not provided in the Register itself, the EPA responded to a public comment on the Uinta Basin, saying that while the monitors in the Basin meet the requirements of EPA regulation and data was collected reasonably, “the data cannot be used for regulatory purposes because of three alleged quality assurance problems”[93]. Ultimately, the EPA did find several Utah counties to be in non-attainment. On May 1, 2018, the EPA designated portions of Davis, Duchesne, Salt Lake, Toole, Uintah, Utah, and Weber Counties as being in ‘non-attainment’ for 8-hour ozone[94]. The specific portions that were found to be in non-attainment were finalized a month later. In the Uinta Basin, all land beneath 6,250 feet in elevation was deemed to be in non-attainment[95]. Currently, these non-attainment rulings are more ‘warnings’, but if the Basin continues to have an ozone problem after the next review in 2021, and especially if the region is now in ‘moderate’ violation rather than ‘marginal’ (80 parts per billion rather than 70), heavier restrictions will be implemented.

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[92] https://www.federalregister.gov/documents/2012/05/21/2012-11618/air-quality-designations-for-the-2008-ozone-national-ambient-air-quality-standards

[93] http://earthjustice.org/sites/default/files/FINAL_Petition_for_Reconsideration.pdf . The 3 identified problems were EPA states that it has not approved the quality assurance plan that was developed by the contractor that operates the monitors, the plan does not include a mechanism that would allow EPA or another regulatory agency to direct corrective actions should quality assurance issues be identified in the monitoring program, and that although the raw data is currently reported in EPA‘s database, it cannot be considered quality assured. Independent watchdog organizations question whether any of these three ‘problems’ justify delaying an attainment designation.

[94] https://www.sltrib.com/news/environment/2018/05/01/feds-give-utah-three-years-to-bring-ozone-pollution-down-to-acceptable-levels/

[95] https://www.govinfo.gov/content/pkg/FR-2018-06-04/pdf/2018-11838.pdf

2 Data & Simulation

2.1 Data

My simulation is parameterized using drilling data from the Uinta Basin. I obtained a wide selection of drilling data from the Utah Department of Natural Resources, Division of Oil, Gas and Mining. I collected data on the location and timing of spuddings, the location and quantity of liquid minerals recovered per month, the location and timing of approved APDs (Applications for Permits to Drill), and characteristics of wells like elevation and whether the well was a horizontal well or a traditional vertical well. The drilling data I collected is the same structure and format as in the prior chapter, but it is maintained by the state of Utah rather than the state of Wyoming.

Ozone monitoring data comes from Utah State University. Ozone data is only available for winter months, but is available daily at dozens of monitors across the state, many of which are in the Basin. I use data measuring the maximum level of ozone sustained over an 8-hour period (called 8-hour ozone) because this is the measurement EPA uses when determining whether an area is in non-attainment.

Data to parameterize the simulated evolution of ozone over time was heavily sourced from Mansfield (2017)[43], one of several papers written by Dr. Mansfield on Uinta Basin ozone that have helped me understand the atmospheric science and chemistry questions associated with the local ozone problem. Dr. Mansfield is associated with the Bingham Research Center[96], which was founded to monitor the ozone air quality in the Basin.

In his 2017 paper, Dr. Mansfield seeks to answer what is still an unresolved

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[96] https://binghamresearch.usu.edu/index

question: What causes ground-level ozone buildup? His regression results suggest that the key determinants are metereological conditions such as the snow pack, the lapse rate (the negative relationship between elevation and temperature), the number of days of inversion (in which the lapse rate is *inverted*, or temperature *increases* with elevation because cold air is trapped in the Basin), and oil & gas development. I used his data set to determine the relationship between different meteorological inputs and the ozone concentration, as well as to establish the distribution of these elements in my simulation.

2.2 Simulation

My simulation predicts the possible distribution of outcomes from the Uinta Basin energy exploration environment. My ABM simulation is based on the 'real options' framework used by Kellogg (2014)[35], the same framework used in the prior chapter concerning sage-grouse regulation. In this model, in each period risk-neutral energy developers compare the expected value of drilling now versus keeping the option to drill in the future. If the developer decides to drill now, it will assume an upfront drilling cost D, and then earn revenues for the lifetime of the well of $P_t * Q_t * \delta$, which correspond to period price, quantity, and discount rate. Current price is determined each period commonly for all developers, but developers have unique assumptions of what future prices will be when they consider drilling. Quantity is assumed to be fixed based on a decline curve generated from a stochastically determined initial-period quantity. When deciding whether to drill in the current period, the developer estimates expected profit from drilling now versus drilling in each of the 10 periods following the initial period. 10 periods are allowed for drilling (representing 2010-2020) to give developers more chances to develop parcels approved in later periods (it is rare for a parcel to be developed more than 2-3 periods after approval).

Developers spud if all future periods have lower expected profits than drilling now and drilling now is expected to generate positive returns. However, if expected revenues from any future period exceeds drilling now or expected returns are negative, the developer chooses not to drill in the current period and then makes the same estimates in the next period. The simulation is run 1,000 times in order to generate bootstrapped estimates of key outcomes including period-to-period and overall ozone concentrations, profit from drilling, number of wells drilled, and the likelihood of the Basin reaching non-attainment levels of ozone. Bootstrapping the outcomes, rather than running the model one time, is necessary in the case of this simulation because the outcomes are sensitive to the stochastic pricing, well quality, and ozone concentration assumptions.

A key aspect of the simulation is the integration of EPA regulation in the expected revenue from drilling. The simulation accounts for the possibility that in the future drilling and extraction are restricted. The likelihood of an unfavorable regulatory regime is directly related to future ozone measurements, which are a function of:

1. The number of spuds in the Basin, which itself is a function of time and prices
2. Random year-to-year noise based on the actual variability of ozone in the Basin

Included in Appendix B is a step-by-step explanation of the stochastic process determining the ozone accumulation each period, which utilizes a complicated algorithm partially based on the work of Mansfield (2017)[43]. The model also simulates the likelihood of a non-attainment rating outside of the actual real-world resolution of different meteorological covariates that is based on the historical distribution of these covariates. This allows me to estimate the a priori likelihood of non-attainment being reached based on historical factors. The model assumes that developers make their decisions on future drilling based on this expected likelihood, as they are not aware of the actual resolution of the meteorogical data.

3 Results

3.1 Main Model Results

The ozone levels measured in the model compare favorably to the real-world ozone levels measured at the Ouray monitoring station, which is located in the heart of the Uinta Basin and is used by Mansfield to calibrate his own model. In Figure 11, I compare the point estimate of the base simulation[97] to the actual ozone concentrations measured in the Basin from 2011-2018[98]. On average, the simulation misses the real-world concentration by 8.7 ppb, or 7.4%.

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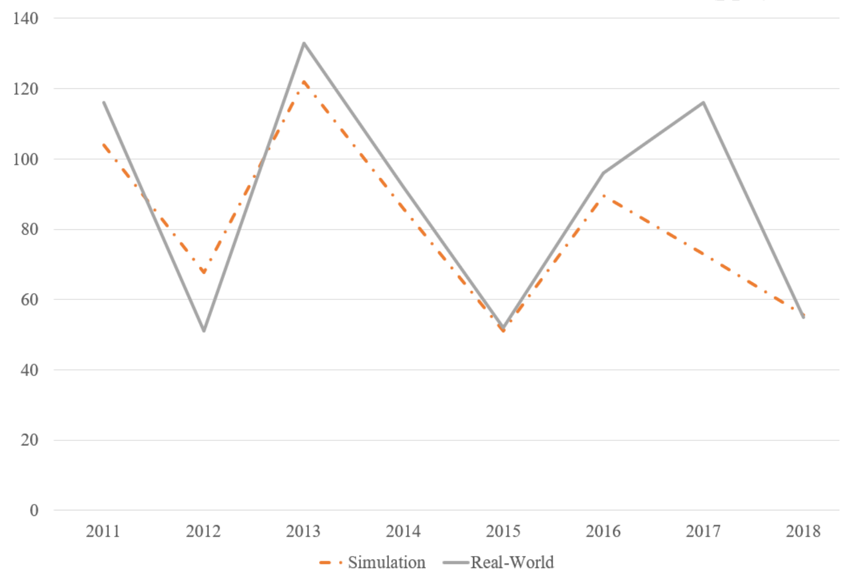
[97] As the simulation is bootstrapped, any mention of the ‘point estimate’ in this study refers to the median of the boostrapped sample. Any reference to the lower or upper bound refers to the 2.5th and 97.5th percentile of the bootstrapped sample, respectively.

[98] These are the 4th-highest 8-hour ozone readings, which is what the EPA considers when designating non-attainment areas. 2010 is not provided because it is not stochastically estimated in the model.

Figure 11: Simulated vs. Real-World Ozone Concentrations



As is clear, there is more variability in the actual ozone levels than in the simulation. The bootstrapped point estimate is by definition less variable than any given iteration, and the 'real-world' outcome could be considered a specific 'iteration' of the model. The largest discrepancy between simulated and actual concentrations is observed in 2017 is because certain meteorological input variables were not available post-2016 and had to be simulated using prior observations. This is also why there is a 'convergence' of estimates post-2016 in upcoming charts.

The Uinta Basin first reached non-attainment in 2012, which is due to the ozone concentrations identified from 2010-2012, although the region was not officially designated as non-attainment until 2018 due to administrative issues[99]. This compares favorably to the simulation, which has a point estimate of 2012 as the first year of non-attainment in all 1,000 models. Additionally, based on historical distributions of the weather data and typical energy development, the model estimates there was

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[99] https://www.federalregister.gov/documents/2012/05/21/2012-11618/air-quality-designations-for-the-2008-ozone-national-ambient-air-quality-standards

Table 12: Simulation With and Without Expropriation Threat

Measurement	Base Model	No Regulatory Risk	% Change
Average ozone	80.4	83.8	4.2%
Likelihood of non-attainment levels	73.0%	78.6%	5.6%
% Parcels drilled	11.1%	13.0%	1.9%
Drill period	2.18	2.30	5.5%
Profit per parcel	97,961	120,839	23.4%
Profit per drilled parcel	927,518	965,204	4.1%

a 73.0% likelihood that the Basin would be declared in non-attainment.

Other measurements in the simulation are reasonable. The median percent of parcels that are drilled is 11.1% (95% confidence interval: 2.7% to 25.5%). The median average profit per parcel is $97,961 ($27,124 to $313,560), while the median average profit of *drilled* wells only is $927,518 ($694,089 to $1,286,686). The median drill period is 2.18 (0.72 to 3.27).

3.2 Green Paradox Specifications

I ran the same model with the same randomization seed, but without any regulation of developers. In this version of the model, not only does the regulator never step in and curtail developer behavior, but developers plan and act under the assumption that there is no regulatory risk. In this model, the median percent of parcels that are drilled is 13.0% (95% confidence interval: 3.1% to 28.7%). The median average profit per parcel is $120,839 ($31,240 to $382,131), while the median average profit of *drilled* wells only is $965,204 ($717,339 to $1,375,126). The median drill period is 2.30 (0.66 to 3.30).

It is illuminating to compare important bootstrapped median measurements from the base model to the no regulatory risk model:

Not surprisingly, parcel profitability would rise significantly in a world with no regulatory threat or restrictions. Across all parcels, profitability would increase by 23.4% (or \$22,878) per parcel), while the profitability on drilled wells only would increase by 4.1% (\$37,686 per parcel). Multiplying by the 5,858 parcels in the study, a back-of-the-envelope calculation suggests that ozone non-attainment restrictions cost the Uinta Basin oil industry \$134 million over the 2010-2018 period. This is a steep cost in profitability, and is roughly on the scale with a prior estimate of a \$270 billion per year cost across the country if the 8-hour ozone threshold were reduced to 60 ppb[100].

Of course, this cost is well worth the lost profitability if the ozone situation is appreciably better with regulation than without it. However, this does not appear to be the case, as ozone levels routinely exceeded NAAQS standards almost every year of the data. The average ozone concentrations would have been only 4.2% higher if there were no EPA regulation. It is also important to remember that unlike many other counties under EPA non-attainment regulation, the Uinta Basin is a sparsely populated area. The combined population of Duschesne and Uintah Counties is only roughly 55,000 Utahns, meaning that the number of people exposed to high ozone levels is low.

To test for the weak green paradox, I can compare the period-by-period ozone concentrations across the model with and without regulation. In my model, there is no green paradox, although an environment without regulation has a higher wait time between the granting of the APD and spudding (median of 2.18 periods with regulation versus 2.30 periods without regulation). This means that while

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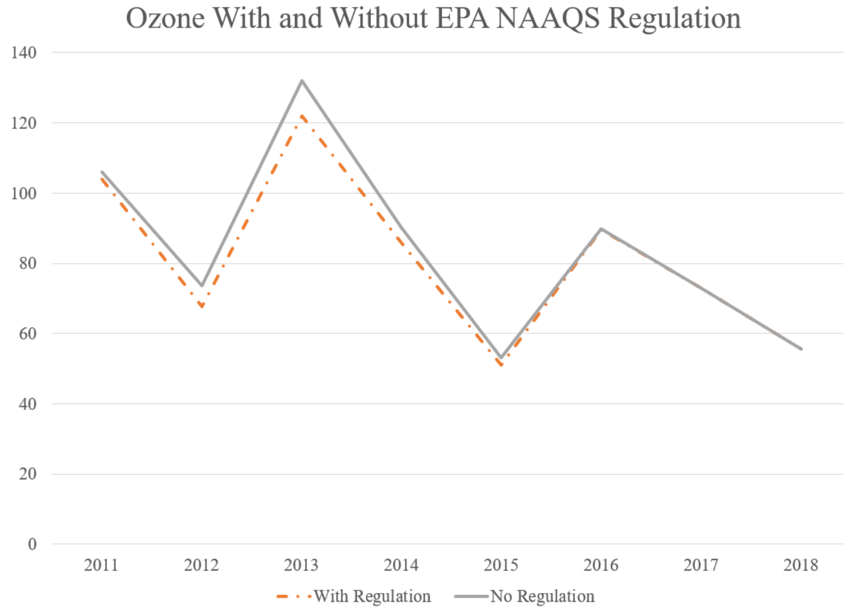
[100] https://www.nam.org/potential-economic-impacts-of-a-stricter-ozone-standard/

developers are ‘hurrying-up-and-drilling’, the clumping of accelerated spudding in earlier periods does not outweigh the effects of there being fewer wells spudded overall, and so ozone concentrations are lower under a no-regulation regime in every period of the model.

Figure 12: Ozone Concentrations: Regulation vs. No Regulation



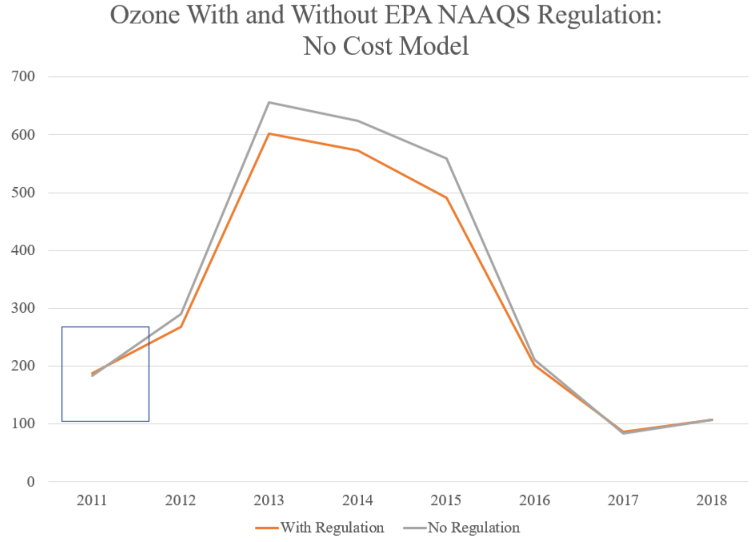
It is important to note that these results are sensitive to the model assumptions. As mentioned in Section 1.1.2, a green paradox is more likely to be found when there is more drilling, especially *more drilling happening later*, as these two factors mathematically produce a stronger shift of spudding to the earlier periods resulting in meaningful ozone accumulation. In the literature, the green paradox is most often considered as a supply-side question and extraction costs are usually considered the key determinant in an optional extraction path [Kollenback (2019)[37]]. The position that low extraction costs are key is corroborated by the theoretical results of Gerlagh (2011)[22] and Grafton, Kompas, & Long (2012)[50], who find that lower resource extraction costs can lead to a green paradox that would not exist otherwise.

A lower cost makes a green paradox more likely, simply because there are more wells being drilled overall, and thus more that are concentrated in the early periods under regulation.

I ran a model that eliminates drilling costs entirely, which are sometimes assumed to be 0 in the literature [see: Eichner and Pethig (2011)[18] and Hoel (2011)[28]]. Unsurprisingly, there is a boom in spudding in a no-cost world with correspondingly higher profits. The median percent of parcels that are drilled is 65.5% (95% confidence interval: 32.0% to 71.0%). The median average profit per parcel is $671,972 ($228,854 to $1,186,609), while the median average profit of *drilled* wells only is $1,050,079 ($614,522 to $1,686,865). The median drill period is 3.43 (2.56 to 4.58). Just as before, I need to run this model against one with no regulation to determine the existence of a green paradox. In the alternative with no regulation, the median percent of parcels that are drilled is 67.7% (95% confidence interval: 30.7% to 71.9%). The median average profit per parcel is $747,445 ($232,237 to $1,313,565), while the median average profit of *drilled* wells only is $1,138,094 ($658,231 to $1,854,628). The median drill period is 3.33 (2.60 to 4.76).

The no-cost model does exhibit a small and brief green paradox, in that ozone emissions are slightly higher during the first period under regulation than without regulation if costs did not exist:

Figure 13: No Costs Ozone Modelling



There is a short one-period (representing one year) span in which ozone concentrations are expected to be higher under a regulatory regime than in a world with no EPA regulation, if drilling costs did not exist. Of course, it is key to point out that even in this imaginary no-cost scenario the increase in ozone concentrations due to the regulation is not meaningfully large, being only 4.1 ppb (or 2.2%) in the first period. All periods following the first see higher ozone concentrations with no regulation than if the EPA steps in and bans drilling during non-attainment. Thus, my model suggests that while the green paradox is something the EPA needs to be mindful of, in the case of the Uinta Basin their regulation did not meaningfully raise concentrations for any period.

Another interesting note is how high ozone levels become in a no-cost drilling context. Here, ozone concentrations spike to a peak exceeding 600 ppb. A reading of 600 doesn't come close to approaching nationwide ozone records, but is so high that breathing will cause neutrophilic inflammation in the lungs[38], which leads to several pulmonary diseases. Even in years that don't approach such a high threshold, ozone levels are elevated to a level where they are more than simply a mild nuisance. Ozone levels projected to be so high because I am using Mansfield's algorithm for ozone formation, which has several non-linear components including interactions between different input variables. In this algorithm a higher proportion of spuddimg can lead to a blowup of estimated ozone concentrations.

Unfortunately, there is no way for me to test whether the regulation in a no-cost environment meets the requirements of the 'strong' green paradox. To have a strong green paradox, not only would ozone concentrations be higher for some short-term period under regulation, but cumulative damages due to the spiked ozone levels would also be higher under regulation. This would require a reliable accounting of damages per-person from a given concentration of ozone, along with a social discount factor to discount damages further in the future. While there have been many studies on the societal damages of ozone, none have given precise estimates at different levels of ozone which would be necessary to ascertain a non-linear effect with extraordinary damages found in cases of elevated ozone levels [see: Lange, Mulholland, & Honeycutt (2018)[38]]. However, given how little ozone increases for just one period under regulation, it is highly unlikely that the EPA 8-hour ozone regulation is a case of the strong green paradox.

3.3 2015 change in standards

In 2015 the EPA changed the standard for non-attainment of 8-hour ozone from 76 ppb to the stricter 71 ppb in an effort to protect at-risk populations like the elderly[101]. Before the transition to the 70 ppb limit was announced, it was unknown

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[101] https://www.epa.gov/sites/production/files/2015-10/documents/20151001_air_quality_index_updates.pdf

Table 13: Simulation: 2015 Change in Standards

Measurement	71 PPB Threshold	76 PPB Threshold	66 PPB Threshold
Average ozone	80.4	81.0	79.7
% chance of non-attainment levels	73.0%	70.0%	79.8%
% Parcels drilled	11.1%	11.4%	10.7%
Drill period	2.18	2.23	2.09
Profit per parcel	97,961	101,269	94,288
Profit per drilled parcel	927,518	925,387	924,514

what the new level would be, or whether the standard would even be changed. There was discussion of an even stricter standard starting at 66 ppb, which was studied by the EPA[102].

My model can easily be adjusted to provide the effect of the precise level of the threshold. The base model, which is meant to simulate the real-world conditions as best as posssible, is calibrated to a standard of 76 ppb through 2014, and shift to a treshold of 71 ppb in 2015. I ran one alternative in which the threshold remains at 76 through the dataset, and another in which the treshold decreases to 66 in 2015, rather than 71.

Results from tweaking the threshold in 2015 are both minor and unsurprising. If the threshold is not changed in 2015 and instead remains at 76 ppb rather than reducing to 71 ppb, 11.4% of parcels are spudded (compared to the base model of 11.1%, and with a confidence interval of 2.6% to 26.6%), drilling on average occurs slightly later (due to the extra spudding post-2015 and less chance of regulation) with a median drill period of 2.3 periods (compared to the base model of 2.2 periods, and with a confidence interval of 0.7 to 3.4) and profitability increases to $101,269 per well (compared to the base model of $97,961, and with a confidence interval of $26,629 to $328,376). Perhaps most interestingly, there is a complement to the green paradox in this model. This model has less restrictive regulation, but period

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[102] https://www.epa.gov/sites/production/files/2015-10/documents/20151001_air_quality_index_updates.pdf

1 ozone is lower in this alternative with no change to the looser regulation than with a 2015 change to 71 ppb (103.6 ppb versus 103.9 ppb, with a confidence interval spanning 86.1 to 124.5 ppb). In all other periods, ozone is higher under the less strict regulatory regime. This exhibits how the strength of the regulation can create a green paradox, even though both alternatives have some level of regulation.

Results are the opposite in the especially strict model, as expected: If the threshold were reduced in 2015 to 66 ppb instead of 71 ppb, 10.7% of parcels are spudded (compared to the base model of 11.1%, and with a confidence interval of 2.7% to 24.2%), drilling on average occurs earlier (due to the less spudding post-2015 and more chance of regulation) with a median drill period of 2.1 periods (compared to the base model of 2.2 periods, and with a confidence interval of 0.7 to 3.2) and profitability decreases to \$94,288 per well (compared to the base model of \$97,961, and with a confidence interval of \$27,300 to \$295,932). Again, there is evidence of a green paradox in period 1, as the 'strictest' ozone standard actually produces the highest period 1 emisions. In this alternative, the 2015 change to 66 ppb produces period 1 ozone concentrations of 104.4 ppb versus 103.9 found in the base model, with a confidence interval spanning 86.5 to 126.1 ppb). In all other periods, ozone is lower under the more strict regulatory regime.

4 Why did the sage-grouse and ozone simulations produce different results?

When comparing Chapters 1 & 2 of this dissertation, a keen reader may have noticed that despite both the sage-grouse and ozone being examples of potential regulatory expropriation, developers respond in opposite ways. Similar numerical simulations concerning oil drilling in adjacent states occuring in roughly the same time period came to opposite conclusions. My work predicts that the possible expropriation of drilling rights in Wyoming caused a wait-and-see response in developers, while developers in the Uinta Basin sped up their drilling and given the right circumstances even may see a green paradox. What causes this opposite reaction to a seemingly similar regulatory problem?

There are three reasons why I find different results across the two contexts:

1. The announcement periods are structured differently. The sage-grouse could be resolved at any time, while the ozone regulation required at minimum 3 years of ozone readings. Thus, there was the possibility that drilling could be banned at any moment in Wyoming, while Uinta Basin producers knew they had at least a couple years (and likely more) before drilling rights could possibly be expropriated. Because oil producers follow a decline curve in which production is halved within only 7 months [see Kellogg (2014)[35]], a couple years or more is plenty of time to extract most of the recoverable liquid resources from a well.
2. There is a different likelihood of regulation between USFWS's decision on the sage-grouse, and EPA's outcome regulating ozone. Ozone regulation is dictated formulaically, with any three-year period in violation mandating improvement. Because ozone readings were consistently high and had reason to increase made a non-attainment result quite likely (my model estimates a 73.0% chance). In contrast, the USFWS uses a more opaque process, and even the evidence that existed suggested there was almost an exactly 50% chance of listing.

Table 14: Simulation With Sage-Grouse Announcement Structure

Measurement	Base Model	No Regulatory Risk	S-G Announcement
Average ozone	80.4	83.8	4.2%
Likelihood of non-attainment levels	73.0%	78.6%	74.4%
% Parcels drilled	11.1%	13.0%	9.0%
Drill period	2.18	2.30	2.40
Profit per parcel	97,961	120,839	71,841
Profit per drilled parcel	927,518	965,204	836,818

3. Spudding a well in Wyoming does not make it any more likely that the regulator steps in, while spudding a well in the Uinta Basin directly increases ozone levels, which increases the likelihood of regulation. This causes a 'race to the bottom' in which no developer wants to be the one who is not allowed to produce because its neighbors spudded first.

I ran a version of the ozone simulation but changed the announcement period structure, likelihood of regulation, and cross-well profitability effects to match the design of the sage-grouse model. In this model, the regulator can intervene immediately, and the intervention follows a memoryless Poisson process with an expected wait time of 6.3 periods[103]. The likelihood drilling and extraction are banned is a constant 53% through the model. Otherwise the simulation remains the same, meaning it is still parameterized by Uinta Basin production and well characteristics, density, and spudding timing.

As is seen in Table 14, when using the sage-grouse announcement period structure combined with the Uinta Basin drilling parameterization, the ozone simulation now provides a 'wait-and-see' response rather than a 'hurry-up-and-drill' reaction to uncertainty. The median drill period rises to period 2.4 (CI: 0.74 to 3.7), an

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[103] The sage-grouse expected wait time is 76 months, which is 6.3 years.

increase of 4.3% over the baseline of ‘no regulation’. Profit falls to $71,841 per well (16,637 to 274,183) and only 9.0% of parcels are spudded (1.9% to 24.1%). This alternative demonstrates the the announcement period structure is critical in the formation of a ‘wait-and-see’ or ‘hurry-up-and-drill’ response to expropriation threat.

5 Conclusion

In this chapter, I constructed a simulation of the drilling environment present in the Uinta Basin from 2010-2020, when the region was subject to potential regulatory oversight by the EPA that could have dire consequences for the local energy industry. Using the real-options framework of Kellogg (2014)[35] and the real-world drilling conditions present in the Basin over the relevant time period, my work shows that developers expected there was a 73% chance that the Basin would fall into non-attainment for 8-hour ozone, and the pending regulation nearly caused a green paradox. In a world without drilling costs, there would have been a brief green paradox.

Envisioning future work on this topic is easy. On a large scale, the EPA and other regulatory agencies need to be on the lookout for policies that have perverse incentives, especially over the short-run. These policies are particularly problematic when there is an ‘announcement’ period preceding the actual enforcement of the law. It is duaring this announcement period when resource holders believe that future regulation is upcoming that a weak green paradox is most likely to occur.

Work on definitively establishing whether a strong green paradox could exist in EPA regulation would also be useful, but this paper strongly suggests that a strong green paradox did not occur in the Uinta Basin. Information from atmospheric and health studies tying differential levels of ozone exposure to differing mortality levels would be required to fill in gaps to answer the question of whether a strong green paradox exists.

Chapter IV

A Cost/Benefit Test of Online Leasing

1 Introduction

Oil, gas, and coal development in the United States is generally leased from the land owner to mineral developers, who have a window to prove there are recoverable reserves in the leased parcel. Given that most mineral development (particularly oil & gas) occurs in the Western states, these landowners are predominantly the federal government (in particular, the Bureau of Land Management [BLM]) and state governments. These auctions often make up a significant portion of state budgets. The state of North Dakota expects to raise \$2.9 billion from oil & gas leasing plus associated royalties, comprising 21.3% of its state budget[104]. Wyoming, a fellow energy-heavy state, raised \$146 million in 2017 solely from leasing revenues[105], making up 5% of its budget[106]. By comparison, the BLM raked in \$1.1 billion in lease revenues alone (not including associated royalties) in 2018, which covered the entire annual budget of BLM.[107]. While over a billion dollars in leasing revenue is a record high, typical years still bring in well north of \$300 million.

Despite the importance of leasing revenues relative to the size of state and federal budgets[108], the leasing process itself has been the subject of little economic research.

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[104] https://www.apnews.com/b200edb6f060494ab5355b5c1e8a3d75

[105] https://trib.com/business/energy/wyoming-oil-and-gas-lease-revenue-increases-by-percent-in/article_64046af2-f540-5b50-be96-40307bbd77bd.html

[106] https://trib.com/news/state-and-regional/budget-bill-makes-further-cuts-to-state-government/article_ce37950a-5098-5abf-a1bd-9ab6f71e128c.html

[107] https://www.doi.gov/news/energy-revolution-unleashed-interior-shatters-previous-records-11-billion-2018-oil-and-gas

[108] The leasing process itself generates around one quarter of energy development revenue for states and the BLM. The remaining three quarters is royalties associated with extraction. These are rough percentages and vary year-to-year depending on the number of parcels auctioned. See: https://www.blm.gov/programs/energy-and-minerals/oil-and-gas/about

Part of this dearth of research is due to limited data: generally, only a parcel's winning bid value is available to the public while losing bids and bidders are kept private, limiting the value of these auctions in furthering our understanding of auction theory. However, there remain key policy questions the available data can still answer. One of those questions is whether a transition to a multi-sided platform enhances lessor revenue beyond the cost of the platform. A multi-sided platform (MSP) is any website, device, or app that brings buyers and sellers together to facilitate transactions. eBay is a classic examples of MSPs. Using a differences-in-difference strategy comparing leasing offices that turned to EnergyNet and those that remained offiline, this paper reviews the implementation of an MSP in the oil & gas leasing industry. I find that EnergyNet significantly increases revenues brought in by public leasing jurisdictions and easily covers the cost of using the MSP.

Prior to the fall of 2016, virtually all public auctions outside of leases by the Colorado and Utah state government were held in-person. State commissions and regional branches of the BLM held quarterly auctions of oil & gas parcels following a nomination process in which lessors would solicit input on which parcels to put up for sale. The timing and location of the auctions were released about half a year in advance. All parcels would be put up for bidding on the same day in an open-outcry ascending bid (English) auction style, meaning individuals or companies looking to lease parcels would need to send a representative to isolated Western state capitals or far-flung BLM offices. Colorado and Utah had unique leasing systems, in that Colorado transitioned to an online system early in 2013, and Utah maintained a first-price sealed-bid auction before the state transitioned to an online system in

2016. Prospective lease holders would mail in their bid values, and the winning bidder would pay the full amount of their bid.

The mineral industry was never happy with in-person bidding, and pressured governments to adopt online leasing. This wish was granted in the National Defense Authorization Act in 2014, which amended the Mineral Leasing Act to allow online sales[109], which was piloted before becoming the norm for the BLM in the fall of 2016. Many Western state oil & gas commissions followed the BLM's lead and simultaneously turned to an online auction platform. Energynet.com, a private company that is not owned or managed by any local, state, or federal government, is the sole platform serving state mineral commissions and the BLM. EnergyNet hosts auctions worth millions of dollars each year. In 2017, over $1.25 billion worth of leases were sold on EnergyNet[110]. EnergyNet takes 1.5% of all BLM revenues and 2% of state revenues raised on its platform, which dwarfs the cut auctioneers working for state governments and the BLM had taken during in-person auctions. Jim Odle, an auctioneer who worked for BLM until 2017, earned only a max of $1,500 for running an auction, which is a negligible amount compared to the millions of dollars of leases he sold each auction[111]. Thus, it is imperative for state and federal governments to understand the costs and benefits of using EnergyNet. There are millions of dollars at stake each year when considering the cut the website takes, which will only grow if more states adopt the platform or the federal government continues allowing previously restricted land to be drilled. If governments are not earning at minimum an extra 1.5%-2% in revenues from online leasing relative to what they would have earned from in-person auctions, the transition to EnergyNet

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[109] http://jacksonholeradio.com/2017/06/blm-wyoming-posts-proposed-parcels-for-oil-and-gas-lease-sale/

[110] https://www.outsideonline.com/2269336/obscure-texas-company-selling-public-land

[111] https://www.outsideonline.com/2269336/obscure-texas-company-selling-public-land

does not pass a cost-benefit analysis.

There are two primary reasons why states and the BLM outsourced their auctioneering to the website EnergyNet. The first is convenience that leads to higher bid values. Lessors believed that by reducing the cost of accessing the auctions, more individuals and companies could participate in each auction. Theoretically, the greater number of bidders along with lower search frictions should increase bid values for parcels, which translates into more favorable payouts and royalties to state governments and the BLM. By outsourcing work to an easily-accessed website, potential lessees could more easily view information about the parcels in question. More concrete signals and less uncertainty generally increases the value of mineral deposits, which commissioners hoped would further increase their revenues[112]. Additionally, by allowing everyone across the world equal access to bidding since no one would be restricted by geography, lessors believed they could increase the distinct number of bidders and diversity of the bidders. Lastly, in-person bids have to be concluded the day of the auction. This can be a daunting undertaking when there are upwards of 300 distinct parcels, and sometimes bidders may miss out on some parcels while others are being auctioned in person. Online auctions do not have these constraints - EnergyNet usually puts parcels up for auction for 2 weeks, allowing bidders ample time and opportunity to bid on any parcels they are interested in.

The second reason many suspect state oil & gas commissions and the BLM transitioned to an online platform is to discourage bad publicity and protests of leasing[113]. As the country has become more interested in climate change and the role

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[112] https://www.energynet.com/page/Bill_Britain_Testifies_Before_House

[113] https://westernwire.net/after-moving-lease-sales-online-blm-see-increased-participation-and-revenues-address-security-concerns/

fossil fuels play in a warming planet and wildlife habitat destruction, protests were a regular occurrence outside oil & gas auctions. Some of this hysteria was caused by Tim DeChristopher, who showed up to a BLM auction in Utah and proceeded to bid on parcels even though he had neither the money nor legal right to bid, earning him two years in prison[114]. Nicole Gentile writes for the Center For American Progress that "The BLM's move toward privatized, online lease sales further shrouds an already-abused and opaque system in secrecy; obstructs public oversight; and likely costs taxpayers millions of dollars in lost revenues each year."[115] Likewise, Mya Frazer writes "Given the agency's stated concern over the DeChristopher incident, critics suggest that the BLM's shift to EnergyNet was motivated by the desire to neutralize protests"[116].

Indeed, the transition to EnergyNet has made it all but impossible for a regular individual citizen to bid on parcels. Registration requires documentation that either the individual works for an energy company or makes at minimum $200,000 per year[117]. Additionally, under penalty of perjury registrants must pledge they have are "engaged in the business of exploring for or producing oil or gas or other minerals as an ongoing business." Whether or not BLM was hoping to avoid more protests or another DeChristopher incident, a movement to online sales immediately removes a physical protest location from environmentalists.

Within major Western newspapers and online news organizations, there is plenty of anecdotal evidence that EnergyNet succeeded in its goal of providing a reliable online platform to raise extra revenue for governments. The Casper Star-Tribune,

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[114] https://www.outsideonline.com/2269336/obscure-texas-company-selling-public-land

[115] https://www.americanprogress.org/issues/green/reports/2018/01/04/444501/trump-administration-selling-public-lands-internet/

[116] https://www.outsideonline.com/2269336/obscure-texas-company-selling-public-land

[117] Sadly, I was rejected for this reason.

the primary newspaper of the northern half of Wyoming and the main source of energy news in the state, twice mentioned the positive effect online leasing appeared to have on prices and the harmonious impact of online leasing on state budgets. At the close of 2017, Heather Richards reported that revenue derived from mineral leasing increased over 800% from 2016 to 2017. She quotes Jason Crowder, assistant director for the Office of State Lands and Investments, Trust Land Management Division, writing "it's unclear what exactly made the revenue shoot up so dramatically, other than the state's decision to switch to an online auctioning system which allows out of state companies to easily bid on Wyoming land. That's the only thing we can point to[118]." In her article, she cites other industry sources that provide other possibilities for the staggering increase, including a deferred sale from the prior year as well as a favorable administration back in power opening up previously inaccessible land. In August 2018 Richards wrote "Both the feds and the Wyoming Department of State Lands and Investment switched to an online auction at the start of 2017. The online sales appeared to increase the number of bidders, adding competition that pushed up prices for sought-after parcels[119]." Here, Richards alludes the possibility that not only have revenues increased due to the fact bidders can participate without a costly trip to Casper, but have also possibly increased simply because of more bidders.

Naturally, EnergyNet itself trumpets its success and the power of its platform versus a 'traditional auction'. Their website claims "It's simple: Greater buyer exposure leads to more competition. More competition leads to higher returns for

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[118] https://trib.com/business/energy/wyoming-oil-and-gas-lease-revenue-increases-by-percent-in/article_64046af2-f540-5b50-be96-40307bbd77bd.html

[119] https://trib.com/business/energy/rise-in-lease-sales-pits-wyoming-s-energy-industry-against/article_8c0d056c-8452-5fd4-b234-9bd226a9dfa1.html

sellers[120]". The same site says that the average transaction has 8.4 bidders per transaction, whereas a traditional auction boasts only 2.3. They also advertise advantages like a quick turnover, a higher 'execution rate'[121] than traditional auctions and even claim their 'success-based commission only' is an advantage over the standard 'commission plus extra promotional fee and penalty fees'. No source is provided for any of their comparisons, but the advertised extra number of bidders, higher execution rate, and the difference in fee structure are important measurements that would help determine whether states are saving money by outsourcing their auctions. Notably, a commission-based system is not strictly superior. If the 'take' of EnergyNet exceeds what the flat fee plus smaller commission would be from someone like Jim Odle, then these fees are actually in excess of what governmental bodies would have paid traditional auctioneers. EnergyNet is privately held, and thus it is not possible to fully appraise the earnings of the company, but Outside Online estimated that the company earned about $15 million in 2017 from running public auctions taken as fees off nearly $1 billion in land sales[122] .

The goal of this paper is to evaluate whether states and the federal government really do benefit from an online leasing system, or if that $15 million paid to EnergyNet was an unrecouped cost. While anecdotal evidence may show that online leasing played a large role in the recent increase in state and federal revenues, it is possible to more rigorously determine the impact online leasing has on revenues. Results broadly show that, yes, online leasing passes the cost-benefit test from the perspective of state treasuries and the BLM. Results indicate that a given parcel will bring in roughly 40% more in revenue when being leased online than if it were leased

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[120] https://www.energynet.com/how_do_i_sell.pl
[121] This is percent of parcels that receive at least the minimum bid.
[122] https://www.outsideonline.com/2269336/obscure-texas-company-selling-public-land

in an in-person auction. The results are robust to different model specifications and several comparisons across state lines. This paper concludes that states should transition to an online leasing system to increase revenue derived from mineral leasing. A back-of-the-envelope calculation suggests that leasing offices are accruing \$136 million extra per year because of EnergyNet adoption, after accounting for costs.

The rest of the paper is organized as follows. Section 2 describes the mechanisms that could generate and puts EnergyNet in the context of recent literature regarding technological change and MSPs. Section 3 provides links to all data sources used in this paper as well as summary statistics. Section 4 describes my differences-in-differences methodology, results to my model, and alternative specifications all showing that online leasing significantly increases bid revenues. In Section 5, I investigate the mechanisms driving this increase, and find evidence that the increase is *not* driven by low-information bidders making up a disproportionate chunk of online bidders, by easier access of information, by less travel costs, or by an increase in the supply of parcels. More bidders at the auction are more likely responsible for the increase. Concluding remarks are provided in Section 6.

2 Mechanism

Showing that a transition to online leasing is a windfall for states is the primary conclusion of this paper. But understanding *why* there is such a large increase in bid values is also valuable. Because there are several mechanisms in which MSPs like EnergyNet can increase bid values, the case of EnergyNet and oil & gas leasing presents an interesting intersection of several literatures within the wider auctions literature.

Andrei Hagiu (2007)[23] details three broad mechanisms with which a MSP enhances welfare for buyers and sellers:

1. Lower search costs
2. Lower transaction costs leading to more efficient bargaining. Hagiu (2007)[23] describes this is reducing costs that occur *after* the purchasing and selling parties have identified each other.
3. Thicker markets

EnergyNet is an MSP that utilizes all three mechanisms. See below:

1. Lower search costs. Potential bidders can bid from the comfort of their home. Online leasing systems like EnergyNet require lower search costs leading to better matching because:
   (a) Bidders do not need to travel to & stay at the city hosting the auction.
   (b) While EnergyNet does not produce any original information that cannot be obtained elsewhere, the platform compiles all relevant public information on the parcel, saving bidders search time.
2. Lower transaction costs:
   (a) Participants do not need to sit through bidding for parcels they are not interested in.
   (b) Participants do not need to monitor the bidding process.
   (c) Because EnergyNet pre-screens and registers participants, there are lower enforcement costs to ensuring bidders pay their bids.
3. Thicker markets leading to higher bids:

(a) A 'thick' market means more buyers and sellers. Given the ease of using EnergyNet relative to operating their own auctions, leasing offices may put more supply up for sale on an online platform.

(b) As only the maximum-valuation bidder wins the auction, only the maximum bid value along with the second-highest bid value matters in determining auction price. A larger sample of bidders increases the expected valuation of the maximum-valuation bidders assuming sample bidders are drawn from any reasonable distribution[123].

(c) 'Additional' bidders who only participate in online auctions are likely to be less knowledgeable about energy leasing due to lack of prior experience. While these 'additional' bidders are likely to have lower valuations than bidders who participate in in-person and online auctions (reducing the impact of the prior advantage), their inaccurate knowledge of parcel value could cause them to overbid for parcels.

Of course, it is valid to argue that some of these categorizations are arbitrary. For example, not needing to travel to the auction location could be considered a lower transaction cost rather than a search cost. Likewise, the higher number of bidders comprising the 'thicker market' is most likely due to the attractiveness of online auctions *because* of lower search and transaction costs.

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[123] For example, assume bidders are drawn from the standard normal distribution. The expected maximum value of a sample draw of $n = 5$ bidders is 1.16, while the expected maximum value of a sample draw of $n = 10$ bidders is 1.52.

2.1 Search Frictions

EnergyNet reduces search frictions in two ways. First, with an online auction platform, bidders do not need to travel to auction locations. This is not a trivial reduction in cost - beyond the transportation costs, there is also food & lodging along with the opportunity cost of the bidder's time in travel and 1-2 days of auction. Prior auction locations were scattered across the Mountain West:

Table 15: Auction Locations

Lessor	Auction Location
BLM - Colorado	Lakewood, CO
BLM - Montana & Dakotas	Billings, MT
BLM - Utah	Salt Lake City, UT
BLM - Wyoming	Cheyenne, WY
Montana - State Office	Rotates among counties throughout MT
North Dakota - State Office	Rotates among counties throughout ND
South Dakota - State Office	Rotates among counties throughout SD
Wyoming - State Office	Cheyenne, WY

Companies or individuals will sometimes reduce these costs by sending a representative as a straw buyer who bids on their behalf. Online leasing eliminates the cost of locating and employing these representatives.

The second way EnergyNet reduces search frictions is by compiling all relevant information on a particular lease in one place. Information EnergyNet usually provides includes leasing details like geographic location, acreage, royalty rate, lease term, application fee, any provisions or stipulations (restrictions on drilling), lease terms and conditions, lease forms, recent offset activity (existing wellbores that are used to guide future wells, providing signaling information that would be useful to the firm), contact information of the lessor, and contact information for EnergyNet.

To locate the relevant pages without EnergyNet, a bidder would need to visit a separate website for each element of information, download all information, and finally compile all information together. EnergyNet also has the advantage of presenting information in a standard manner across states. Someone new to Wyoming leasing, even if they are experienced with Colorado leasing, would not know where to obtain relevant information from Wyoming's leasing office.

As is logical, the literature suggests that lower search costs (whether for product information or simply to join the marketplace) enhances welfare for both buyers and sellers because of better matching of buyer to seller. Tadelis & Zettelmeyer (2011)[59] consider a real-world MSP that connects used car buyers and sellers that functions very similar to EnergyNet. The authors randomize the amount of information about the cars and find that more easily accessible information enhances seller revenue for all quality of cars, even if the information disclosed is negative. This is due to the better matching of buyers' heterogeneous preferences with the proper vehicle.

Recent literature in the oil & gas auctions literature comes to the same conclusion. Covert & Sweeney (2019)[11] compare formal auctions of oil & gas leasing rights to informal, negotiated contracts and find that auctions lead to a better lessor-developer match. This better match enhances production.

2.2 Transaction Costs & Bargaining

EnergyNet generally runs semi-sealed modified second-price auctions[124] (henceforth referred to as 'eBay auctions'). This is the same format as eBay, in which buyers must exceed the bid value of the prior maximum bidder by some ϵ amount in order to win the auction. If the bidder submits a bid value far above the previ-

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[124] https://www.energynet.com/how_do_i_sell.pl

ous maximum, they win the auction at the next-highest valuation plus ϵ, which is invariably \$1 per acre. Provided there are no transaction costs, the outcomes of an eBay auction and a traditional English auction will be the same (Hasker & Sickles 2010)[25].

However, there are transaction costs in in-person English auctions that are eliminated on EnergyNet. Unlike in-person bidding, buyers can go straight to the parcel(s) that interest them, rather than sitting through other parcels' auctions. Additionally, buyers do not need to monitor the auctions they are interested in. Like eBay, EnergyNet allows for a 'maximum bid' and will bid on a buyer's behalf if their bid value is exceeded, up until the maximum bid value.

Lastly, lessors do not need to worry about payment with EnergyNet. Welfare is enhanced (including generating higher prices) when the seller is confident they will be paid the winning bid amount. However, enforcing payment is tricky. Other MSPs where enforcement is critically important like eBay and the dark-web marketplace Silk Road rely upon 'reputation' as an enforcement mechanism to ensure payment (see: Houser & Wooders (2006)[31] and Hardy & Norgaard (2016)[24]). Buyers and sellers generate reputation through prompt and accurate delivery of goods and payments, leading to a more efficient market. EnergyNet doesn't need to rely upon a reputation metric because it has a thorough vetting process with legal ramifications including perjury if a bidder misrepresents his background or reneges on payment. Since EnergyNet handles payments and market participants do not need to write reviews of one another, EnergyNet's payment system also saves participants time.

2.3 Thicker Markets

There can be a harmonious relationship between buyers and sellers on EnergyNet, creating a thick market with many buyers and sellers. Because it is easier to run an auction using EnergyNet than by yourself, sellers can auction off more parcels at once. This increased supply along with lower search costs attracts more bidders. From the perspective of the seller, more buyers can't be a bad thing. An additional bidder may have a valuation above the current maximum bid value, which would increase the final selling price.

Prior research by Jackson Dorsey (2019)[14] investigates a new technology with direct similarities to my research environment. He considers the introduction of EnergySage Inc. EnergySage is similar in both name and spirit to EnergyNet. It provides an online platform connecting installers of solar panels with potential customers searching for quotes. Before the introduction of EnergySage, consumers needed to contact installers directly, and installers needed to personally visit each house to produce a quote. Rarely did a consumer ask more than a single installer to provide an estimate for installation at their house. This led substantial market power, in that there were few plausible sellers that could connect with any given buyer. Dorsey writes, "If collecting price quotes is costly for buyers, any installer asked to give a quote can expect to be bidding against few or no other sellers, thereby giving that installer incentive to charge a higher markup".

On EnergySage consumers upload information and pictures of their house to solicit quotes. The necessity of personal home visits from suppliers limited the number of 'bids' per house, and Dorsey finds that switching from an in-person to online platform increases the number of bids submitted from just 1 bid to almost

4 bids per project[125]. Seeing increasing number of bids significantly changes the equilibrium price of solar panel installation. Simply due to the fact that there are more bidders, the price is bid down as more suppliers enter the market and the chance the customer is connected with an efficient installer increases. Additionally, and potentially more importantly, suppliers on EnergySage know they are competing against other installers. Thus, their pseudo-monopoly is broken and suppliers provide both a lower-price and higher-quality product in response to competition.

In-person liquid mineral development auctions have the opposite problem. There is often only one interested bidder for any given parcel, giving that bidder monopsony power. The bidder pays the reservation price, and wins the lease even if they are willing and able to pay more. Bringing in any other bidder with a valuation above the reservation price, even if their valuation is below the current bidder, will increase the winning bid value.

It is easy to imagine the 'marginal' bidder joining the EnergyNet auction but not the in-person English auction being a casual, low-valuation participant. Those with high valuations are likely to participate in the auction regardless to ensure they win the parcels they want. These low-valuation marginal bidders are also likely to be low-information bidders. Low-information bidders are those with little experience and are likely to be those who bid on parcels as individuals (rather than energy development companies). While low-information bidders probably have lower *average* valuations than experienced bidders because of credit constraints and possible risk-aversion, low-information bidders have a wider variance in parcel valuation. As sample size (bidders) increases, the low-value bidders will have a

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[125] Dorsey sometimes refers to these projects as 'auctions', because the solicitation of quotes functions similarly to an auction.

higher expected maximum valuation than high-value bidders[126]. An influx of low-information bidders could increase lease price at the cost of match quality.

3 Data

3.1 Data Summaries

State land leasing and BLM field offices conduct regular auctions of parcels under their jurisdiction, and also provide data on the winning bids for each parcel. Generally, each lessor provides two key files for each sale: the "Sales Notice", which is released 1-2 months prior to a sale and contains information like parcel lease number and location, and the "Sale Results", which provides the winning bid value and bidder (or indicates that no bidder bid the reservation price). By combining the two files for each sale, I obtain records representing each parcel leased in a given auction with the following fields: Bid Value Per Acre, Acres, Township, Range, Winning Bidder, and Auction Date. I standardized the Bidders across datasets because Bidder is not consistent from auction to auction or across states. Other than the Utah state leasing office, no state or federal jurisdiction provides any information on losing bids or bidders, including whether any losing bids were even entered.

When comparing parcel count by year, it is clear that most of my data comes from 2004-2013, before the transition to online leasing. But it is important to note that Wyoming and especially North Dakota are far better represented in the data

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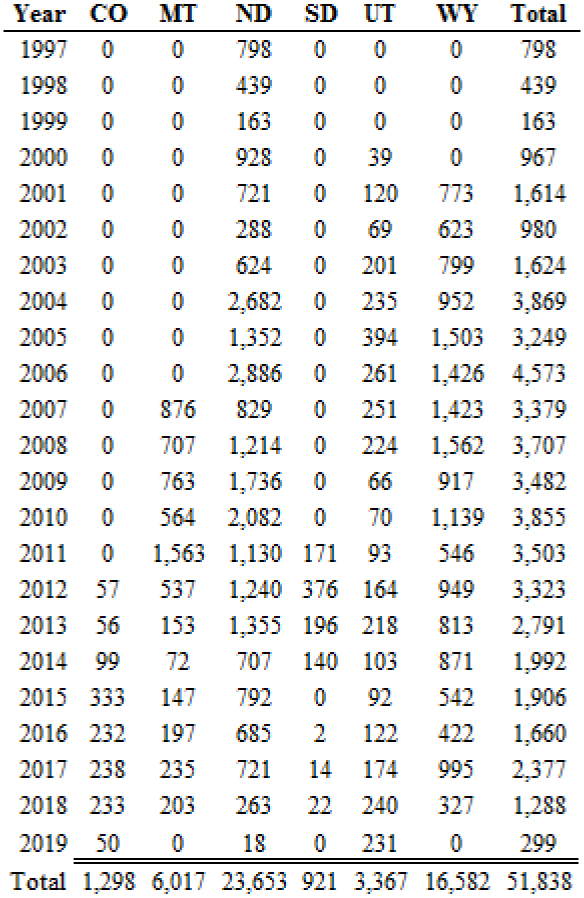
[126] For example, assume the valuation of high-knowledge bidders are drawn from the normal distribution $H \sim N(10, 1)$ and the valuation of low-information bidders are drawn from the normal distribution $L \sim N(1, 5)$. With a small sample size of 10, the high-knowledge bidders have the higher expected maximum value ($11.5 > 8.7$), but at a sample size of 100, the expected value of the maximum of the low-information bidders exceeds the expected maximum of the high-knowledge bidders ($13.5 > 12.5$).

Table 16: Leases by State Over Time

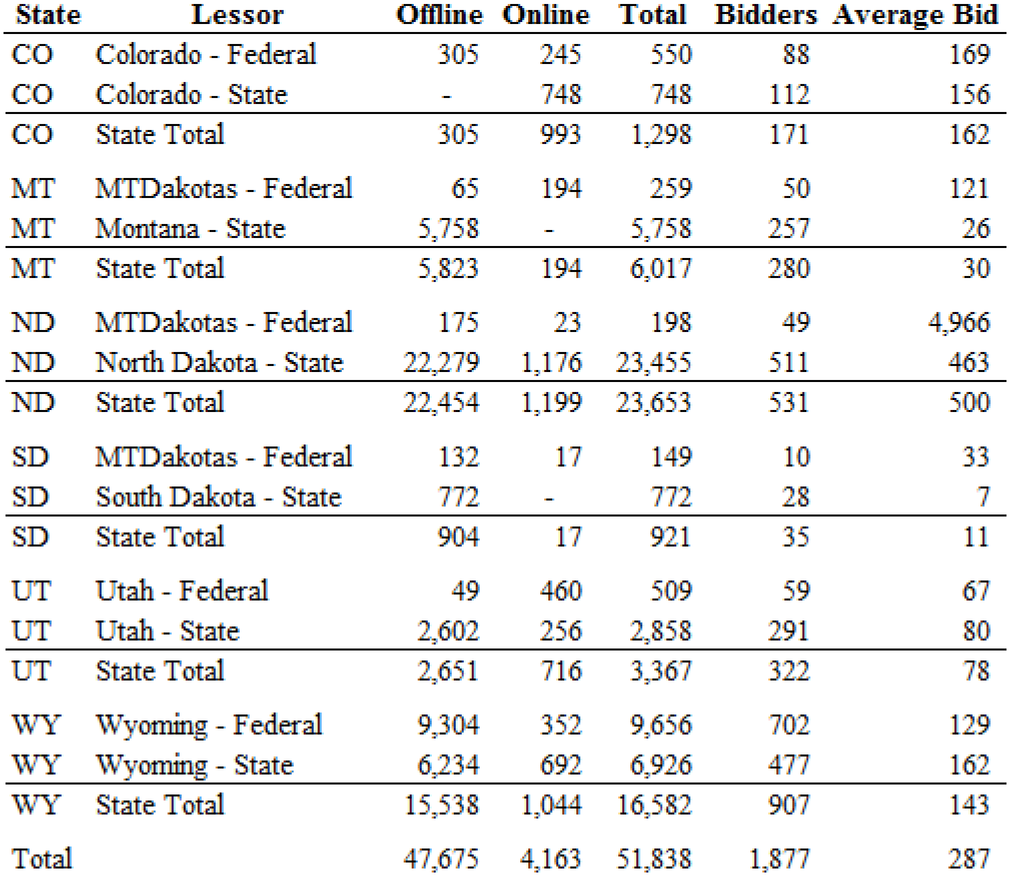


Year	CO	MT	ND	SD	UT	WY	Total
1997	0	0	798	0	0	0	798
1998	0	0	439	0	0	0	439
1999	0	0	163	0	0	0	163
2000	0	0	928	0	39	0	967
2001	0	0	721	0	120	773	1,614
2002	0	0	288	0	69	623	980
2003	0	0	624	0	201	799	1,624
2004	0	0	2,682	0	235	952	3,869
2005	0	0	1,352	0	394	1,503	3,249
2006	0	0	2,886	0	261	1,426	4,573
2007	0	876	829	0	251	1,423	3,379
2008	0	707	1,214	0	224	1,562	3,707
2009	0	763	1,736	0	66	917	3,482
2010	0	564	2,082	0	70	1,139	3,855
2011	0	1,563	1,130	171	93	546	3,503
2012	57	537	1,240	376	164	949	3,323
2013	56	153	1,355	196	218	813	2,791
2014	99	72	707	140	103	871	1,992
2015	333	147	792	0	92	542	1,906
2016	232	197	685	2	122	422	1,660
2017	238	235	721	14	174	995	2,377
2018	233	203	263	22	240	327	1,288
2019	50	0	18	0	231	0	299
Total	1,298	6,017	23,653	921	3,367	16,582	51,838

than other states. In fact, nearly 50% of all parcel observations are from North Dakota, and North Dakota in the only state represented before 2000. Colorado and South Dakota do not have any data available before 2010.

Breaking the data out further by lessor, it is immediately clear that state leasing offices, not the BLM, are the lessors on most of the observations. Although the federal government manages far more land than states in the West, the predominance of states is not surprising. On the supply side, states are often more generous with the quantity of parcels sold in each auction. On the demand side, developers value state land more than federal land, as state land usually comes with fewer

Table 17: Online vs. Offline Leases by State



State	Lessor	Offline	Online	Total	Bidders	Average Bid
CO	Colorado - Federal	305	245	550	88	169
CO	Colorado - State	-	748	748	112	156
CO	State Total	305	993	1,298	171	162
MT	MTDakotas - Federal	65	194	259	50	121
MT	Montana - State	5,758	-	5,758	257	26
MT	State Total	5,823	194	6,017	280	30
ND	MTDakotas - Federal	175	23	198	49	4,966
ND	North Dakota - State	22,279	1,176	23,455	511	463
ND	State Total	22,454	1,199	23,653	531	500
SD	MTDakotas - Federal	132	17	149	10	33
SD	South Dakota - State	772	-	772	28	7
SD	State Total	904	17	921	35	11
UT	Utah - Federal	49	460	509	59	67
UT	Utah - State	2,602	256	2,858	291	80
UT	State Total	2,651	716	3,367	322	78
WY	Wyoming - Federal	9,304	352	9,656	702	129
WY	Wyoming - State	6,234	692	6,926	477	162
WY	State Total	15,538	1,044	16,582	907	143
Total		47,675	4,163	51,838	1,877	287

restrictions.

Because most of my data predates the transition to online leasing and Montana and South Dakota state leasing offices never went online, the large majority (80.3%) of parcels are sold offline, whether through the mail (Utah state office) or in-person English auctions (all other leasing jurisdictions). Average bid value varies considerably among states and lessors. South Dakota has the lowest bid value, with an average of only $11/acre. North Dakota has by far the highest value per acre at $500, with its small number of federal parcels going for an average of almost $5,000 per acre. This is because all of the federal parcels up for lease in North Dakota are located in the Bakken Formation, a highly productive play.

3.2 Data Sources

All leasing data can be downloaded from the following links: Colorado State Land Board,Montana Department of Natural Resources and Conservation, North Dakota Trust Lands, South Dakota School and Public Lands, The State of Utah School and Institutional Trust Lands Administration, Wyoming Office of State Lands and Investments, Colorado BLM Regional Office,Montanas & Dakotas BLM Regional Office,Utah BLM Regional Office , and theWyoming BLM Regional Office, or by inquiry to the author.

4 Impact on Bidding

4.1 Methodology

This paper utilizes a reduced-form standard difference in differences (DiD) strategy to evaluate whether online leasing leads to higher bid values. DiD analysis evaluates the impact of a treatment (in this case, a particular auction being held online rather than in person) on an outcome (bid value) across a treatment and control group over multiple periods, in which the treatment is only active for some of the periods. In these regressions, certain jurisdictions serve as the control populations (these are states that never transitioned to an online leasing system, or were always online, namely Montana, South Dakota, and Colorado), and other jurisdictions serve as treatment states (jurisdictions that transitioned to an online system in late 2016, namely North Dakota, Utah, Wyoming and the BLM). The primary regression equation is:

$$log(Bid_{i,s}) = YearSeasonFE_s + TownshipRangeFE_i + FederalFE_{i,s} + Online_{i,s} + Nearby_{i,s} + \epsilon_{i,s} \tag{8}$$

[127]where $log(Bid_{i,s})$ is the bid value of a parcel located in township-range i during Year/Season s, $YearSeasonFE_s$ is a categorical fixed-effect for Year/Season[128] s. Season fixed-effects control for contemporaneous market conditions, such as the prices of oil & gas and cost and tax structures common to the industry nationwide. $TownshipRangeFE_i$ is a categorical fixed-effect for township-range i[129]. Controlling for township-range accounts for the time-invariant characteristics of the well location, and is also the geographic level state leasing agencies and the BLM use to auction off parcels. Otherwise, it would be possible that significant findings are due to differing levels of expected oil & gas well production, eliminating the possibility that results are driven simply by the online auctioned parcels being of higher quality than those sold in person. $FederalFE_{i,s}$ represents a fixed-effect that is equal to 1 when the parcel is managed by the federal government, rather than a state office. $Online_{i,s}$ is a binary equal to 1 if the observed auction was held online. Errors are clustered at the township-range level for all models, including alternative specifications and robustness checks. $Nearby_{i,s}$ is a binary equal to 1 if the parcel is in the same township-range as another parcel leased by the same winning

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[127] The regression equation is similar to Fitzgerald (2010)[21], in that he also regresses bids on sale and geographic fixed-effects. However, Fitzgerald's geographic fixed-effect is less precise than mine (he uses county) and he regresses the entire bid value rather than per-acre bid value, meaning he also must control for lease size.

[128] Different jurisdictions do not hold their auctions on the same date, but often will host one auction per season, or one auction every other season. Both federal and state leasing agencies hold auctions at regular times each year in the same areas. For example, the Montana/Dakotas branch of the BLM auction off parcels in Montana in December/January, May and October, and parcels in the Dakotas in July and September.Controlling for the year/season allows me to take into account the current market conditions prevailing in any given season, and isolate the effect of online leasing independent from time-varying effects.

[129] Note that a given township-range will never span multiple states; any township/range will be unique to one state.

developer in the last five years. I control for nearby managed parcels because developers may have inside information about the parcel in question gathered from tests and production from nearby parcels. Additionally, developers may be interested in continguous plots. Errors are clustered at the township-range level for all models, including alternative specifications and robustness checks. Note that results do not meaningfully change if lessor-specific controls are used (for example, controlling for different federal leasing offices separately versus subsuming them into a 'federal' fixed-effect) and if winning-bidder specific controls are used.

There is one potential threat to validity with this methodology that I cannot fully account for. It is possible that states expecting they had more to gain by switching to an online leasing system are indeed those that transitioned. This would bias my result upwards. I do not have any way to control for this, but there is no indication in any news reports or from my discussion of state leasing representatives that this was the case. Moreover, the fact that all states that transitioned and the BLM made the transition effectively simultaneously in late 2016/early 2017 makes it doubtful that there is an endogeneity issue in my model.

One of the primary reasons states and the federal government elected to move to an online system was to avoid in-person protests of lease sales. These protests are embarrassing to state leasing offices and were effective. On several occasions states were forced to delay in-person auctions to avoid conflict with protestors[130] . If there were selection into treatment, states with more exposure to protests would be more likely to enroll in online leasing. To evaluate this possibility, I used Google News to count all news articles from January 2000-June 2016 that included the terms

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[130] https://archive.sltrib.com/article.php?id=3287268&itype=CMSID

‘lease’,‘protest’,‘climate’, and the given state[131]. I run an alternative in which I search for the word ‘environment’ instead of ‘climate’. There was no correlation between the number of articles concerning environmental protests and selection into treatment:

Table 18: News Articles on Protests

State	Articles - Climate	Articles - Environment	Oil Rank	Gas Rank	Treatment
Montana	245	167	13	20	No
South Dakota	88	176	25	30	No
North Dakota	61	69	2	12	Yes
Utah	179	336	10	11	Yes
Wyoming	141	346	8	8	Yes

There does not appear to be a discernible relationship between local interest in protests and selection into treatment. When counting articles mentioning ‘climate’, the average count of articles from states that did not transition to online leasing actually *exceeds* the count of average number of articles from states that did transition, 166.5 articles to 127[132]. The relationship is reversed when counting articles mentioning ‘environment’, with 171.5 articles from states that did not go online versus 250.3 articles for states that did go online. Moreover, more articles from states that went online would be expected because they are heavier energy producing states with more auctions to protest[133].

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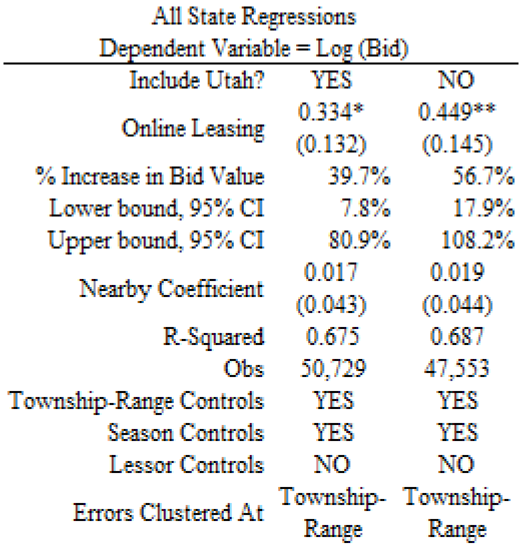
[131] Omitting ‘climate’ from this list does change results in that more articles are written about states that transitioned than those that did not. However, many articles about leasing ‘protests’ without mentioning climate concern the formal ‘protest’ process, rather than an in-person demonstration opposing leasing. Any parcel put up for auction can be ‘protested’, which means that some third party does not think the parcel should be up for nomination. Parties that often protest parcels include environmental groups, other governmental bodies, private businesses, and citizens living nearby. They may be motivated by wildlife or environmental interests, loss of recreational opportunities, or the desire to develop the land instead for agriculture or housing. The formal ‘protest’ process is not an in-person demonstration; it is a written process in which the protestor identifies specific parcels that are ‘under protest’ and if their claims have merit the leasing jurisdiction delays those specific parcels from being sold. For more information on the ‘protest’ process, see this link: https://www.gao.gov/assets/310/308276.pdf .

[132] Colorado is missing from this chart, because it has always used online leasing.

[133] https://www.eia.gov/energyexplained/oil-and-petroleum-products/where-our-oil-comes-from.php, https://www.eia.gov/tools/faqs/faq.php?id=46&t=8. Note that for gas production only onshore production was considered when creating the state rankings, although the table would not meaningfully change if offshore production were considered as well.

Table 19: All States Pooled Results



All State Regressions

Dependent Variable = Log (Bid)

Include Utah?	YES	NO
Online Leasing	0.334*	0.449**
	(0.132)	(0.145)
% Increase in Bid Value	39.7%	56.7%
Lower bound, 95% CI	7.8%	17.9%
Upper bound, 95% CI	80.9%	108.2%
Nearby Coefficient	0.017	0.019
	(0.043)	(0.044)
R-Squared	0.675	0.687
Obs	50,729	47,553
Township-Range Controls	YES	YES
Season Controls	YES	YES
Lessor Controls	NO	NO
Errors Clustered At	Township-Range	Township-Range

4.2 Results

My base model includes data from all states in analysis (Colorado, Montana, North Dakota, South Dakota, Utah, and Wyoming), including both state leasing office parcels and BLM parcels. This is called the ‘pooled’ model. The pooled model evaluates the average effect of moving to an online platform across all included states. The lessor fixed-effects ensure that this treatment effect is not due to the state office vs. the BLM (or both jurisdictions) moving online together in late 2016. Note that I run the model with and without Utah because of Utah’s unique auction format.

There is convincing and consistent evidence that the online leasing platform EnergyNet significantly increases bid revenue for state and federal coffers. The base model including Utah implies that bids increased 39.7% due to online leasing. The same model excluding Utah indicates online leasing leads to a 56.7% increase in bids. Both models are significant at the 0.1% level.

An increase of 39.7% in bids for a given parcel is remarkable, and clearly shows that the EnergyNet system covers its 'take' (2% of sale revenues from states, and 1.5% from BLM). Even the lower bounds of the 95% confidence interval (7.8% and 17.9%) exceed the cost of implementing the system. A back-of-the-envelope calculation suggests that using EnergyNet instead of in-person auctions provides an extra \$136 million per year to the states and federal government[134].

Because state and federal leasing offices did not transition at precisely the same time because of differing jurisdictional laws and regulations, the pooled regression is an example of a 'staggered' DiD model. A staggered DiD model is one in which transition to treatment is not simultaneous across the treated, and can result in biased coefficient estimates if different groups respond to treatment heterogeneously [see Baker, Larcker, & Wang (2021)[3]]. However, there are reasons to think this is not a serious concern in the context of my pooled regression:

1. All switches were completed over a small window relative to the entire range of analysis (July 2016 to February 2017)

2. Offices have only 3-4 sales per year, meaning that even though offices switched at different dates, there were not many auctions in the 'intermediate' period.

3. Most importantly, only the pooled model is 'staggered'. Models run across a single state border - whether limited to parcels near the border in the spatial RD model or using the whole state data - do not have the staggering issue. Likewise, the state vs. BLM model also does not have a problem with 'staggered' treatment. These other models produce effects at least as large as the pooled model, typically clearing higher significance thresholds as well.

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[134] 39.7% increase in bids less 1.75% take (average of 1.5 and 2% take) multiplied by the 'typical' \$358 million from all leasing revenues across the country. See: https://www.instituteforenergyresearch.org/fossil-fuels/gas-and-oil/2018-oil-and-gas-lease-sales-generated-record-revenue-of-1-1-billion/

Table 20: Neighboring States Results

Lease Price Regressions - State vs. State Comparisons
Dependent Variable = Log (Bid)

Control State	MT	SD	CO	MT	SD	CO
Treatment State	ND	WY	WY	WY	ND	UT
Online Leasing	0.342+	0.685**	0.746***	0.593**	0.922***	0.241
	(0.194)	(0.258)	(0.191)	(0.198)	(0.208)	(0.238)
% Increase in Bid Value	40.8%	98.4%	110.9%	80.9%	151.4%	27.3%
Lower bound, 95% CI	-3.8%	19.6%	45.0%	22.7%	67.3%	-20.2%
Upper bound, 95% CI	105.9%	228.9%	206.6%	166.7%	278.0%	102.9%
Nearby Coefficient	0.006	0.065	0.058	0.045	0.063	0.039
	(0.080)	(0.039)	(0.039)	(0.039)	(0.088)	(0.103)
R-Squared	0.773	0.595	0.589	0.632	0.767	0.664
Obs	29,381	17,314	17,265	22,168	24,527	4,034
Township-Range Controls	YES	YES	YES	YES	YES	YES
Season Controls	YES	YES	YES	YES	YES	YES
Lessor Controls	NO	NO	NO	NO	NO	NO
Errors Clustered At	Township-Range	Township-Range	Township-Range	Township-Range	Township-Range	Township-Range

4.3 Alternative Specifications

4.3.1 State vs. Neighboring State

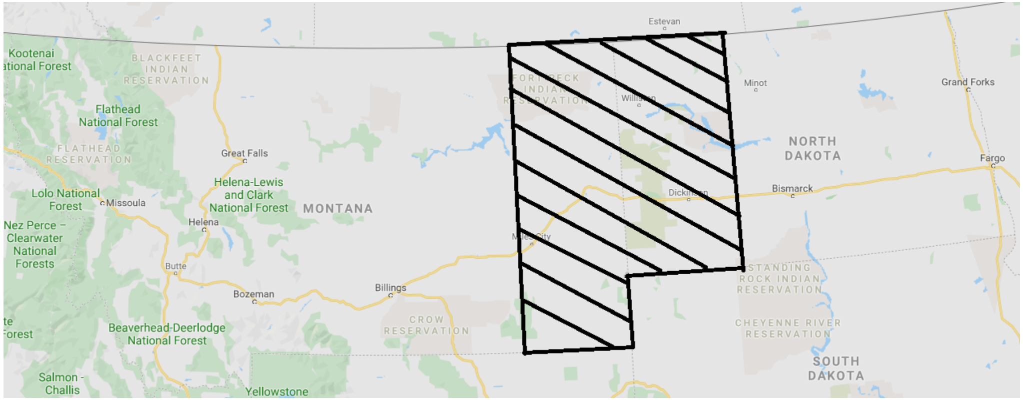
In these regressions, I expand the model by comparing a treatment state to an adjacent control state (for example, the states of Wyoming and Colorado). This effectively breaks down the main model 'pooled' regression into discrete state-to-state analyses. The same econometric model is used as in the pooled regression (Equation 8). All observations within a state are used in these regressions.

The online leasing variable is statistically significant at least at the 10% level across all treatment/adjacent control state combinations other than Colorado/Utah, and presents a premium of at least 27.3% for online leasing. The fact that the coefficient exceeds the 2% 'take' for EnergyNet for *all* state borders and is almost always significant (usually at the 1% level) presents strong evidence that a transition to EnergyNet is a financial win for leasing offices. Certain state combinations show particularly strong impacts of online leasing - particularly, the Colorado/Wyoming border and North Dakota/South Dakota border, which suggests that bids are more than doubled. While an effect that large may be implausible, the strong and consistent relationship seen across all possible state combinations suggests that the effect of online leasing is not driven by only one state's transition.

4.3.2 Spatial Discontinuity

In this section, I repeat the adjacent state regressions provided in Section 4.3.1 but only include observations near the state state border. By limiting the state-to-state comparisons, the regression analysis becomes a spatial discontinuity differences-in-difference model. The advantage of spatial DiD is that land on either side of the border is especially likely to be similar, making the identification of the causal effect of online leasing even more resilient than simply using geographic fixed effects. To ensure that similar geology and local factors are controlled for, I only consider township-ranges within 2 degrees of latitude/longitude of the state border. Parcel location is assumed to be the centroid [135] of the township/range[136]. Figure 14 is a sample map of township ranges that I restrict to for the North Dakota/Montana state border.

Figure 14: State Border Restriction



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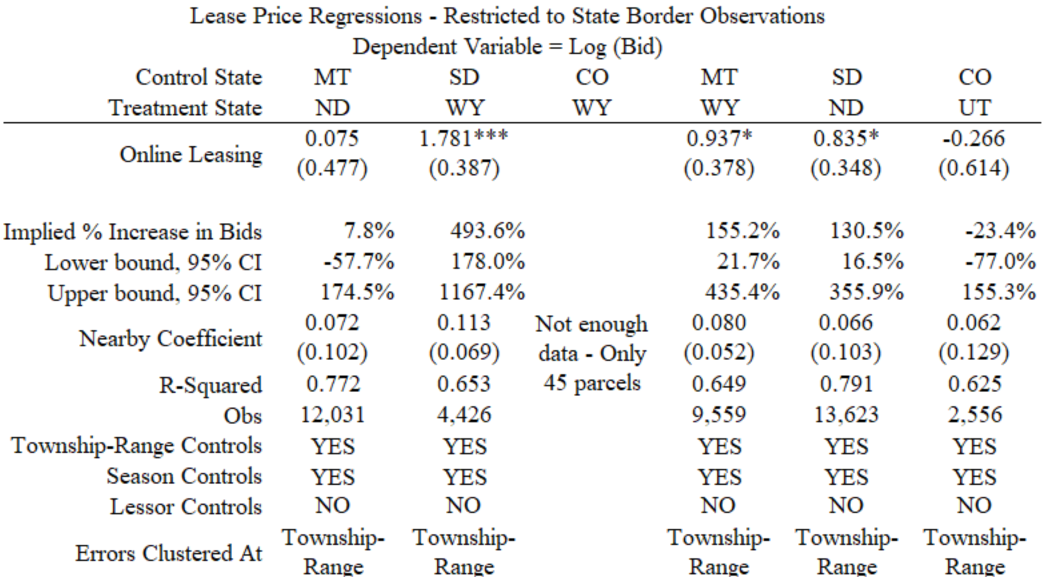
[135] Special thanks to Bill Clark of EarthPoint for providing township-range centroids at a very generous discounted academic rate. Please see Bill's website for a variety of GIS services: www.earthpoint.us

[136] Township-ranges are 6 mile x 6 mile squares, meaning the maximum error on this estimate will be 8.5 miles.

Table 21: Spatial Discontinuity Results



Lease Price Regressions - Restricted to State Border Observations

Dependent Variable = Log (Bid)

Control State	MT	SD	CO	MT	SD	CO
Treatment State	ND	WY	WY	WY	ND	UT
Online Leasing	0.075 (0.477)	1.781*** (0.387)		0.937* (0.378)	0.835* (0.348)	-0.266 (0.614)
Implied % Increase in Bids	7.8%	493.6%		155.2%	130.5%	-23.4%
Lower bound, 95% CI	-57.7%	178.0%		21.7%	16.5%	-77.0%
Upper bound, 95% CI	174.5%	1167.4%		435.4%	355.9%	155.3%
Nearby Coefficient	0.072 (0.102)	0.113 (0.069)	Not enough data - Only 45 parcels	0.080 (0.052)	0.066 (0.103)	0.062 (0.129)
R-Squared	0.772	0.653		0.649	0.791	0.625
Obs	12,031	4,426		9,559	13,623	2,556
Township-Range Controls	YES	YES		YES	YES	YES
Season Controls	YES	YES		YES	YES	YES
Lessor Controls	NO	NO		NO	NO	NO
Errors Clustered At	Township-Range	Township-Range		Township-Range	Township-Range	Township-Range

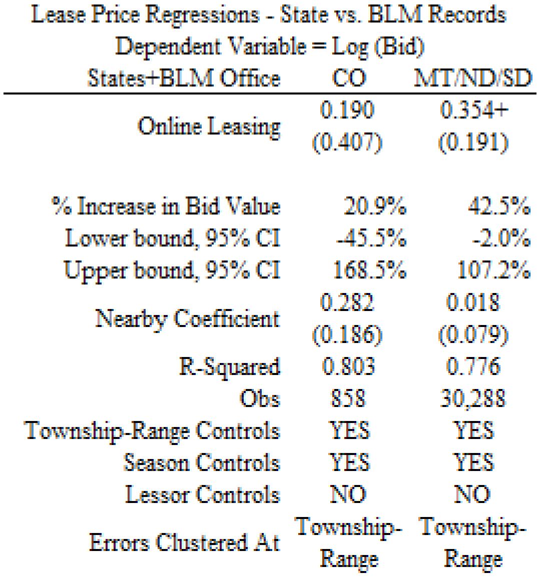
The regression specification is again the same as Equation 8. Results of the spatial discontinuity model are presented in Table 21.

The lack of consistency using only observations along the state border is striking when considering the consistency displayed in the pooled regressions and entire state-to-state comparisons. All borders still exhibit a positive relationship between online leasing and price other than Colorado/Utah, and for the other borders the relationship is statistically significant at least at the 5% level except along Montana/North Dakota, but the coefficients cover an implausibly large range. There are a relatively low number of parcels, especially when considering that township-range controls, season controls, lessor controls, and developer controls are still included. This accounts for higher standard errors in the estimation of the effect.

4.3.3 State vs. BLM

The comparison of BLM regional office results to state leasing office results is particularly ripe for analysis because these organizations manage the same township-

Table 22: States vs. BLM Results



Lease Price Regressions - State vs. BLM Records

Dependent Variable = Log (Bid)

States+BLM Office	CO	MT/ND/SD
Online Leasing	0.190 (0.407)	0.354+ (0.191)
% Increase in Bid Value	20.9%	42.5%
Lower bound, 95% CI	-45.5%	-2.0%
Upper bound, 95% CI	168.5%	107.2%
Nearby Coefficient	0.282 (0.186)	0.018 (0.079)
R-Squared	0.803	0.776
Obs	858	30,288
Township-Range Controls	YES	YES
Season Controls	YES	YES
Lessor Controls	NO	NO
Errors Clustered At	Township-Range	Township-Range

ranges within the same state, with the split between the jurisdictions occurring at the section level[137]. There are two BLM regional offices that transitioned to an online leasing system in late 2016 while the local state system maintained the same system. The Colorado BLM moved to an online system while the state office has conducted their auctions online since 2013. Additionally, the Montana & Dakotas regional office moved online in late 2016 but the state-level offices of Montana and South Dakota remain in-person to this day. Because Montana and the Dakotas are managed by the same regional office, I have combined those three states into one regression. The econometric specification is the same as Equation 8.

Results in the BLM vs. state office specifications are still positive, indicating a 20.9% increase in the Colorado specification and a 42.5% increase in the Montana & Dakotas specification. However, only the Montana & Dakotas specification produces statistically significant results, perhaps because the Colorado specification

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[137] A section is 1/36 of a township-range and measures 1x1 square miles. Traditionally, states are delegated the 16th and 36th sections of each township-range by the federal government with the purpose of funding state education systems.

Table 23: Quantile Results

Bid Value Quantile Regressions

Dependent Variable = Log (Bid)

Quantile->	1	2	3	4
Online Leasing	0.030	-0.021	0.102	0.018
	(0.045)	(0.087)	(0.067)	(0.177)
% Increase in Bid Value	3.0%	-2.1%	10.7%	1.8%
Lower bound, 95% CI	-5.7%	-17.4%	-2.9%	-28.0%
Upper bound, 95% CI	12.5%	16.1%	26.3%	44.0%
Nearby Coefficient	-0.013	0.020	-0.000	0.043
	(0.014)	(0.026)	(0.017)	(0.045)
R-Squared	0.827	0.518	0.453	0.739
Obs	12,331	11,234	12,703	12,181
Township-Range Controls	YES	YES	YES	YES
Season Controls	YES	YES	YES	YES
Lessor Controls	NO	NO	NO	NO
Errors Clustered At	Township-Range	Township-Range	Township-Range	Township-Range
Include Utah?	YES	YES	YES	YES

includes only 858 parcels.

4.4 Quantile Analysis

Quantile analysis involves ordering the data by the outcome variable and then running the same model on separate sections of the data to determine whether the effect is being driven by a segment of the data. This helps determine the economic - not statistical - significance of the issue. For example, if the effect of increasing bid values by online leasing were being driven by the lowest-value parcels only, say in which bid values were changing from \$4 to \$5 per-acre while high-quality parcels were not seeing an effect, there would be little economic and practical importance to online leasing.

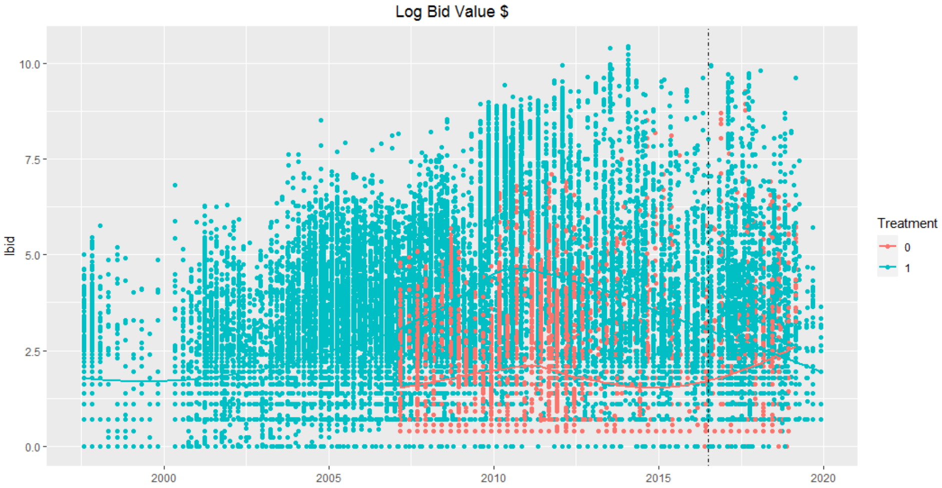
I split up the data into 4 equal buckets based on bid value, and ran the same model as Equation 8. Results are presented in Table 23 by quartile of data.

Altough the effect of online leasing is notably smaller in the quantile regressions than the main model, it is clear that the effect is not being driven by the lowest-value parcels. There is not a meaningful relationship between parcel quality and the change in revenue due to online leasing. These results matches the news articles praising the revenues derived from online leasing. If it were the lowest value parcels seeing the largest increase, it is possible states would not have seen the windfall revenue gains post-transition.

4.5 Parallel trends check

Typically DiD analyses will include a ‘parallel trends’ test showing that a given policy only impacted the treated observations and did not affect the control observations. This is usually shown by displaying running trends of the data with no discernible change in slope of the control observations when the policy in question begins, but a noticeable change in slope for the treated observations. This shows that the result found by the DiD model is in fact causal, and is not due to some spillover in the policy from the control observations responding to the treatment. Figure 15 plots the parallel trends chart comparing the log bid against the year. In this chart, a dot labeled ‘treatment’ represents a parcel from a lessor that transitioned to online in late 2016, while a dot not labeled ‘treatment’ is from one of the 3 lessors that did not transition (Colorado, Montana, and South Dakota state offices).

Figure 15: Parallel Trends - Online Leasing



Interestingly, the parallel trends chart indicates that the trend was *not* the same before the transition in late 2016, but that trends were moving in the opposite direction, making the estimation of a large positive impact on bid values from online leasing conservative. If anything, the trend before online leasing indicates that average bid values in treatment jurisdictions were decreasing faster than non-treatment leasing offices. Of course, this parallel trends chart includes data from 6 different states and even within each state 2 different leasing agencies, so the mix of the parcels being included matters. My regressions control for parcel township-range, so the time-invariant quality of the land being offered is controlled for. This is why what is an apparent *negative* impact on bid value from looking at the parallel trend chart is in fact a positive effect.

5 Investigation of Mechanism

In this section of the paper, I explore whether the different mechanisms described in Section 2 really are driving the increase in bids. The conclusions of this section are that a disproportionate influx of low-information bidders and more easily-accessed information are not driving the increase. It is possible that a higher number of overall bidders and more efficient bidding may be stimulating bids. In Table 24 I provide a guide to the possible mechanisms, along with my conclusions.

Table 24: Mechanism Breakout

Mechanism	Is this mechanism increasing bids?
1a:Bidders don't need to travel	NO
1b: EnergyNet compiles information	NO
2: Lower transaction costs	N/A
3a: More parcels supplied	NO
3b: More bidders	YES
3c: Influx of low-information bidders	NO

N/A means I have no way to answer the question. I have no feasible way to determine whether online leasing lowers transaction costs.

5.1 Does zero travel costs increase bids?

Before online leasing, auction participants gathered at state and federal leasing offices, requiring travel and lodging in the auction city. Online leasing doesn't require any travel, equalizing the costs of participation between bidders near and far from the auction itself. Thus, if travel was a prohibitive factor in the sale of parcels, online leasing should result in more winning bidders being from out of state.

5.1.1 Comparing Home State to Auction State

To evaluate whether online leasing leads to less bidder travel, I compare the home state of winning bidders to the location of the auction. This is not a perfect comparison for three reasons:

1. Many leasing companies have several locations, or have an employee in a state closer to auctions.

2. This process does not discriminate by distance. For example, someone living in Evanston, Wyoming is further from Wyoming state and BLM auctions in Cheyenne than some living in Fort Collins, Colorado.
3. I was not able to locate the developer state for 11,979 observations, or 21.5% of observations.

These three drawbacks will attenuate any effects I find.

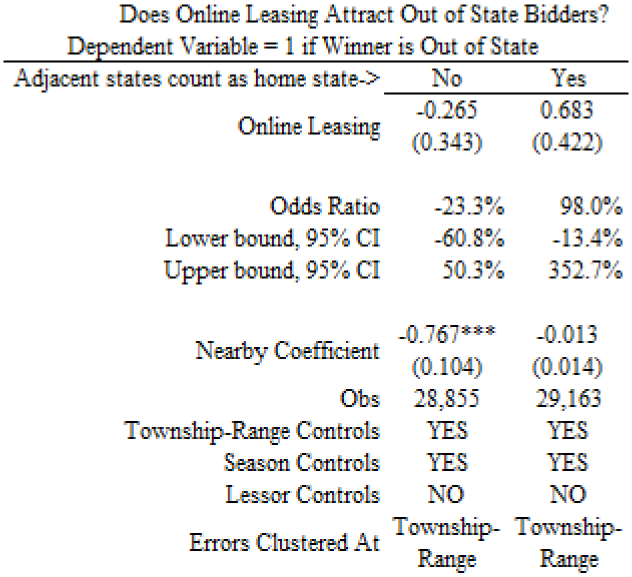
In these regressions, I run a logistic regression to determine whether online leasing leads to a higher likelihood that the winning bidder is not from the state of the auction. The regression equation is:

$DifferentState_{i,s} = YearSeasonFE_s + TownshipRangeFE_i + FederalFE_{i,s} + Online_{i,s} + Nearby_{i,s} + \epsilon_{i,s}$

In this regression, a positive and significant coefficient on the 'Online' variable indicates that online leasing increases the chance the winning bidder is from out of state. I ran a robustness check in which adjacent states would also count as being in the 'same' state, meaning that a winning bidder would only be considered 'out of state' for a parcel in the state of Utah if they were not from Utah, Wyoming, Montana, Idaho, Nevada, Arizona, or Colorado.

Results show no effect between leasing format and likelihood that the winner is from out-of-state. Although this could be a function of the attenuation bias described above, the small value of the coefficients relative to the standard error, along with the flipping of the sign in the own-state only and adjacency models indicate that there is not a meaningful relationship between the measures.

Table 25: Home vs. Out of State Bidders



Does Online Leasing Attract Out of State Bidders?

Dependent Variable = 1 if Winner is Out of State

Adjacent states count as home state->	No	Yes
Online Leasing	-0.265	0.683
	(0.343)	(0.422)
Odds Ratio	-23.3%	98.0%
Lower bound, 95% CI	-60.8%	-13.4%
Upper bound, 95% CI	50.3%	352.7%
Nearby Coefficient	-0.767***	-0.013
	(0.104)	(0.014)
Obs	28,855	29,163
Township-Range Controls	YES	YES
Season Controls	YES	YES
Lessor Controls	NO	NO
Errors Clustered At	Township-Range	Township-Range

5.1.2 Using 'New State' Winners

An alternative specification is to instead use the bidder as the central focus of analysis, rather than the parcel. In this regression, the outcome variable is again a 0/1 binary, but is a 1 when the parcel was won by a bidder winning in that state for the first time. This regression measures the relationship between leasing format and the likelihood that the winner has 'expanded their horizon' and won a bid in a new state. Given the lower travel costs under online leasing, this may happen more often under an online format. The regression equation is[138]:

$$NewState_{i,s} = YearSeasonFE_s + TownshipRangeFE_i + FederalFE_{i,s} + Online_{i,s} + \epsilon_{i,s}$$

Results indicate that there is no relationship between online leasing and bidders 'expanding their horizons' to new states. Overall, the evidence suggests that if online leasing increases revenues through less travel, it does so only marginally, and

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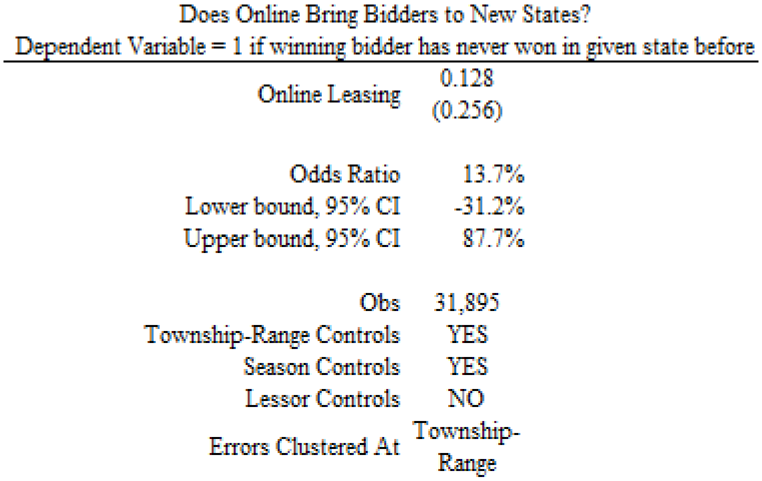
[138] Note that nearby parcels are not controlled for, because the outcome variable is whether or not the bidder has won in the state before. By definition if a bidder is winning for the first time in a given state it does not already control nearby parcels.

Table 26: New State Results



Does Online Bring Bidders to New States?

Dependent Variable = 1 if winning bidder has never won in given state before

Online Leasing	0.128 (0.256)
Odds Ratio	13.7%
Lower bound, 95% CI	-31.2%
Upper bound, 95% CI	87.7%
Obs	31,895
Township-Range Controls	YES
Season Controls	YES
Lessor Controls	NO
Errors Clustered At	Township-Range

that is not what is driving the increased bid values.

5.2 Easier information access does not increase bids

Almost all ‘mechanisms’ listed in the beginning of this section apply uniformly across parcels, rather than increasing the bids of some parcels versus others. For example, there were 12 registered bidders[139] for the in-person auction of BLM Utah leases on May 19, 2015 in Salt Lake City. All 14 parcels had the same number of potential bidders (12), from the parcel that sold for $500 an acre to the 3 parcels that did not garner any bids. Likewise, all 156 parcels auctioned during the March 25, 2019 EnergyNet were available to all 42 registered bidders, regardless of the quality of the parcel.

The converse of this situation is a mechanism that amplifies the bidding of certain parcels more than others. One of these mechanisms is mechanism 1.B: lower search costs for information on the parcel. EnergyNet compiles publicly available documentation on parcels in a user-friendly format, while gathering all relevant files

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[139] https://www.blm.gov/sites/blm.gov/files/uploads/BiddersList_0.pdf

for a given parcel without EnergyNet is burdensome. Developers are unlikely to research all parcels, especially those being auctioned from low-productivity areas. This effect is amplified by the fact that developers are less likely to be familiar low-productivity areas from prior experience, meaning they cannot substitute lack of parcel information with personal private information. Thus, it is possible that the gains from EnergyNet would accrue most to parcels from low-productivity areas.

In his analysis of split-estate bidding, Fitzgerald (2010)[21] shows that co-ownership of mineral rights leads to lower bids, presumably because developers must contend with multiple leasing agencies and regulations when drilling. He also finds that the effect of split-ownership is strongest for the most expensive parcels, as those sure-fire parcels also have the most to lose by additional costs from split ownership. Overall, his results show a monotonically increasing discount attributable to split ownership as parcel value increases, meaning that the highest-value parcels lose the largest share of their bids due to split ownership.

Fitzgerald's methodology can be used to help answer the 'mechanism' question in online leasing regarding information. I sort the township-ranges in my pooled dataset (all states included) by average lease value and then split the pooled data into four datasets by quartile of equal numbers of townsip-ranges[140]. I only include township-ranges with parcels auctioned before July 2016 to split the data by behavior observed before the treatment, although I have a robustness check with the data split using all observations. I then run the main model across the dataset by quartile. If there are meaningful effects from enhanced access to information, it is likely that the 'online leasing' binary will be strongest for the first quartile, and

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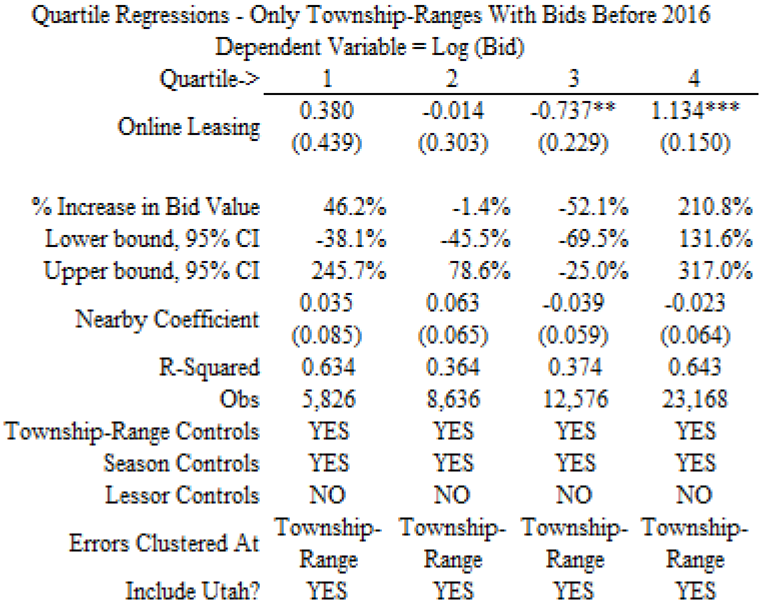
[140] Note that this produces an increasing number of observations per quartile, as township-ranges in higher quartiles have more parcels auctioned per quartile than lower quartiles. The higher number of parcels auctions corresponds to the higher quality of land in those township-ranges.

Table 27: Quartile Regressions 1 Results



Quartile Regressions - Only Township-Ranges With Bids Before 2016

Dependent Variable = Log (Bid)

Quartile->	1	2	3	4
Online Leasing	0.380 (0.439)	-0.014 (0.303)	-0.737** (0.229)	1.134*** (0.150)
% Increase in Bid Value	46.2%	-1.4%	-52.1%	210.8%
Lower bound, 95% CI	-38.1%	-45.5%	-69.5%	131.6%
Upper bound, 95% CI	245.7%	78.6%	-25.0%	317.0%
Nearby Coefficient	0.035 (0.085)	0.063 (0.065)	-0.039 (0.059)	-0.023 (0.064)
R-Squared	0.634	0.364	0.374	0.643
Obs	5,826	8,636	12,576	23,168
Township-Range Controls	YES	YES	YES	YES
Season Controls	YES	YES	YES	YES
Lessor Controls	NO	NO	NO	NO
Errors Clustered At	Township-Range	Township-Range	Township-Range	Township-Range
Include Utah?	YES	YES	YES	YES

become less important as I consider higher quality township-ranges.

In fact, I see the opposite. It is the fourth quartile that sees virtually all of the price premium effect of online leasing. This means that it is in fact the parcels from areas already most familiar to developers that accrue the largest increase in bids from online leasing.

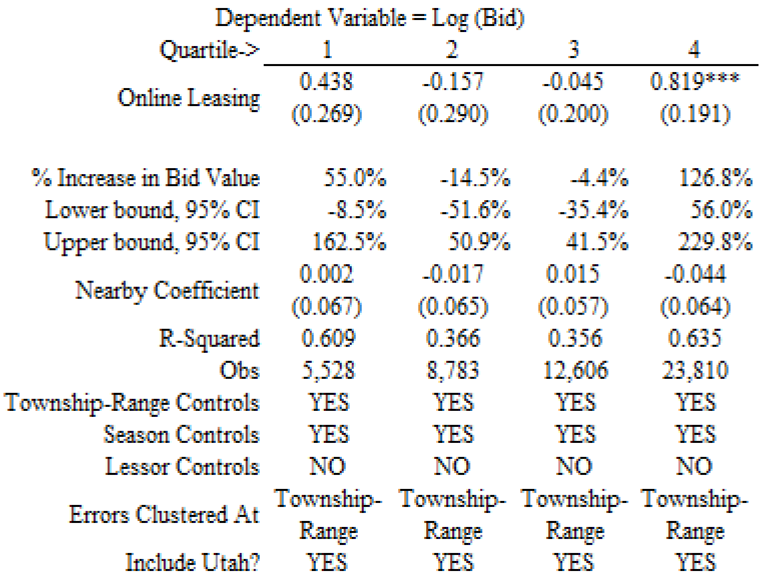
I ran a robustness check of these results using data from all parcels, which resulted in narratively identical results.

It is clear that the benefits from online leasing flow disproportionately to parcels that were already receiving attention from bidders, making more easily accessible information an unlikely conduit for the general rise in bids.

5.3 EnergyNet does not increase supply of parcels

A 'thicker' market typically implies more demand *and* supply. To determine whether online leasing increases the supply of parcels, I count the number of parcels

Table 28: Quartile Regressions 2 Results



Quartile Regressions - All Township-Ranges Included

Dependent Variable = Log (Bid)

Quartile->	1	2	3	4
Online Leasing	0.438	-0.157	-0.045	0.819***
	(0.269)	(0.290)	(0.200)	(0.191)
% Increase in Bid Value	55.0%	-14.5%	-4.4%	126.8%
Lower bound, 95% CI	-8.5%	-51.6%	-35.4%	56.0%
Upper bound, 95% CI	162.5%	50.9%	41.5%	229.8%
Nearby Coefficient	0.002	-0.017	0.015	-0.044
	(0.067)	(0.065)	(0.057)	(0.064)
R-Squared	0.609	0.366	0.356	0.635
Obs	5,528	8,783	12,606	23,810
Township-Range Controls	YES	YES	YES	YES
Season Controls	YES	YES	YES	YES
Lessor Controls	NO	NO	NO	NO
Errors Clustered At	Township-Range	Township-Range	Township-Range	Township-Range
Include Utah?	YES	YES	YES	YES

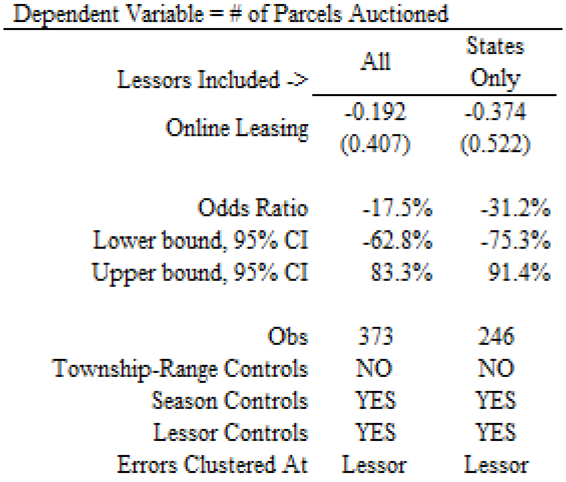
being put up for sale at each auction. Without other effects like a transition to an MSP, a change in the nationwide oil & gas market, or a switch to a new political administration, the supply of parcels should be relatively constant from year-to-year. States and the BLM put different sections of their jurisdiction up for sale at regular times of the year. The econometric model is:

$$Parcels_s = Online_s + YearSeasonFE_s + StateFE_s + LessorFE_s + \epsilon_s$$

I regress the number of parcels put up for auction in auction s on season, state, and lessor fixed-effects, along with the *Online* binary. If EnergyNet increases the number of parcels up for auction, the *Online* coefficient will be positive.

There is no evidence that EnergyNet increases the quantity supplied of parcels. In fact, the coefficient on *Online* is negative, whether all jurisdictions are considered or only state leasing offices. This is not surprising, because the energy leasing market is not a regular industry. State governments and the BLM have a mandate to manage their resources responsibly, extracting fair rents for their use. The goal

Table 29: Supply Results



Dependent Variable = # of Parcels Auctioned		
Lessors Included ->	All	States Only
Online Leasing	-0.192 (0.407)	-0.374 (0.522)
Odds Ratio	-17.5%	-31.2%
Lower bound, 95% CI	-62.8%	-75.3%
Upper bound, 95% CI	83.3%	91.4%
Obs	373	246
Township-Range Controls	NO	NO
Season Controls	YES	YES
Lessor Controls	YES	YES
Errors Clustered At	Lessor	Lessor

of lessors is not to sell as many parcels as possible, but to lease their lands for the good of the state population.

Although the coefficient on the *Online* variable is never statistically significant, meaning that the model does not establish a link between online leasing and parcel availability, a reduction in parcel quantity is interesting because the increase in bid values could simply be a function of supply and demand. If lessors reduce the number of parcels available (reduce supply), price rises. Of course, this assumes a local market to energy, and that developers have no outside option. Energy development is a worldwide market, and it is safe to assume that a reduction in parcel availability under online leasing, if it even exists, should not change the equilibrium price of leases.

5.4 There is evidence EnergyNet attracts more bidders

More bidders indicates higher interest in a parcel, and drives prices upwards because bidders must compete with each other and will bid closer to their reservation price. Strong evidence of a causal relationship between online leasing and increasing number of bidders would be immensely valuable in determining what mechanisms are causing the growth in bids. However, no state governments other than the Utah School and Institutional Trust Lands Administration (SITLA) nor the BLM keeps the distinct number of bidders per parcel from their legacy offline in-person auctions. In-person auctions are rapid-fire and taking note of who bid what would be difficult, especially given that the same few bidders may outbid each other multiple times. Tracking this information would be a waste of resources, since the only bid that matters to governments is the winning bid. Because of this, I have no way to identify how many bidders bid on a specific parcel.

5.4.1 Using Winning Bidders

In lieu of a dataset with the number of bidders for states other than Utah, I instead use the number of *winning* bidders per auction. Of course, this is an imperfect proxy - there is no definite relationship between the number of winning bidders and the number of losing bidders of a parcel. However, the number of winning bidders could reasonably be assumed to be well-correlated with the number of bidders. Moreover, the winning bidders are more important than the losers from the perspective of state and federal leasing agencies, as the winning bidders represent the high-valuation revenue generators. The appeal of regressing winner bidder counts on online leasing is that the story is causal using a differences-in-differences methodology comparing treatment and control states before and after late 2016.

In this section I collapse sales down to the auction level. For each auction, I count the number of distinct winning bidders and the number of parcels available.

I also sum the total bid value as a proxy for land quality independent of parcel count. Finally, I limit to auctions with a minimum of 10 parcels (adjusting the minimum number does not meaningfully drive results). I use the following regression specification:

$WinningBidders_s = Online_s + Parcels_s + BidValue_s + YearSeasonFE_s + LessorFE_s + \epsilon_s$

I again control for Season fixed effects, which controls for universal market conditions like the prices of oil and gas. I also still use lessor fixed effects, which control for the time-invariant characteristics of the leasing office and inherently also control for jurisdiction-wide land quality. I do not control for township-range fixed effects because the regressions are at the auction level, with each observation in the dataset representing one specific auction. Because Montana and the Dakotas are grouped under one BLM leasing jurisdiction, using state-level controls would need to entail splitting one auction into 3, so state is not controlled for. Instead, the Lessor controls, which are determined by geography, control for the time-invariant quality of parcels across the leasing agency's jurisdiction. Errors are clustered at the lessor level.

The coefficient on online leasing is positive, but not significant (p-value $>$ 0.1). This indicates that the model predicts online leasing does increase the number of winning bidders by almost 2 bidders per auction, but the model can not differentiate the effect from the null hypothesis of no effect. This provides only limited, inconclusive evidence that online leasing increases the number of bidders. More auctions (N = 383)[141] would assist in determining whether the relationship is sig-

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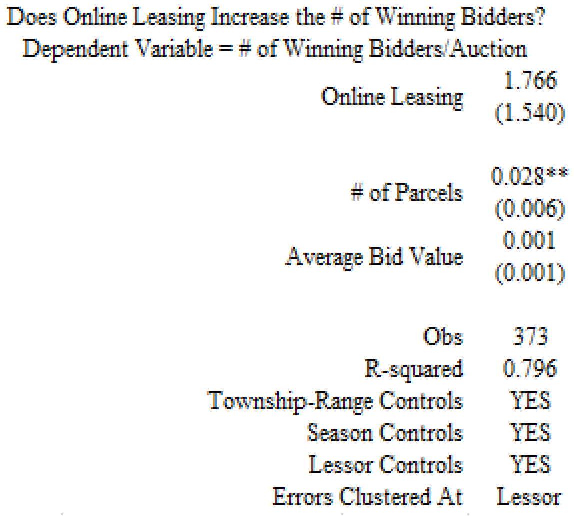
[141] This number is less than the total number of auctions (422), because some auctions are the only sales in a given quarter.

Table 30: Number of Bidders Results



Does Online Leasing Increase the # of Winning Bidders?

Dependent Variable = # of Winning Bidders/Auction

Online Leasing	1.766 (1.540)
# of Parcels	0.028** (0.006)
Average Bid Value	0.001 (0.001)
Obs	373
R-squared	0.796
Township-Range Controls	YES
Season Controls	YES
Lessor Controls	YES
Errors Clustered At	Lessor

nificant. Not surprisingly, the coefficients on parcel count and total bid amount are positive and significant at the 5% and 0.1% level, respectively. More parcels being offered, and higher bids, are associated with more distinct winning bidders.

5.4.2 Using Non-Reservation Price Bids

One thing we do know is that any parcel selling above the reservation price has more than 1 bidder. If there is only 1 bidder, the winning bid will be the reservation price regardless of the bidder's true valuation. This is true of both English auctions and eBay auction formats[142]. Thus, a higher share of non-reservation price bidders is indicative of more overall bidders. To test whether online leasing increases the likelihood of a bid beyond the reservation price, I run the following regression:

$$Non{-}reservationPrice_{i,s} = YearSeasonFE_s + TownshipRangeFE_i + LessorFE_{i,s} + Online_{i,s} + \epsilon_{i,s}$$

The outcome variable in this regression is whether the parcel won by a bid greater than the reservation price. The BLM, state of Colorado, and state of South

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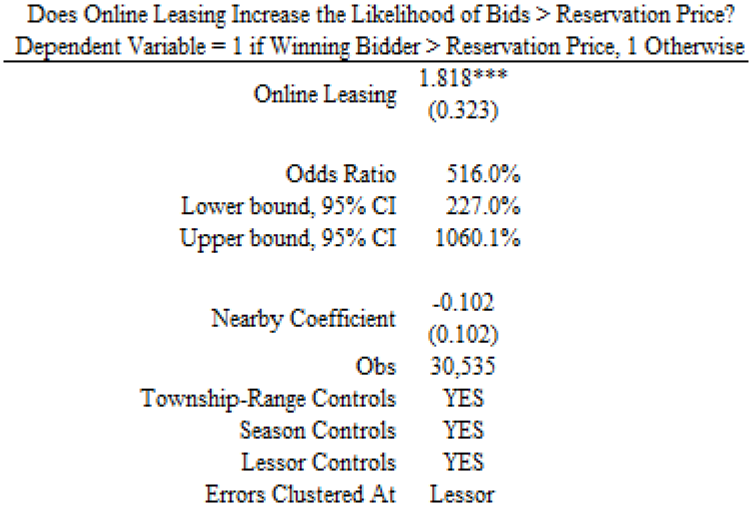
[142] The exception to this rule is parcels sold through the Utah State Leasing Office, as SITLA uses a first-price sealed-bid auction. This means that the winning bidder pays whatever he bid, even if he is the sole bidder. I have excluded Utah state office parcels from the regression.

Table 31: Reservation vs. Non-Reservation Price Results



Does Online Leasing Increase the Likelihood of Bids > Reservation Price?
Dependent Variable = 1 if Winning Bidder > Reservation Price, 1 Otherwise

Online Leasing	1.818*** (0.323)
Odds Ratio	516.0%
Lower bound, 95% CI	227.0%
Upper bound, 95% CI	1060.1%
Nearby Coefficient	-0.102 (0.102)
Obs	30,535
Township-Range Controls	YES
Season Controls	YES
Lessor Controls	YES
Errors Clustered At	Lessor

Dakota have a reservation price of \$2/acre. The states of North Dakota, Utah, and Wyoming have a reservation price of \$1/acre. The state of Montana has a reservation price of \$1.50 per acre. If online leasing leads to more instances of multiple bidders, the coefficient on the *Online* variable will be positive. I utilize the same controls as in prior regressions other than controlling for developer, which controls for time-invariant land quality and contemporaneous market conditions. Errors are again clustered at the lessor level.

The answer is a resounding ‘yes’. Online leasing leads to more bids that exceed the reservation price. The logistic regression indicates that there is over a *five-hundred* percent increase in the odds that the bid will exceed the reservation price if the parcel is sold online vs. in-person. This result is so large in magnitude that it provides convincing evidence that online leasing really is bringing in new bidders to the auction, which is raising revenue.

5.5 The extra participants are not low-information bidders

5.5.1 Experience level of winning bidder

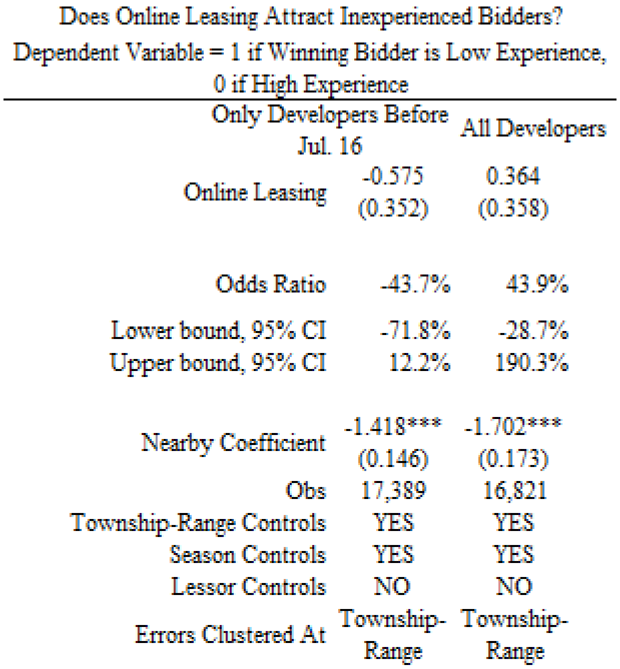
Using developer experience, I find that an influx of low-information bidders are definitively *not* driving the increase in bids. I run the following logistic differences-in-difference regression across my pooled dataset:

$LowExperience_{i,s} = YearSeasonFE_s + TownshipRangeFE_i + FederalFE_{i,s} + Online_{i,s} + Nearby_{i,s} + \epsilon_{i,s}$

The outcome variable in this regression is whether the parcel was won by a high-experience (or conversely, low-experience) developer. I split developers into 'high-experience' and 'low-experience' developers based on total parcels won by the winning bidder, splitting the data as equally as possible into 'large' and 'small' developers. If online leasing allows a surge of predominantly low-experience, low-information bidders, the coefficient on the *Online* variable will be negative. I utilize the same controls as in prior regressions other than controlling for developer, which controls for time-invariant land quality and contemporaneous market conditions. Errors are again clustered at the township-range level.

The split of developers into high and low experience could be impacted by the transition to online leasing itself as I use all the data when counting how many leases a given developer won. To avoid this problem, I only consider leases won before July 2016 in determining which developers are 'high' and 'low' experience. As some developers only win auctions post July 2016, those developers are excluded from the model. I ran separate models in which all data is considered. For both the main specification and robustness check, winning more than 5 parcels qualifies a developer as being 'high' experience, while winning 5 or fewer makes the developer

Table 32: Bidder Experience Results



Does Online Leasing Attract Inexperienced Bidders?
Dependent Variable = 1 if Winning Bidder is Low Experience, 0 if High Experience

	Only Developers Before Jul. 16	All Developers
Online Leasing	-0.575 (0.352)	0.364 (0.358)
Odds Ratio	-43.7%	43.9%
Lower bound, 95% CI	-71.8%	-28.7%
Upper bound, 95% CI	12.2%	190.3%
Nearby Coefficient	-1.418*** (0.146)	-1.702*** (0.173)
Obs	17,389	16,821
Township-Range Controls	YES	YES
Season Controls	YES	YES
Lessor Controls	NO	NO
Errors Clustered At	Township-Range	Township-Range

‘low’ experience.

These regressions preclude differential bidder experience as being a driver for increased bids. The strongly negative coefficient on nearby parcels is not surprising; having a nearby parcel by formulation makes a bidder more likely to be an ‘experienced’ bidder.

I further test for the experience of the winning bidder by evaluating whether the auction was won by a ‘new’ winner. A new winner is defined as someone who has not won a parcel before, in any leasing jurisdiction’s auctions. The regression model is[143]:

$$NewWinner_{i,s} = YearSeasonFE_s + TownshipRangeFE_i + FederalFE_{i,s} + Online_{i,s} + \epsilon_{i,s}$$

The coefficient on *Online* is negative, indicating that online leasing is *less likely*

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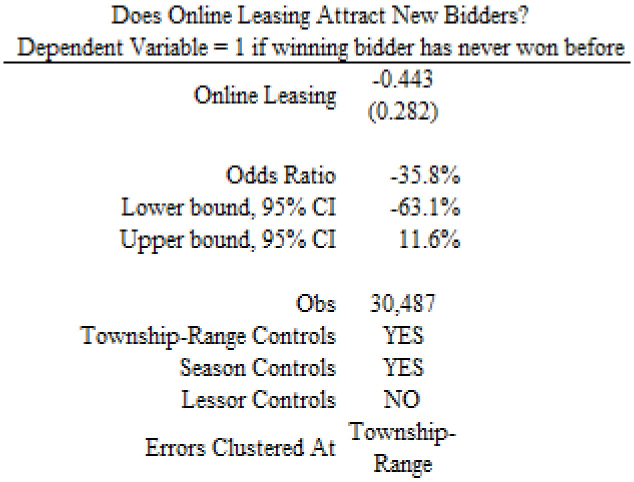
[143] Note that nearby parcels are not controlled for, because the outcome variable is whether or not the bidder has ever won before. By definition if a bidder is winning for the first time it does not already control nearby parcels.

Table 33: New Bidder Results



Does Online Leasing Attract New Bidders?

Dependent Variable = 1 if winning bidder has never won before	
Online Leasing	-0.443 (0.282)
Odds Ratio	-35.8%
Lower bound, 95% CI	-63.1%
Upper bound, 95% CI	11.6%
Obs	30,487
Township-Range Controls	YES
Season Controls	YES
Lessor Controls	NO
Errors Clustered At	Township-Range

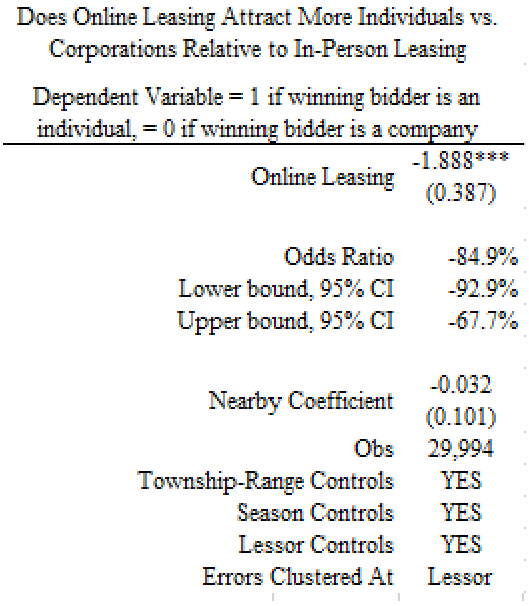
to produce winners that are new to leasing auctions relative to in-person auctions.

5.5.2 Individuals vs. companies

Just as more experienced bidders are more likely to be highly knowledgeable about the productive capacity of tracts up for auction, larger developers are also more likely to have an accurate prediction of production. While I do not have revenue data for bidders, I can proxy for this by flagging winning bidders as 'individuals' or 'corporations'. Mineral leasing auctions are not limited to just corporations; individuals representing themselves attend and often win auctions. These individuals are often tangentially connected to a larger company or will resell the parcels to developers. However, sometimes they are simply community members, or are speculators with little knowledge of the industry. To determine whether online leasing increased the likelihood that winners were smaller individual players rather than corporations, I ran the following logistic regression:

$$Individual_{i,s} = YearSeasonFE_s + TownshipRangeFE_i + FederalFE_{i,s} + Online_{i,s} + Nearby_{i,s} + \epsilon_{i,s}$$

Table 34: Individual vs. Company Results



Does Online Leasing Attract More Individuals vs. Corporations Relative to In-Person Leasing

	Dependent Variable = 1 if winning bidder is an individual, = 0 if winning bidder is a company
Online Leasing	-1.888*** (0.387)
Odds Ratio	-84.9%
Lower bound, 95% CI	-92.9%
Upper bound, 95% CI	-67.7%
Nearby Coefficient	-0.032 (0.101)
Obs	29,994
Township-Range Controls	YES
Season Controls	YES
Lessor Controls	YES
Errors Clustered At	Lessor

Results show that online auctions are much more likely to be won by corporations than individuals. Just as above, there is no indication that smaller players like individuals are more likely to participate in online auctions than in-person auctions. My analysis strongly suggests that online leasing does not disproportionately attract low-information bidders. If anything, high-information bidders are more drawn to online leasing.

The finding that using an MSP results in high-information bidders rather than low-information bidders winning auctions despite the ‘equalizing’ aspect of online auctioning fits well with the literature. Lewis & Wang (2013)[41] build upon Tadelis & Zettelmeyer (2011)[59] with a theoretical model confirming that MSPs that lower search costs enhance seller revenue and generate additional welfare for buyers and sellers as a whole. However, their theoretical extension proves that buyers with weak preferences (low-information buyers) can be harmed with easier search because of more competition leading to a better match. These results provide empirical support for Lewis & Wang's theoretical results, as I show that with online leasing the higher-information, experienced bidders are those more likely to win auctions.

6 Conclusion

This paper showed through a differences-in-differences model focusing on oil & gas parcels being leased on state borders that auction format has a meaningful implication for state and federal energy revenues. The increase is most likely due to extra high-information bidders joining the auction. The presence of extra bidders increases bid values for both low and high-value parcels, leading to an estimated increase of an extra $136 million for the federal and state governments.

A future extension of this work could be to determine the welfare implications of moving to online leasing. The analyses presented above are presented exclusively from the perspective of the leasing office, in which higher revenues in excess of extra cost is strictly preferred to lower revenues. However, if this extra revenue is solely a transfer of wealth from developers to leasing jurisdictions, there is not a social welfare improvement, but simply a transfer of welfare from private companies to public coffers. For example, if Developer A valued Parcel 123 in Wyoming at $5 an acre and was the only bidder in an in-person auction, Developer A would receive the parcel for only $1 an acre, giving Developer A a surplus of $4 per acre and Wyoming $0 per acre. But if Developer B with valuation $3 is only willing to participate in online auctions, moving online will net Wyoming an extra $2 per acre, as Developer A will need to outbid Developer B to win the lease. In this case, Developer A and Wyoming split the $4 per acre surplus down the middle with $2 apiece. Note that there is no welfare enhancement in this situation; whether or not the parcel was sold online or in-person Parcel 123 is leased to Developer A and $4 per acre of surplus is generated.

There are two ways online leasing could enhance social welfare:

1. Certain parcels would only be bid on using online leasing; in person, no developer would bid the minimum bid. In this situation, welfare is enhanced because the parcel has the possibility of being developed.
    (a) Establishing this mechanism is not trivial. While I know which parcels are bid on and which are not for all jurisdictions, the parcels being put up for auction are not exogenously determined. Parcels may be requested by developers to be up for auction, or may be nominated by the lessor itself because the lessor wants to lease the parcel, both of which are not determined formulaically and can be politically influenced.
2. The parcel is won by a more efficient developer using online leasing than in-person leasing. Efficiency varies on both allocative and productive dimensions. Some developers are low-cost developers, and are able to extract a given amount of oil from a parcel at a lower cost. This is the allocative efficiency story. Likewise, some developers are able to extract more oil from the parcel, representing increased production.
    (a) Getting reliable estimates of the allocative and productive efficiencies is not trivial. To calculate the allocative efficiency, I would need cost data from developers, which are not publicly accessible. Productive efficiency gains are possible to estimate incompletely. Production data is publicly available by each state's mineral management agency, but connecting this

production data to a given lease is not easy (see Section 6.1, in which I describe how I can only connect about 8% of wells to a specific lease in Wyoming). Production data generally does not provide what lease number the well pertains to, and even a geographic join is not sufficient, because multiple leases (even to the same developer!) are common for a specific township/range/section combination. Geographic joins also require developer name standardization, and names are not standardized even within a state between its leasing data and its production data. If leases could be reliably linked to specific wells, then another DiD analysis like those presented above could help determine whether more productive developers are winning online bids.

Of course, whether or not there is welfare enhancement from transitioning to an online leasing system, the policy implication from this paper is clear. Transitioning to an online leasing system from an in-person auction provides a large and consistent increase in bid values for parcels relative to an in-person auction. The extra revenue derived from hosting an auction on EnergyNet far exceeds the cost incurred by using the EnergyNet service. States potentially mulling the switch, like Montana and South Dakota, should find this evidence encouraging the movement to an online leasing platform.

A Simulation: Sage-Grouse

A.1 Introduction

The drilling-under-regulatory uncertainty model was run 2,500 times (representing 2,500 drilling decisions). The goal of the model is to collect mean and median drilling times, well profits, and well production, and see how those summary statistics change as input parameters are adjusted. In each run of the model, the developer begins with a well and must optimally determine when (if at all) to spud the well. The developer is given the decision rule to drill if expected profits from the well exceed the expected value from waiting and drilling in a future period. An operator may wait to drill because price and cost volatility may produce a more favorable state than the state the operator finds itself in when making the decision.

The developer weighs the following criteria when deciding in which period to drill:

1. Present and expected future oil prices
2. Present and expected future drilling costs
3. Their discount factor
4. The expected productivity of their well
5. When a decision is expected from the regulator on whether drilling is allowed on the parcel
6. How likely it is the regulator will disallow drilling

Each of the 2,500 simulated drilling decisions contains an evolution of prices and costs over time, but firms are only given 120 periods (months) in which to decide to drill. If a firm does not decide to drill in the first 120 periods, it is assumed the firm will never drill[144]. Each period after drilling, the firm gains revenue from the drilled well as it extracts mineral resources.

A.2 Transition Equations and Initial Parameter Values

Because my simulation model is to be compared to my theoretical model constructed in Section 3, the value of any given well w in the model exactly matches Equation 4, dependent on when the operator decides to drill:

$$\Pi_w = \pi_0 + \delta^t \sum_{t=1}^{\infty} \left(\left[e^{-t\lambda}\pi_t + \sum_{i=1}^{t} (e^{-(i-1)\lambda} - e^{-i\lambda})(1-l)\pi_t \right] \right), \text{ with } \pi_t = P_t Q_t - D_t.$$

State variables change through the model, mostly consistent with the Kellogg work. Below I list how each variable changes from period to period.

Price transitions from one period to the next following the first-order Markov process:

$$lnP_{t+1} = lnP_t + \mu(P_t, \sigma^2) - \sigma^2/2 + \sigma\epsilon_{t+1}$$

In this equation, the next period's price is determined by the current price plus a mean-reverting price drift and a random shock depending on the volatility (σ) of the price data. These price equations are the exact same as in Kellogg, except that I make a simplifying assumption that firms do not change their estimates of price volatility over time. In Kellogg, all volatilities are labeled σ_t as he allows changes in the volatility.

The mean-reverting price drift equation $\mu(P_t, \sigma^2) - \sigma^2/2$ taken from Kellogg is:

$$\mu(P_t, \sigma^2) - \sigma^2/2 = \kappa_{p0} + \kappa_{p1}P_t + \kappa_{p2}\sigma^2 - \sigma^2/2$$

Because Kellogg's drilling cost data are too low to properly represent the Wyoming

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[144] The largest standard primary period to drill (in which developers must drill or they forfeit their rights to the parcel) is 10 years, which is 12 x 10 = 120 periods (months).

oil market, I modify his treatment of costs. In my model, there is only one large upfront cost of spudding the well, and no maintenance or continual costs post-spudding. Costs transition from one period to the next following the first-order Markov process:

$D_{t+1} = D_t + \rho\alpha\epsilon_{t+1}$

Cost volatility is assumed to be proportional to price volatility σ by factor α. Kellogg makes the same assumption since he is not able to estimate cost volatility. The other difference is that the error rate of costs is expected to be correlated, but not perfectly match ($0 < \rho < 1$), the price shock. This is logical, because as the price of oil increases there is competition for rigs and labor, and so these figures will usually move together. Kellogg models cost shocks in the same manner.

I model production in the same manner as Kellogg, in that I estimate hyperbolic decay in production. Kellogg shows that production in typical wells roughly follows hyperbolic decay, with production rapidly declining month-to-month. I confirmed this hyperbolic relationship using Wyoming production data. Specifically, I assume that production declines over time in the following manner:

$Q_t = \frac{Q_0}{1+kt}$

Thus, at any period, the production will be a hyperbolically decayed value dependent on the spud period's production Q_0 and a decay factor k. This implies that the developer does not have any control over extraction rates once the well is drilled.

The source of all parameters is described below.

1. $\delta = 0.992$ Kellogg stipulates that the typical discount factor for a mineral developer is 0.910. This value was on an annual level, so I bring that discount

factor to the month level.

2. $\lambda = 1/76$ While compiling the ratio of species that were eventually listed, I found that on average it takes USFWS 76 months to make a decision.
3. $l = 0.53$ This is the % of species in Listing Priority Number 8 that were eventually listed. See Section 2.3 for my work.
4. $\sigma = 0.194$ This was computed by Kellogg.
5. $\alpha = 1.16$ This was computed by Kellogg.
6. $\rho = 0.413$ This was computed by Kellogg.
7. $\kappa_{p0} = 0.0094$ This was computed by Kellogg.
8. $\kappa_{p1} = -0.00054$ This was computed by Kellogg.
9. $\kappa_{p2=0.401}$ This was computed by Kellogg.
10. $k = 0.022$ This was estimated using Wyoming production data.

My model makes many of the same assumptions as Kellogg, which include:

1. Developers are risk-neutral (although runs of the model incorporating risk-aversion see even stronger responses)
2. Developers are price-takers in oil prices.
3. Developers do not exercise monopsony power in rig rentals.
4. Firms' drilling decisions are independent of one another.

For my purposes, I also make some additional assumptions:

1. Firms are completely responsive to a change in expected price volatility.

2. Firms do not update their valuation of the well's productive capability over time (although I maintain a diversity of original well production capability - not all wells are created equal)
3. USFWS orders a total shutdown of drilling (I am not considering a partial shutdown only during mating season)

Like many simulations, the model depends on initial starting values. For example, since quantity follows a strictly decay across periods, a higher initial value of production per period will necessarily increase all period productions as well as profits. Kellogg begins with initial values equal to the market conditions existing in the Texas oil market in 1993-2003. Because I am using a different time period as well as a different geographic setting, I sourced as many initial values from my setting as possible. My initial values and justifications for each are presented below:

1. Price is set to $70 per barrel. This is the average price of a barrel of oil from 2001-2015.
2. The cost of a well is centered at $3 million per well, with a standard deviation of $1 million[145] to provide heterogeneity in costs across wells that reflects varying difficulty in drilling. These numbers are sourced from local news reports detailing the costs of drilling in Wyoming from 2013-2016[146].
   (a) Note that costs are often expected to decrease as firms become more adept at mastering new technology. This could especially be expected for industries like liquid mineral extraction, because there is a wealth of public

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[145] This was calculated by taking the standard deviation of drilling costs at different locations across the state.

[146] http://www.buffalobulletin.com/news/article_139d34f8-4c78-11e3-97dd-001a4bcf6878.html, https://www.roseassoc.com/the-current-costs-for-drilling-a-shale-well/

knowledge about drilling mechanics of rival firms as well as real-world observable evidence of behavior. Thus, this could be a particularly ripe industry for learning-by-doing, including learning spillovers from company to company. However, Covert (2015)[12] finds minimal evidence of learning-by-doing or spillovers, suggesting that costs do not meaningfully decline over time.

3. Initial production is set at 1,238 barrels per month per well, and the hyperbolic decay factor of $k = 0.022$. The first month's production is centered at 1,238 barrels with a standard deviation across wells of 1,791 barrels, providing heterogeneity in anticipated production across wells. These numbers are respectively the average and standard deviation of number of barrels produced in the first full month of production by oil wells in Wyoming from 2001 to 2015, using data provided by the Wyoming Oil and Gas Conservation Commission. The decay rate was determined by fitting a hyperbolic decay curve to the initial value and the average 3-year production of Wyoming oil wells of 33,071 barrels[147].
    (a) Note that in period 0, there is a 64% chance the well's initial quantity is set to 0. This is to represent the percentage of wells that are never drilled by developers even though they received approval from the state to commence drilling[148]. What this represents on the ground is a developer obtaining a new lease, performing seismic tests, and discovering the well is most likely not going to be profitable at any reasonable price due to low

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[147] 3 years' worth of production was used to match Kellogg's methodology, although the length of time does not meaningfully change model parameters.

[148] https://www.wyofile.com/industry-sitting-on-permits/

productive capacity.

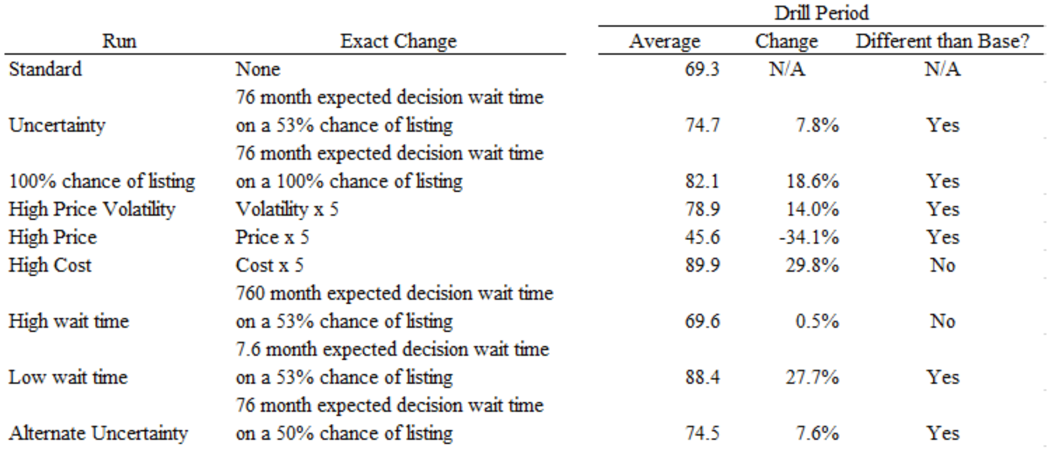
A.3 Results

The model was tested for several different parameterizations of the 2,500 runs to compare the effects of changing parameters. The goals of this exercise were to:

1. Compare simulated results to empirical results and comparative statics, including:
   (a) Estimating changes in drilling time, profits, and production by imposing a 53% likelihood the regulator will disallow drilling in the future
   (b) Estimating changes in drilling time, profits, and production by imposing a 100% likelihood the regulator will disallow drilling in the future
   (c) Estimating changes in drilling time, profits, and production by varying the length of time before a decision is expected
2. Confirm Kellogg's results, which were:
   (a) Price volatility delays drilling
   (b) Price increases speed drilling
   (c) Cost increases delay drilling

To explore these possibilities, I ran several runs of the model, changing the parameters to test the model. After collecting and summarizing each of the 2,500 drilling times, profits, and production totals, each parameter change was tested against the 'base' model using a Welch 2-sample T-test to determine whether the means of the distributions were significantly different. I also tested the change of using an

Table 35: Sage-Grouse Simulation Results: Drill Period

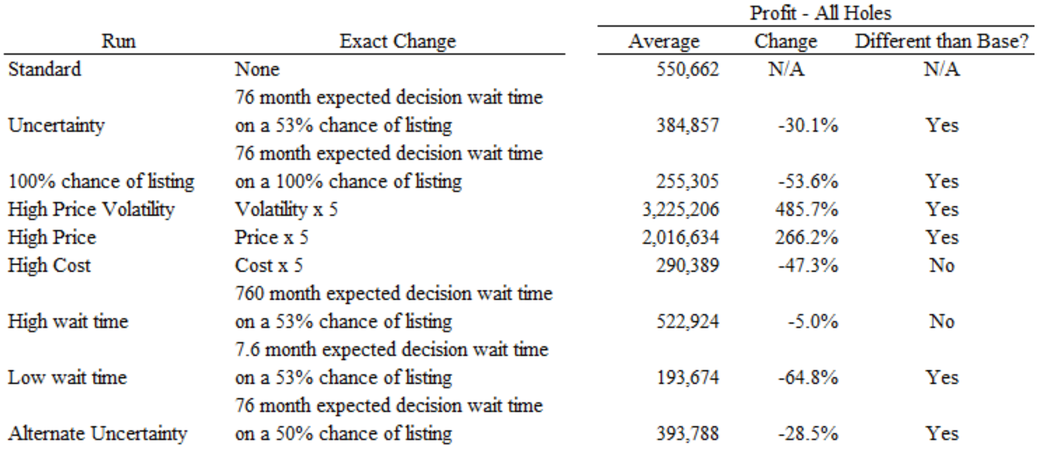


Run	Exact Change	Drill Period		
		Average	Change	Different than Base?
Standard	None	69.3	N/A	N/A
Uncertainty	76 month expected decision wait time on a 53% chance of listing	74.7	7.8%	Yes
100% chance of listing	76 month expected decision wait time on a 100% chance of listing	82.1	18.6%	Yes
High Price Volatility	Volatility x 5	78.9	14.0%	Yes
High Price	Price x 5	45.6	-34.1%	Yes
High Cost	Cost x 5	89.9	29.8%	No
High wait time	760 month expected decision wait time on a 53% chance of listing	69.6	0.5%	No
Low wait time	7.6 month expected decision wait time on a 53% chance of listing	88.4	27.7%	Yes
Alternate Uncertainty	76 month expected decision wait time on a 50% chance of listing	74.5	7.6%	Yes

alternative definition of the listing likelihood. As noted in Section 2.3, considering only listing decisions from the lower 48 implies the sage-grouse has an exactly 50% chance of being listed. Additionally, considering a wider range of possible listing priority numbers rather than solely the sage-grouse's LPN of 8 also implies a 50% listing probability. The model labeled 'Alternate Uncertainty' is a run with a 50% chance of listing, rather than 52.6%. Results are not substantially different from the 52.6% model.

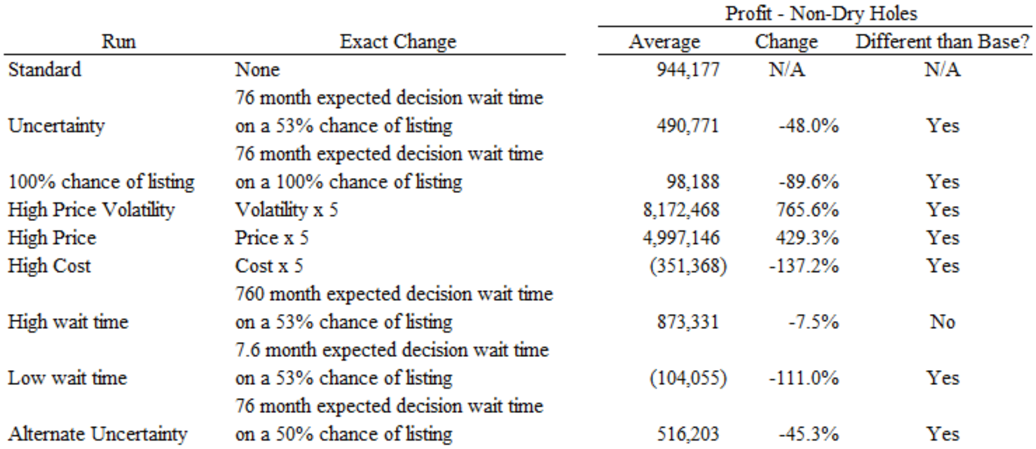
All results from the simulations match Kellogg's work, my theoretical work, and my empirical results in direction and are similar in magnitude. Most importantly, the average wait time under uncertainty is 7.8% higher than in the base model, and 18.6% higher if there is a 100% chance the sage-grouse is listed, consistent with a 'wait-and-see' approach to the uncertainty. Results across all models are provided in Tables 35-39, along with the results of the T-test with a 95% confidence interval. The difference between the two profit calculations is that one set only averages the value of non-dry holes, while the other takes dry holes into account. Dry holes are discovered 64% of the time, as described in Appendix A.2.

Table 36: Sage-Grouse Simulation Results: Profit - All Holes



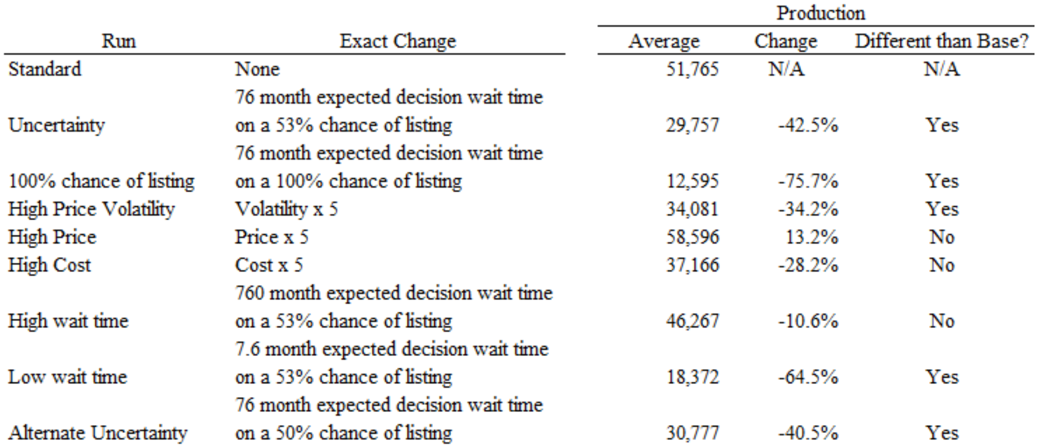
Run	Exact Change	Profit - All Holes		
		Average	Change	Different than Base?
Standard	None	550,662	N/A	N/A
Uncertainty	76 month expected decision wait time on a 53% chance of listing	384,857	-30.1%	Yes
100% chance of listing	76 month expected decision wait time on a 100% chance of listing	255,305	-53.6%	Yes
High Price Volatility	Volatility x 5	3,225,206	485.7%	Yes
High Price	Price x 5	2,016,634	266.2%	Yes
High Cost	Cost x 5	290,389	-47.3%	No
High wait time	760 month expected decision wait time on a 53% chance of listing	522,924	-5.0%	No
Low wait time	7.6 month expected decision wait time on a 53% chance of listing	193,674	-64.8%	Yes
Alternate Uncertainty	76 month expected decision wait time on a 50% chance of listing	393,788	-28.5%	Yes

Table 37: Sage-Grouse Simulation Results: Profit - Non-Dry Holes



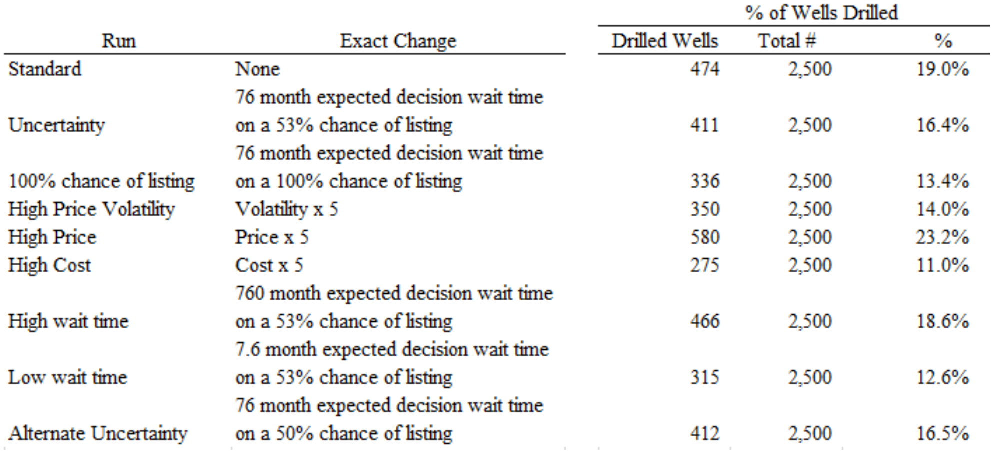
Run	Exact Change	Profit - Non-Dry Holes		
		Average	Change	Different than Base?
Standard	None	944,177	N/A	N/A
Uncertainty	76 month expected decision wait time on a 53% chance of listing	490,771	-48.0%	Yes
100% chance of listing	76 month expected decision wait time on a 100% chance of listing	98,188	-89.6%	Yes
High Price Volatility	Volatility x 5	8,172,468	765.6%	Yes
High Price	Price x 5	4,997,146	429.3%	Yes
High Cost	Cost x 5	(351,368)	-137.2%	Yes
High wait time	760 month expected decision wait time on a 53% chance of listing	873,331	-7.5%	No
Low wait time	7.6 month expected decision wait time on a 53% chance of listing	(104,055)	-111.0%	Yes
Alternate Uncertainty	76 month expected decision wait time on a 50% chance of listing	516,203	-45.3%	Yes

Table 38: Sage-Grouse Simulation Results: Production



Run	Exact Change	Production		
		Average	Change	Different than Base?
Standard	None	51,765	N/A	N/A
Uncertainty	76 month expected decision wait time on a 53% chance of listing	29,757	-42.5%	Yes
100% chance of listing	76 month expected decision wait time on a 100% chance of listing	12,595	-75.7%	Yes
High Price Volatility	Volatility x 5	34,081	-34.2%	Yes
High Price	Price x 5	58,596	13.2%	No
High Cost	Cost x 5	37,166	-28.2%	No
High wait time	760 month expected decision wait time on a 53% chance of listing	46,267	-10.6%	No
Low wait time	7.6 month expected decision wait time on a 53% chance of listing	18,372	-64.5%	Yes
Alternate Uncertainty	76 month expected decision wait time on a 50% chance of listing	30,777	-40.5%	Yes

Table 39: Sage-Grouse Simulation Results: % of Wells Drills



Run	Exact Change	% of Wells Drilled		
		Drilled Wells	Total #	%
Standard	None	474	2,500	19.0%
Uncertainty	76 month expected decision wait time on a 53% chance of listing	411	2,500	16.4%
100% chance of listing	76 month expected decision wait time on a 100% chance of listing	336	2,500	13.4%
High Price Volatility	Volatility x 5	350	2,500	14.0%
High Price	Price x 5	580	2,500	23.2%
High Cost	Cost x 5	275	2,500	11.0%
High wait time	760 month expected decision wait time on a 53% chance of listing	466	2,500	18.6%
Low wait time	7.6 month expected decision wait time on a 53% chance of listing	315	2,500	12.6%
Alternate Uncertainty	76 month expected decision wait time on a 50% chance of listing	412	2,500	16.5%

B Simulation: Ozone

B.1 Introduction

The drilling-under-regulatory uncertainty model was run 1,000 times. Within each of the 1,000 iterations, 5,858 independent parcel-lessees[149] decide whether/when to develop their parcels. Not all 5,858 parcels are able to be drilled immediately, however. I 'release' the number of parcels that were approved each year from 2010-2018, meaning that the following number of parcels are available to be developed each period $Y_{2010}, Y_{2011}, ...Y_{2018}$.

The goal of the model is to collect mean and median drilling times through 11 different periods[150], well profits, and well production, and see how those summary statistics change as input parameters are adjusted. In each run of the model, the developer begins with a well and must optimally determine when (if at all) to spud the well. The developer is given the decision rule to drill if expected profits from the well exceed the expected value from waiting and drilling in a future period. An operator may wait to drill because price and cost volatility may produce a more favorable state than the state the operator finds itself in when making the decision.

The developer weighs the following criteria when deciding in which period to drill:

1. Present and expected future oil prices

2. Their discount factor

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[149] There were 5,858 APDs for potential oil wells approved during the years 2010-2018 in the Uinta Basin.

[150] 11 periods represents 2010-2020 for development. 11 was chosen because I took APD data from 2010-2018, which were the years before a non-attainment level of ozone was reached. Extending 2 extra periods in the model gives the developers with parcels approved and released late in the model several opportunities to drill. Note that in all charts and table of this paper year 2010 is Period 0 and is sometimes not displayed because the only action taken in Period 0 is the resolution of Period 0 drilling decisions.

3. The expected productivity of their well
4. The likelihood of drilling regulation in future periods
    (a) This likelihood is dependent on expected ozone levels, which itself is dependent on drilling from prior periods and the expected number of wells drilled in each future period.
    (b) This likelihood is also dependent on the elevation of the parcel. Higher elevation parcels have a lower likelihood of experiencing a negative regulatory regime.

When considering whether or not to drill in each period, the developer compares the expected value of drilling now (the discounted stream of profits from the current period and all future periods) against maintaining the discounted value option of drilling in the future. Developers are assumed to be risk-neutral (like Kellogg 2014), and once a well is drilled, it is permanently drilled (the well cannot be re-drilled and cannot be un-drilled). When considering to drill, the firm expects to receive a declining revenue curve for 53 periods[151]:

$$\Pi_w = \pi_0 + \delta^t \sum_{t=1}^{53} \pi_t, \text{ and } \pi_0 = P_0 Q_0 * (1 - \lambda_0 * r_w) - D_w \ \pi_t = P_t Q_t * (1 - \lambda_t * r_w)$$

In the above equation, Π_w represents the aggregate profit from drilling across 53 future periods. π_0 is the profit from the present period, which is a function of the initial quantity Q_0, the present price P_0, the current-period's regulation likelihood λ_0[152] discounted by the well's chance of being subject to regulation (r_w) and the parcel's cost of drilling D_w. D_w is defined as a draw from the normal distribution

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[151] The average oil well in the Uinta Basin produces for 53 months.

[152] Since this is the *current period's* likelihood of regulation, this likelihood will always resolve to 0 or 1 (the developer knows whether or not extraction is allowed in the current period). A develope never drills in a period with a restriction likelihood of 1.

centered around μ_D with standard deviation σ_D, with a minimum set at 0. Each well has its own specific D_w.

Future profits, discounted by δ each period, are dependent on the period-specific price P_t, the period-specific quantity Q_t, and the period-specific regulation likelihood λ_t discounted by r_w. Please see Section B.2 for a detailed breakdown of the determination of all parameters of the model, including formulas determining initial and future prices, quantities, drilling costs, and regulation likelihoods.

The model is dynamic in that each period is taken across all wells simultaneously, and in the following period developers update their expectation of future profits and regulation based on how manywells were drilled in the prior period (for example, in period 2, a developer bases its decision on how many wells were drilled in periods 0 and 1, and how many it expects to be drilled in periods 2 through 10. Then in period 3, the decision is based on how many parcels were drilled in 0 through 2 and how many the developer expects to be drilled in 3 through 10).

In each period, the regulator calculates the ozone level of the prior three periods and compares this average to the legally-mandated threshold of non-attainment:

$$P(Regulation) = \begin{cases} 0 & avg(O_{t-1}, O_{t-2}, O_{t-3}) < T \\ 1 & avg(O_{t-1}, O_{t-2}, O_{t-3}) \geq T \end{cases}$$

If the average of the prior 3 periods' 8-hour ozone meets or exceeds the threshold T, the model assumes that extraction is not allowed. In practice it also disallows drilling, because no developer will ever drill when expected revenue in the current period is equal to 0. This 'penalty' exceeds the actual penalty incurred in the Basin when it was declared in marginal non-attainment in 2018, but certainly could be on the horizon if either the concentrations break the moderate non-attainment threshold or even simply remain at the same elevated marginal non-attainment levels. The model allows a 'turn-on/turn-off' phenomenon, where the unfavorable regulatory regime may not be permanent. If the ozone level improves, developers resume well completions and extraction.

The model also incorporates heterogeneous risk of exposure to the regulator. Every parcel is given a specific chance of being subject to regulation, r_w. If this constant is equal to 0, the developer is certain to *not* be subject to regulation and ozone concentration will not factor into that developer's decision. On the other extreme, if this constant is equal to 1, the developer will certainly be subject to drilling and extraction regulations imposed by the regulator. Finally, if $0 < r_w < 1$, then the developer *may* be subject to regulation, but isn't certain of whether it would be impacted by a regulatory decision. In this case, the developer discounts current and future revenues by the factor $r_w * \lambda_t$, or the likelihood the drilling and extraction restrictions are in place scaled by the chance the developer would be subject to the restrictions. r_w is calculated for each well and is defined by a draw from $min(max(N \sim (\mu_r, \sigma_r), 0), 1)$, which means it is drawn from a normal distribution centered around μ_r with standard deviation σ_r and bounded by the interval [0,1]. This phenomenon is meant to mimic the widely expected possibility (and actual result) that only low-elevation parcels would be subject to any negative regulations.

B.2 Initial Parameter Values and Transition Equations

The model is parameterized to as best possible match the actual drilling context of the Uinta Basin from 2010-2018. As discussed in Section B.1 above, each iteration comprises 5,858 parcels considering whether to drill over 9 periods, with each period considering the discounted value of extracting reserves for 53 periods into the future. Other parameterizations and their respective derivations from the actual drilling data are discussed below. Throughout the model, several parameters change to allow for heterogeneous experiences by different developers and to integrate the change in ozone and expected regulation based on the prior period's drilling outcome.

B.2.1 Transition Equations - Price and Quantity

1. Price (not unique to each parcel - every parcel experiences the same price level within the same period of the simulation). Each period, the price experiences a mean-reverting process of the equation $P_t = max(N \sim (P_{t-1}, \sigma_p) + S_p * (P_l - P_{t-1}), 0)$.
    (a) P_t is the current price of a barrel of oil
    (b) P_{t-1} is the prior period's price of a barrel of oil
    (c) σ_p is the standard deviation in the price of a barrel of oil
    (d) S_p is the 'speed' of the price of oil, which represents how quickly it returns to the long-run price.
    (e) P_l is the long-run price of a barrel of oil
2. Quantity (unique to each parcel within each period). Each period, the pro-

duction quantity declines along the curve $Q_t = \frac{Q_0}{1+kt}$.

(a) Q_t is the well's current period production

(b) Q_0 is the well's initial period production

  i. Q_0 is defined as a draw from the normal distribution centered around μ_q with standard deviation σ_q, with a minimum set at 0. $Q_0 = max(N \sim (\mu_q, \sigma_q), 0)$. Each well has its own specific Q_0.

  ii. Note that since Q_0 and k are known to the developer (although Q_0 is determined stochastically), the model assumes that the developer knows precisely how much oil will be extracted in each period during and after spudding.

(c) k is the hyperbolic decline factor

(d) t is the period

B.2.2 Transition Equations - Ozone

The level of ozone in the Basin fluctuates through each period based on metereological factors and oil development. Factors influencing the level of ozone were identified by Mansfield (2017)[43]. Mansfield (2017)[43] provides an accompanying dataset with Uinta Basin daily data of the above data from winter 2010 to winter 2016[153]. I take his entire dataset and supplement with data from 2017 and 2018. For later years, I was not able to locate data on snow depth, solar zenith angle, or humidity, so I imputed values based on the mean value from 2010-2016 on day α. For example, to construct humidity on March 3, 2018, I averaged the humidity on

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[153] Only wintertime data is available because Uinta Basin ozone information is only monitored consistently in the wintertime. Additionally, Mansfield (2017) data on spudding rates are estimated based on the assumption that a certain rig is rented for 15 days to spud a well.

March 3 of 2011, 2012, 2013, 2014, 2015, and 2016.

To determine the relationship between a period's ozone level and the inputs provided by Mansfield (2017)[43], I run the Mansfield 8-variable regression model with 7 of his variable inputs:

$y_\alpha = A + \Sigma_j B_j x_j + \Sigma_{[j,k]} C_{j,k} x_{j\alpha} x_{k\alpha}$

In this equation, y represents ozone concentrations at the Ouray weather station (the station used by Mansfield), α represents a certain day from December 2015-March 2020, and x is a specific covariate. The 7 covariates in my regression model are:

1. The lapse rate (the change in temperature relative to elevation, measured in $\frac{°K}{km}$)
2. Temperature (measured in $°C$)
3. Snow pack (measured in mm)
4. Solar zenith angle
5. Consecutive days of inversion
6. Absolute humidity (measured in $mbar$)
7. Number of wells spudded

Other than the exclusion of active wells, my regression model is identical to Mansfield's. The active well rate does not appear in the ozone transition equation because the ozone regression equation indicates that extraction rates *decrease* ozone concentrations, which cannot be correct. Mansfield (2017)[43] is also perplexed by this relationship, writing "[I]ts downward trend is contrary to our expectation. We do not have a complete understanding of this behavior, but a few observations can be made. As seen in Figure 8, petroleum production was at its lowest for the 2010 and 2016 winters, yet Winter 2010 has had more exceedances than any season on record. This fact alone indicates that petroleum production is probably not a good proxy variable for ozone percursor emissions. Improvements in operating procedures and equipment over the 7-year course of study suggest the same thing. Finally, with standard error in the model at about 11 ppb, sensitivities around 6 ppb or lower may not have strong statistical significance." Because of this inexplicably negative correlation and lack of evidence of a statistically significant relationship, I have decided to exclude production from the ozone formulation equation. This means that only the spudding of new wells, and not the extraction rate or even number of extracting wells, has any influence on my model.

Running the above regression model results in 36 parameters tranforming given meteorological and development conditions (1 intercept, 7 linear effects, and 28 quadratic effects [each of the 7 covariates is paired with all 7 covariates]). I take all parameters that do not directly use the number of wells spudded[154] to create a base level of estimated ozone concentrations every day of the model. For each winter, I order in descending ozone concentration and select the day with the 4th highest concentration, as EPA considers the 4th highest record when determining NAAQS standards. I added the effects of spudding including linear and quadratic effects for each period at the end of each iteration based on how many wells were spudded in the model each period. The actual parameters from the regression model for spudding must be scaled to an annual level, because the typical rig is

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[154] The number of wells spudded is not included because the number of wells spudded is determined within the model.

active for 15 days. Thus, I scale the coefficients by 15/365=4%. After adding the effects of spudding to the prior ozone concentrations, I have finished calculating the 'simulated' annual ozone level displayed in Figure 11 of the chapter on ozone regulation. The 'actual' annual ozone level is simply the 4th highest reading at the Ouray monitor each winter.

However, developers do not have the luxury of perfect foresight when determining optimal drilling time. When considering what they expect future ozone concentrations to be, agents rely on draws from a normal distribution characterized by long-run averages and variation in each variable:

1. The lapse rate (the change in temperature relative to elevation, measured in $\frac{{}^{\circ}K}{km}$) $\mu = -0.3, \sigma = 7.6$
2. The number of consecutive inversion days (days in which temperature and elevation are *positively* correlated) $\mu = 4, \sigma = 8$
3. Snow pack (measured in mm) $\mu = 104, \sigma = 86$
4. Solar zenith angle $\mu = 56.3, \sigma = 6.7$
5. Humidity (measured in $mbar$) $\mu = 3.3, \sigma = 1.3$
6. Temperature (measured in $^{\circ}C$) $\mu = 1.0, \sigma = 8.6$

B.2.3 Expected Future Price and Ozone Transition Equations

Along with the period-to-period movement of price, quantity, and ozone concentrations, firms also *project* into the future when considering whether to drill. The transition equations parcel-holders use in this projection are exactly the same as in the actual transition equations for price and quantity[155], but slightly differs for ozone.

1. Ozone level (not unique to each parcel - every parcel experiences the same price level within the same period of the simulation). Firms anticipate that ozone concentrations will follow the following formula in future periods: $O_t = max(N \sim (\mu_o + (W_y + W_p * P_t) * O/W), \sigma_o), 0)$. In this equation, the anticipated ozone level fluctuates over time based on the number of wells that are expected to be completed, which is based on the expected future prices. All variables are the same as in the ozone state transition equation, with the following additions:
   (a) $\mu_o = 57$ parts per billion is the long-run average ozone concentration in the Basin (mean of ozone in the Mansfield data)
   (b) W_y is the constant additional number of wells expected to be drilled each period, regardless of price.
   (c) W_p is the constant additional wells expected to be drilled each period based on the expected price of period t
   (d) P_t is the expected price of period t, which is estimated using the same transition equation as the actual price transition equation
   (e) $O/W = 0.091$, the contribution to ozone of a single spud based on my own calculation of the linear effect of one spudding on ozone concentrations in the Basin, isolated from other effects.
   (f) $\sigma_o = 24$ parts per billion is the standard deviation of ozone concenrations in the Mansfield data

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[155] Howvever, note that each parcel will have a different projection of the price, as each takes an independent draw in each period of its projection from the normal distribution.

B.2.4 Initial Parameter Values

1. $W = 5858$ There were 5,858 APDs (potential wells) approved between 2010 and 2018 in the Uinta Basin. They are released according to the annual number of parcels approved in the Uinta Basin:
   0. 506 new parcels (506 cumulative)
   1. 777 (1,283)
   2. 1,182 (2,465)
   3. 1,138 (3,603)
   4. 1,075 (4,678)
   5. 485 (5,163)
   6. 109 (5,272)
   7. 325 (5,597)
   8. 261 (5,858)
2. $Periods = 53$ The average oil well produces for 53 months in the Uinta Basin. Thus when a developer calculates expected well revenue they do so over 53 periods.
3. $\delta = 0.91$ Kellogg stipulates that the typical discount factor for a mineral developer is 0.910.
4. $\mu_q = 3,516$. This is the mean of the first month's production of oil wells in the Uinta Basin from 2010-2018.
5. $\sigma_q = 6,197$. This is the standard deviation of the first month's production of oil wells in the Uinta Basin from 2010-2018.

6. $k = 0.085$ k is the decline rate, meaning how much production is expected to fall each period as a share of the initial value. This was estimated using Uinta Basin production data, fitting a decline curve starting at 3,516 barrels per month that ultimately produces a lifetime mean of 72,679 barrels across 53 months (the average production lifetime of a well).
7. P_0 is the price of a barrel of oil in 2010, \$82.
8. P_l is the average price of a barrel of oil from 2010-2018, \$72.
9. σ_p is the standard deviation of the price of a barrel of oil from 2010-2018, \$24.
10. S_p is determined to be 0.055, which was determined from this document[156] as the half-life of the price of oil returning to its long-run price is given to be 13 months.
11. $\mu_d = \$2,096,066$. This is the mean cost of wells drilled in the Uinta Basin from 2010-2018, assuming a cost of \$150 per foot of depth for a traditional well and a cost of \$500 per foot of depth for a horizontally drilled well based on this[157] information, and a mixture of traditional and horizontal wells consistent with the actual drilling in the Basin over the given time period.
12. $\sigma_d = \$681,853$. This is the standard deviation of the drilled wells with the same assumptions as above.
13. O_0 is 57 parts per billion, the long-run average of ozone concentrations in the Basin.

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[156] https://core.ac.uk/download/pdf/52955755.pdf

[157] https://www.oilgasequity.com/resources/drilling-completion-facts/#:~:text=The%20cost%20to%20complete%20a,foot%20of%20lat

14. W_y= 2.5% of the total well count of 5,858. This was determined to be the typical number of extra wells drilled each year in the Uinta Basin from 2010 to 2018, after taking account the impact of price.

15. W_p= 0.2% of the total well count of 5,858. This was determined to be the typical number of wells drilled per dollar of the price of oil, after taking into account the typical growth in the number of drilled wells.

16. $W_0 = 1,572$. This is equal to the number of active oil wells in 2010 in the Uinta Basin that were drilled before that year.

17. $\mu_r = 0.5$ The actual share of parcels of elevation greater than or equal to 6,250 feet is 22%, not 50%. However, I used 50% because I had no way to estimate the uncertainty around the estimate. Had I used 22%, any estimate of the uncertainty would either have to allow the likelihood of not being subject to regulation to be less than 0% or greater than 1%, or produce a biased estimate after putting [0,1] bounds on the likelihood.

18. $\sigma_r = 1$ This is the standard deviation around the regulatory risk of $r_w = 0.5$. 1 was selected arbitrarily to provide heterogeneity in the regulatory risk.

19. $T = 0.71$ parts per billion. Across the entire country, the EPA declares 'marginal' non-attainment of 8-hour ozone at 71 parts per billion[158].

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[158] https://www.epa.gov/green-book/ozone-designation-and-classification-information

C Empirical Robustness Checks and Extra Analyses

C.1 Timing and Speed of Drilling

C.1.1 Decomposition of 'Wait-and-see' Duration Model

As described in Section 6.1, there are in fact two discrete steps I am combining into one process in my Cox hazard rate survival models:

1. APD submission to spudding
2. Spudding to completion

Either one or both of these processes could be subject to 'wait-and-see' or 'hurry-up-and-drill'. My duration model shows that the combination of the processes shows a 'wait-and-see' story. Testing these processes separately provides a 'wait-and-see' story for both components of the completion. That is, developers under uncertainty delay spudding their well after submitting an APD, and also complete their wells more slowly once spudded.

The first component I tested was the timing from APD submission to spudding:

The specified Cox hazards model is the same as in Section 6.1 :

$SpuddingAge_w = Season_s + Field_i + Interaction_{w,s} + WellControls_w$

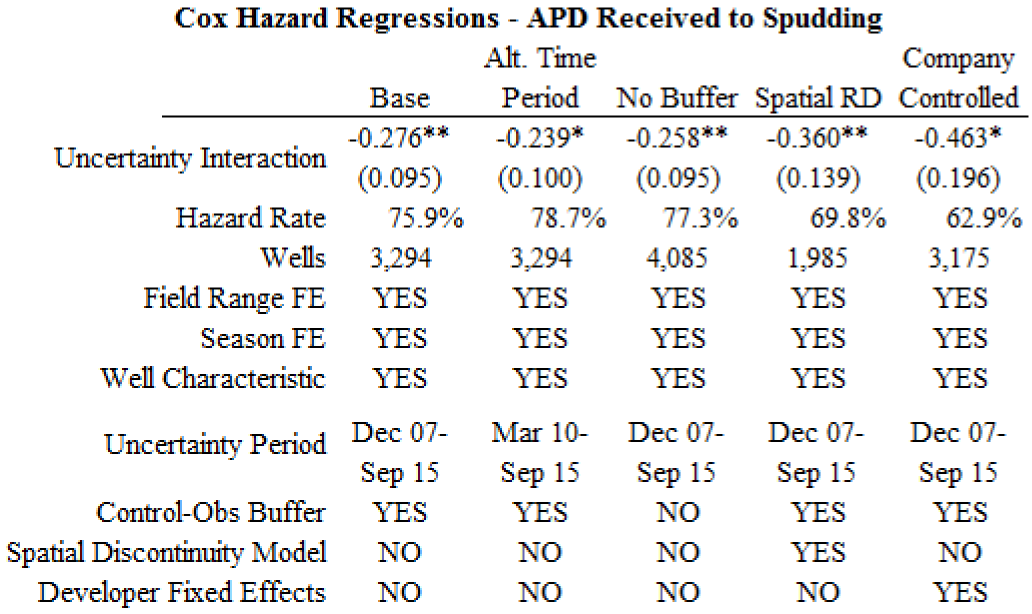
All variables in this equation are the same as the Cox hazards model. The dependent variable $SpuddingAge_w$ represents the number of days between APD submission and spudding. Errors are clustered at the field level.

The second component I tested was the timing from spudding to completion:

The specified Cox hazards model is the same as in Section 6.1 :

$Days_w = Season_s + Field_i + Interaction_{w,s} + WellControls_w$

Table 40: Drilling Timing Results: APD to Spud



Cox Hazard Regressions - APD Received to Spudding

	Base	Alt. Time Period	No Buffer	Spatial RD	Company Controlled
Uncertainty Interaction	-0.276** (0.095)	-0.239* (0.100)	-0.258** (0.095)	-0.360** (0.139)	-0.463* (0.196)
Hazard Rate	75.9%	78.7%	77.3%	69.8%	62.9%
Wells	3,294	3,294	4,085	1,985	3,175
Field Range FE	YES	YES	YES	YES	YES
Season FE	YES	YES	YES	YES	YES
Well Characteristic	YES	YES	YES	YES	YES
Uncertainty Period	Dec 07- Sep 15	Mar 10- Sep 15	Dec 07- Sep 15	Dec 07- Sep 15	Dec 07- Sep 15
Control-Obs Buffer	YES	YES	NO	YES	YES
Spatial Discontinuity Model	NO	NO	NO	YES	NO
Developer Fixed Effects	NO	NO	NO	NO	YES

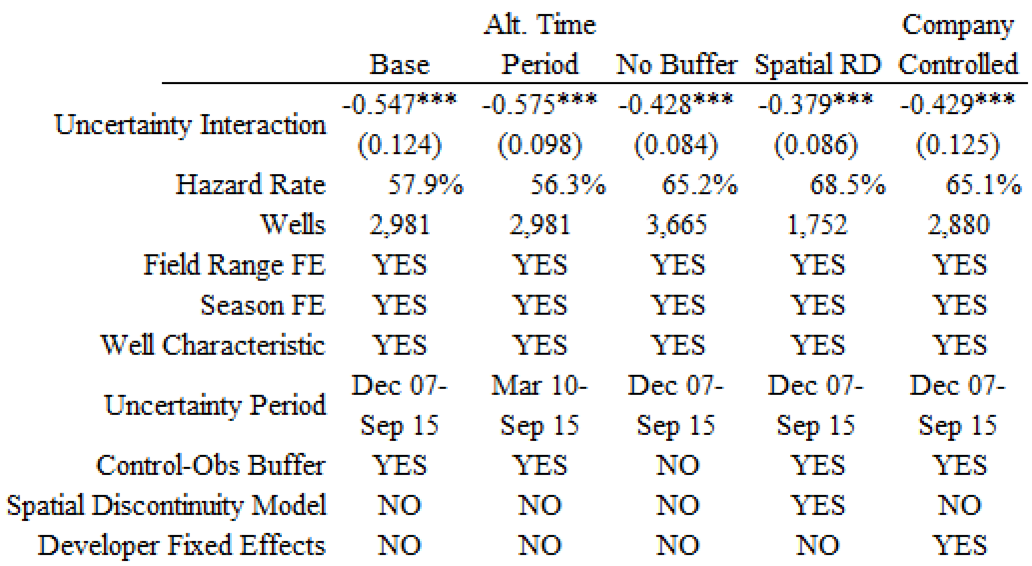
All variables in this equation are the same as the Cox hazards model. The dependent variable $Days_w$ represents the number of days between spudding and completion. Errors are clustered at the field level.

Both components show a sizable ‘wait-and-see’ effect. The effect is larger for the second component (spudding to completion), with a 57.9% hazard rate, compared to a 75.9% hazard rate for the submission of the APD to spudding. Since both measurements have a hazard rate significantly below 1, it is clear that developers delay both components of the well completion.

C.1.2 Risk Aversion Test

While both my simulation and Kellogg’s theoretical and empirical work do not make the assumption that developers are risk-averse, risk aversion has the potential to make the impact of ‘wait-and-see’ even stronger, as risk-averse firms would shy away even further from territory subject to uncertainty. One possible way to test

Table 41: Drilling Timing Results: Spud to Completion



Cox Hazard Regressions - Spudding to Completion

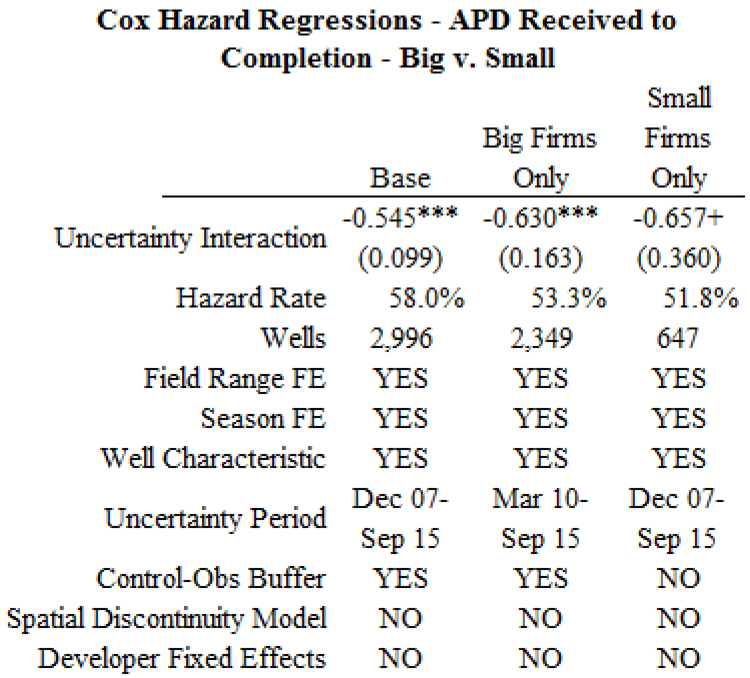
	Base	Alt. Time Period	No Buffer	Spatial RD	Company Controlled
Uncertainty Interaction	-0.547*** (0.124)	-0.575*** (0.098)	-0.428*** (0.084)	-0.379*** (0.086)	-0.429*** (0.125)
Hazard Rate	57.9%	56.3%	65.2%	68.5%	65.1%
Wells	2,981	2,981	3,665	1,752	2,880
Field Range FE	YES	YES	YES	YES	YES
Season FE	YES	YES	YES	YES	YES
Well Characteristic	YES	YES	YES	YES	YES
Uncertainty Period	Dec 07-Sep 15	Mar 10-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15
Control-Obs Buffer	YES	YES	NO	YES	YES
Spatial Discontinuity Model	NO	NO	NO	YES	NO
Developer Fixed Effects	NO	NO	NO	NO	YES

for risk-aversion is to break up the 'wait-and-see' regressions into different runs based on the size of the company, as smaller firms with a larger portion of their budget invested in any single well could reasonably be considered more risk-averse. I segregated drilling data into those drilled by 'large' companies (those with more than 20 wells) and 'small' companies (those with 20 or fewer wells). Errors are clustered at the field level, and the specified Cox hazards model is the same as in Section 6.1 :

$$CompletionAge_w = Season_s + Field_i + Interaction_{w,s} + WellControls_w$$

In these regressions, both 'large' and 'small' developers have a 'wait-and-see' effect. Because both categories of developers see a 'wait-and-see' response I find it unlikely that risk aversion is driving my empirical (or for that matter, simulated) results.

Table 42: Risk Aversion Results



Cox Hazard Regressions - APD Received to Completion - Big v. Small

	Base	Big Firms Only	Small Firms Only
Uncertainty Interaction	-0.545*** (0.099)	-0.630*** (0.163)	-0.657+ (0.360)
Hazard Rate	58.0%	53.3%	51.8%
Wells	2,996	2,349	647
Field Range FE	YES	YES	YES
Season FE	YES	YES	YES
Well Characteristic	YES	YES	YES
Uncertainty Period	Dec 07- Sep 15	Mar 10- Sep 15	Dec 07- Sep 15
Control-Obs Buffer	YES	YES	NO
Spatial Discontinuity Model	NO	NO	NO
Developer Fixed Effects	NO	NO	NO

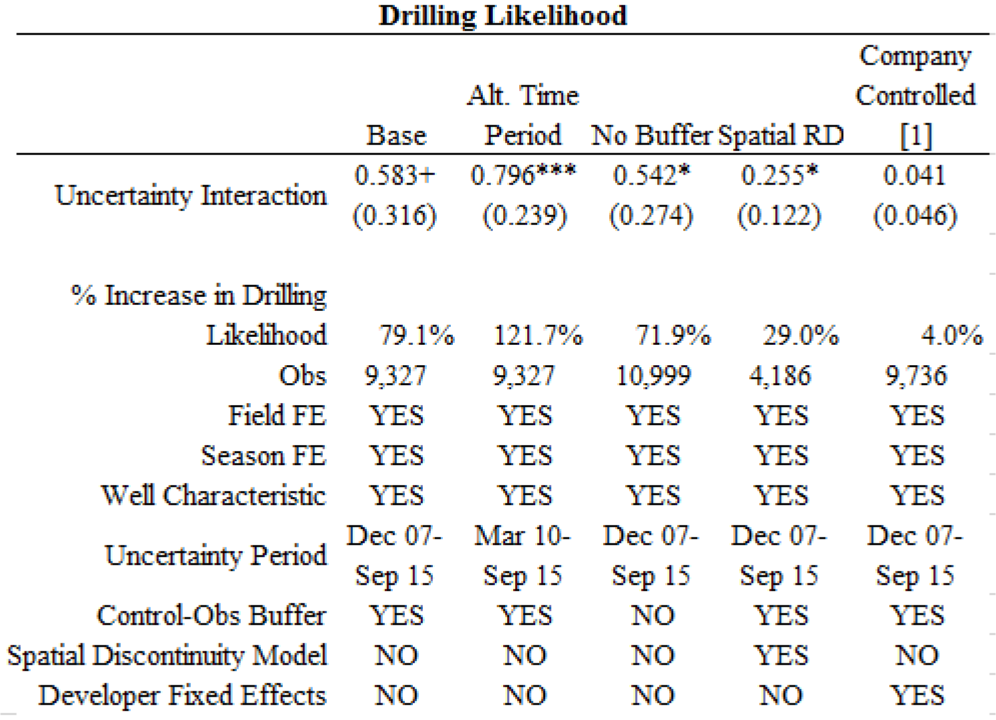
C.1.3 Likelihood to Drill

There is question of the intensive versus extensive margin of drilling. Above, I measure the impact of the sage-grouse uncertainty on the *intensive* margin - or delays in wells that are drilled regardless of the uncertainty. There is also the question of the *extensive* margin, or wells that were not drilled at all due to the uncertainty. I used a logistic difference in differences regression model to measure whether uncertainty impacted the likelihood to drill given that a firm has received permission to drill:

$$Drilled_w = Season_s + Field_i + Interaction_{w,s} + WellControls_w$$

The dependent variable in the equation, $Drilled_w$, takes on a value of 1 when the well is drilled. Well controls like depth, elevation, direction of the well, and land type are still included because this information is required to be listed on the APD

Table 43: Drilling Likelihood Results



Drilling Likelihood

	Base	Alt. Time Period	No Buffer	Spatial RD	Company Controlled [1]
Uncertainty Interaction	0.583+ (0.316)	0.796*** (0.239)	0.542* (0.274)	0.255* (0.122)	0.041 (0.046)
% Increase in Drilling Likelihood	79.1%	121.7%	71.9%	29.0%	4.0%
Obs	9,327	9,327	10,999	4,186	9,736
Field FE	YES	YES	YES	YES	YES
Season FE	YES	YES	YES	YES	YES
Well Characteristic	YES	YES	YES	YES	YES
Uncertainty Period	Dec 07-Sep 15	Mar 10-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15
Control-Obs Buffer	YES	YES	NO	YES	YES
Spatial Discontinuity Model	NO	NO	NO	YES	NO
Developer Fixed Effects	NO	NO	NO	NO	YES

even before spudding[159], meaning both completed wells and incomplete wells have populated well characteristic controls.

Unexpectedly, all specification coefficients are positive and most are statistically significant. While the base specification is only significant at the 10% level, the alternate time period is significant at the 0.1% level, and the 'no buffer' and regression discontinuity specifications are significant at the 5% level. The base model with company controls is not statistically significant[160].

The somewhat inconsistent results make conclusions difficult, but the fact the coefficient is consistently positive is surprising on its own. The simulation as well as economic logic predicts that the coefficient on the uncertainty interaction in this model should be negative. The simulation predicts that 2.5% of wells that would

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[159] https://casetext.com/regulation/wyoming-administrative-code/agency-055-oil-and-gas-conservation-commission/subagency-0001-general-agency-board-or-commission-rules/chapter-3-operational-rules-drilling-rules/section-3-8-application-for-permit-to-drill-or-deepen-a-well-form-1

[160] This model had to be run as a linear probability DiD model rather than a logistic DiD model because the likelihood function did not converge.

have been drilled absent uncertainty would not be drilled under uncertainty. The logistic DiD results show the opposite. They show an *increase* in the chance a given well is drilled. While a story of a lower drilling rate or an unchanged drilling rate are sensible (especially given the small effect seen in the simulation), a large and positive effect observed in some of the alternative specifications is tough to rationalize.

This seemingly contradictory story is the same found by Melstrom (2017) [46] in his review of the lesser prairie chicken ESA listing. Of the time periods he tested[161], all but one indicate that upcoming and active development restrictions did indeed cause developers to move out of habitat territory. Interestingly, the one period that Melstrom finds an *increase* in wells drilled is the 'candidate' period, in which the prairie chicken was being reviewed for inclusion under an LPN of 8, which was the same LPN held by the sage-grouse. Melstrom interprets the evidence that firms moved towards prairie chicken habitat during the initial review period during a lower LPN as evidence that firms are speeding up habitat development in an effort to beat the regulator. His only explanation of why firms would develop quicker under a review but then back out once the LPN was raised to 2 from 8 is speculation that developers' interests changed over the time period.

My results suggest the same result: firms do drill more in habitat territory under review - but they do so later, closer to the end of the primary period in which they have to drill or forfeit their right to do so. It is possible the looming threat of expropriation makes it unlikely the developers will ever hold a lease for the parcel

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[161] The steps Melstrom tests for an effect for are the initial candidate announcement, when USFWS changed its LPN from 8 to 2, the proposed regulations that were put out before the listing decision, drilling restrictions put in place by an interstate wildlife agency just before the listing, and the actual listing decision which resulted in the prairie chicken being declared 'threatened'.

in core habitat again, making the the end of the primary period the ultimate ‘use it or lose it’ situation.

C.1.4 Likelihood to Drill Horizontally + Well Depth

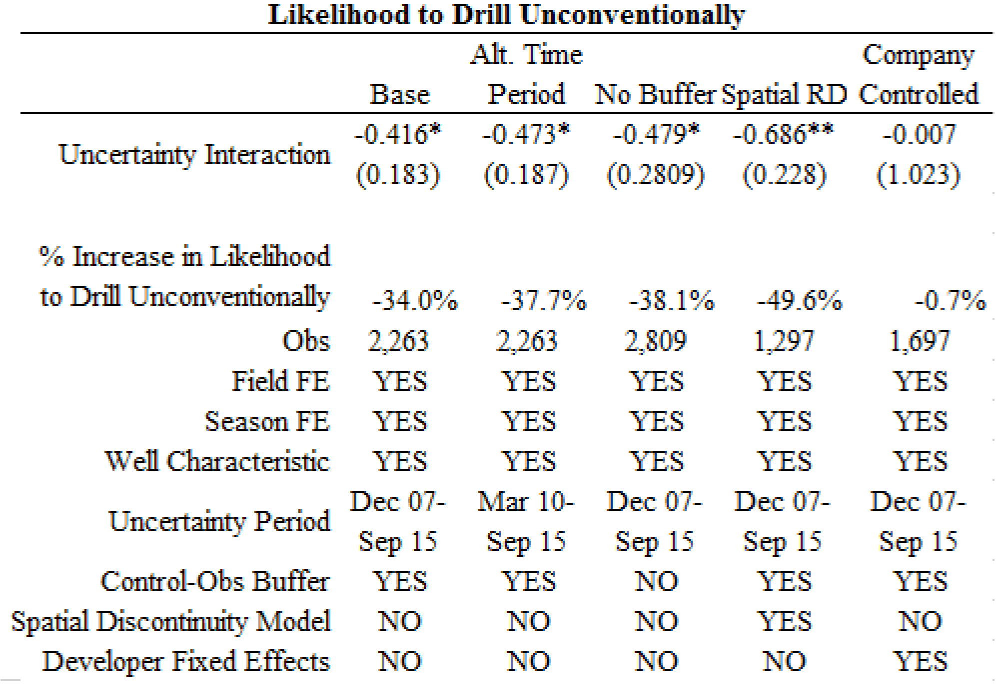
I tested whether firms were more likely to engage in horizontal drilling (versus vertical) drilling at all. Drilling horizontally would indicate firms are leaving themselves more options in the future to respond to uncertainty resolution. Newell, Prest, and Vissig (2016)[48] write that “[C]onventional oil and gas investments resemble high-risk/high-reward, ‘big game trophy hunting,’ which involves drilling many dry holes in search of a few highly productive ones. This stands in stark contrast to modern unconventional extraction from shale, which is commonly said to resemble a ‘manufacturing process’ in that operators have much more flexible and certain control over their production levels.” This process allows the developer to more flexibly adjust plans in the face of uncertainty. However, this flexibility comes at a cost. Horizontal wells are roughly three times costlier than conventional wells, meaning even a risk-neutral firm facing regulatory uncertainty may refrain from drilling a horizontal well. Given these competing effects, the expected result of uncertainty is ambiguous.

I again utilize a logistic difference in differences model to determine whether developers are more likely to drill horizontally under uncertainty, using the same controls as in the refracking model (less age controls, as wells are spudded at age = 0):

$$Horizontal_w = Season_s + Field_i + Interaction_{i,s} + WellControls_w$$

In this equation, the outcome variable is equal to 1 when the well is drilled

Table 44: Unconventional Drilling Likelihood Results



Likelihood to Drill Unconventionally

	Base	Alt. Time Period	No Buffer	Spatial RD	Company Controlled
Uncertainty Interaction	-0.416*	-0.473*	-0.479*	-0.686**	-0.007
	(0.183)	(0.187)	(0.2809)	(0.228)	(1.023)
% Increase in Likelihood to Drill Unconventionally	-34.0%	-37.7%	-38.1%	-49.6%	-0.7%
Obs	2,263	2,263	2,809	1,297	1,697
Field FE	YES	YES	YES	YES	YES
Season FE	YES	YES	YES	YES	YES
Well Characteristic	YES	YES	YES	YES	YES
Uncertainty Period	Dec 07- Sep 15	Mar 10- Sep 15	Dec 07- Sep 15	Dec 07- Sep 15	Dec 07- Sep 15
Control-Obs Buffer	YES	YES	NO	YES	YES
Spatial Discontinuity Model	NO	NO	NO	YES	NO
Developer Fixed Effects	NO	NO	NO	NO	YES

unconventionally, and 0 when it is a standard vertical well. Errors are clustered at the field level.

Results are consistently negative and almost always significant at the 5% level. This indicates that it is possible developers are in fact *less likely* to drill horizontally under regulatory uncertainty. This could be due to apprehension of investing millions of dollars in a well, or it could be due to the fundamental nature of the uncertainty. Developers may be less likely to drill horizontally in response to regulatory uncertainty than price uncertainty. While maintaining the option of expanding your well to respond to price volatility is plausible, a prohibition due to regulation is likely to impact your ability to extract from the entire parcel. This mitigates the flexibility of drilling horizontally.

There is no effect whatsoever on the depth of the well due to uncertainty. I tested well depth because it is plausible that developers may avoid deep wells during

Table 45: Depth Results

Depth Regressions

	Base	Alt. Time Period	No Buffer	Spatial RD	Company Controlled
Uncertainty Interaction	-0.005	0.006	0.003	0.053+	0.015
	(0.028)	(0.017)	(0.021)	(0.028)	(0.034)
% Increase in Depth	-0.5%	0.6%	0.3%	5.4%	1.5%
Obs	3,074	3,074	3,796	1,863	3,074
R-Squared	0.869	0.869	0.845	0.843	0.938
Adjusted R-Squared	0.855	0.855	0.829	0.813	0.926
Field FE	YES	YES	YES	YES	YES
Season FE	YES	YES	YES	YES	YES
Well Characteristic Controls	YES	YES	YES	YES	YES
Uncertainty Period	Dec 07-Sep 15	Mar 10-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15
Control-Obs Buffer	YES	YES	NO	YES	YES
Spatial Discontinuity Model	NO	NO	NO	YES	NO
Developer Fixed Effects	NO	NO	NO	NO	YES

uncertainty due to the higher cost of reaching those reserves. I ran the following DiD regression:

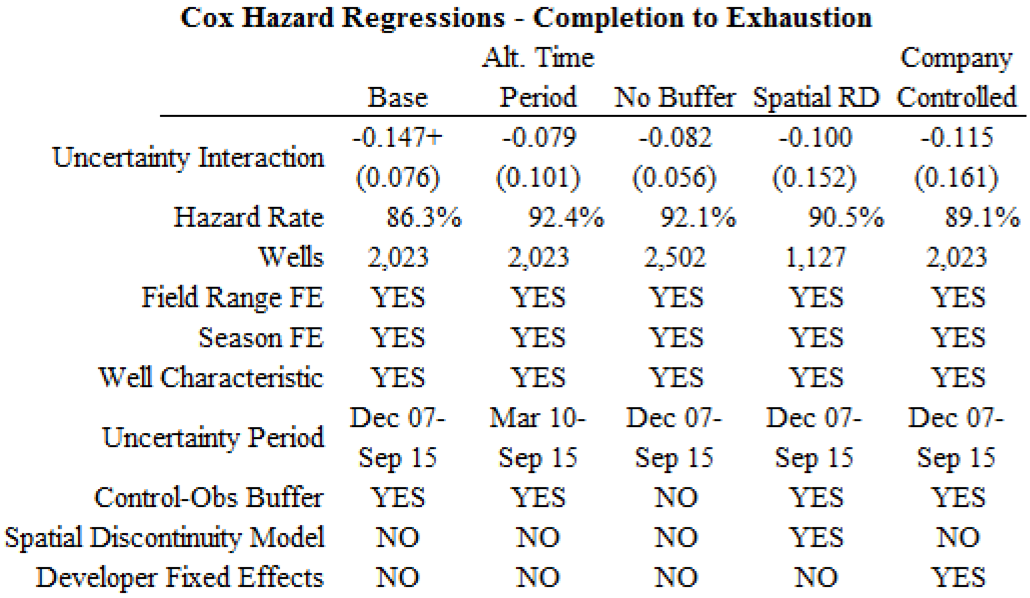
$$Log(Depth_w) = Season_s + Field_i + Interaction_{w,s} + WellCharacteristics_w$$

I regress depth upon the fixed-effects of season drilled, field location, the uncertainty interaction, and well characteristics. Well characteristics in this regression include elevation, land type, and drilling direction.

C.1.5 Speed to finish extracting a well

As discussed in Section 6.5, I did not find evidence firms sped up production of already drilled wells in an effort to beat the regulator. This supports the notion that developers have little ability to adjust the rate of extraction. To supplement this test, I also performed an analysis of the effect uncertainty has on the speed to finish extracting a well. Just as with the 'wait-and-see' duration survival analysis

Table 46: Completion to Exhaustion Results



Cox Hazard Regressions - Completion to Exhaustion

	Base	Alt. Time Period	No Buffer	Spatial RD	Company Controlled
Uncertainty Interaction	-0.147+ (0.076)	-0.079 (0.101)	-0.082 (0.056)	-0.100 (0.152)	-0.115 (0.161)
Hazard Rate	86.3%	92.4%	92.1%	90.5%	89.1%
Wells	2,023	2,023	2,502	1,127	2,023
Field Range FE	YES	YES	YES	YES	YES
Season FE	YES	YES	YES	YES	YES
Well Characteristic	YES	YES	YES	YES	YES
Uncertainty Period	Dec 07-Sep 15	Mar 10-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15
Control-Obs Buffer	YES	YES	NO	YES	YES
Spatial Discontinuity Model	NO	NO	NO	YES	NO
Developer Fixed Effects	NO	NO	NO	NO	YES

models, I use Cox proportional hazards modeling to determine whether uncertainty leads to quicker depletion of the well's resources:

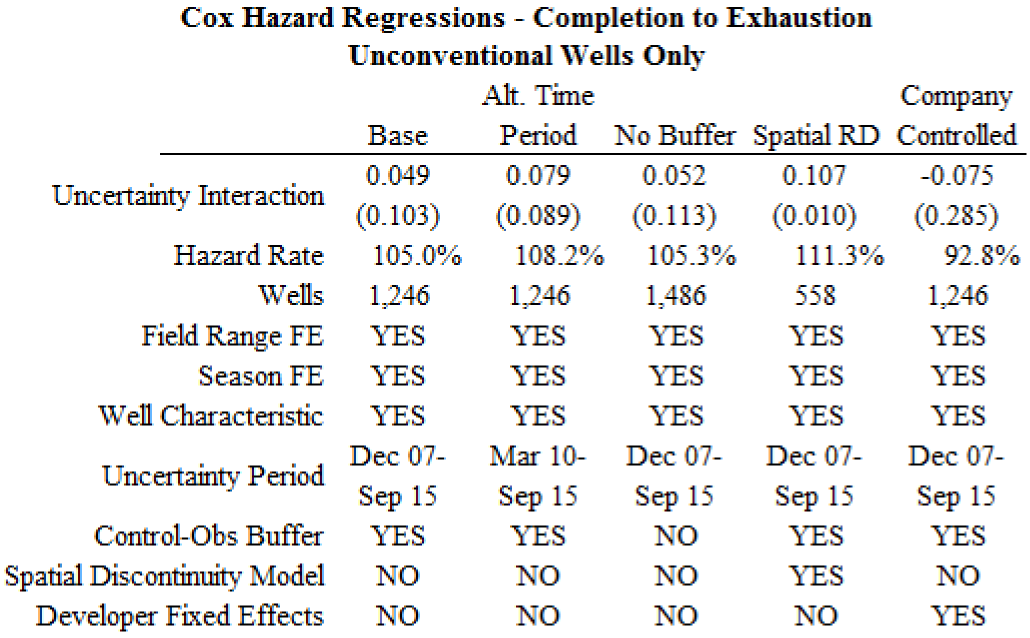
$$ExhaustionDays_w = Season_s + Field_i + Interaction_{w,s} + WellControls_w$$

$ExhaustionDays_w$ represents the number of days between well completion and the last month of extraction. I again use season and field fixed effects, and the same well controls as in other duration models (alternative time period, removal of buffer, spatial discontinuity, and controlling for developer). Errors are clustered at the field level. Results are presented in Table 46.

Results broadly indicate that firms do *not* speed exhausting their wells under uncertainty. The only specification in which a statistically significant effect was found, the base model, indicates *slowing* if anything.

The model was also run using unconventional well data only. Results are similar, in that no specification shows an effect of uncertainty. These results lend further support to the production regressions that did not show a statistically significant

Table 47: Completion to Exhaustion Results: Unconventional Wells Only



Cox Hazard Regressions - Completion to Exhaustion
Unconventional Wells Only

	Base	Alt. Time Period	No Buffer	Spatial RD	Company Controlled
Uncertainty Interaction	0.049 (0.103)	0.079 (0.089)	0.052 (0.113)	0.107 (0.010)	-0.075 (0.285)
Hazard Rate	105.0%	108.2%	105.3%	111.3%	92.8%
Wells	1,246	1,246	1,486	558	1,246
Field Range FE	YES	YES	YES	YES	YES
Season FE	YES	YES	YES	YES	YES
Well Characteristic	YES	YES	YES	YES	YES
Uncertainty Period	Dec 07- Sep 15	Mar 10- Sep 15	Dec 07- Sep 15	Dec 07- Sep 15	Dec 07- Sep 15
Control-Obs Buffer	YES	YES	NO	YES	YES
Spatial Discontinuity Model	NO	NO	NO	YES	NO
Developer Fixed Effects	NO	NO	NO	NO	YES

increase in production rates under uncertainty.

C.1.6 Refracking

Extraction rates are not the only potential ‘choice’ variable firms have when trying to pre-empt an unfavorable regulatory decision.‘Re-fracking’ a well through chemical stimulation is a method firms can use to enhance and speed production. Wells are refracked by sending miniature plastic balls in wells that plug low-pressure cracks, boosting the well’s productivity both in the short-term and overall[162].

Refracking is not something the state of Wyoming tracks, and thus must be inferred from the production data. I identify 8,248 times in the production data that oil wells increase their production from one quarter to another by at least 500 barrels per month (excepting the first to second quarter of production, which could be representative of less than a full first month’s production). My regression

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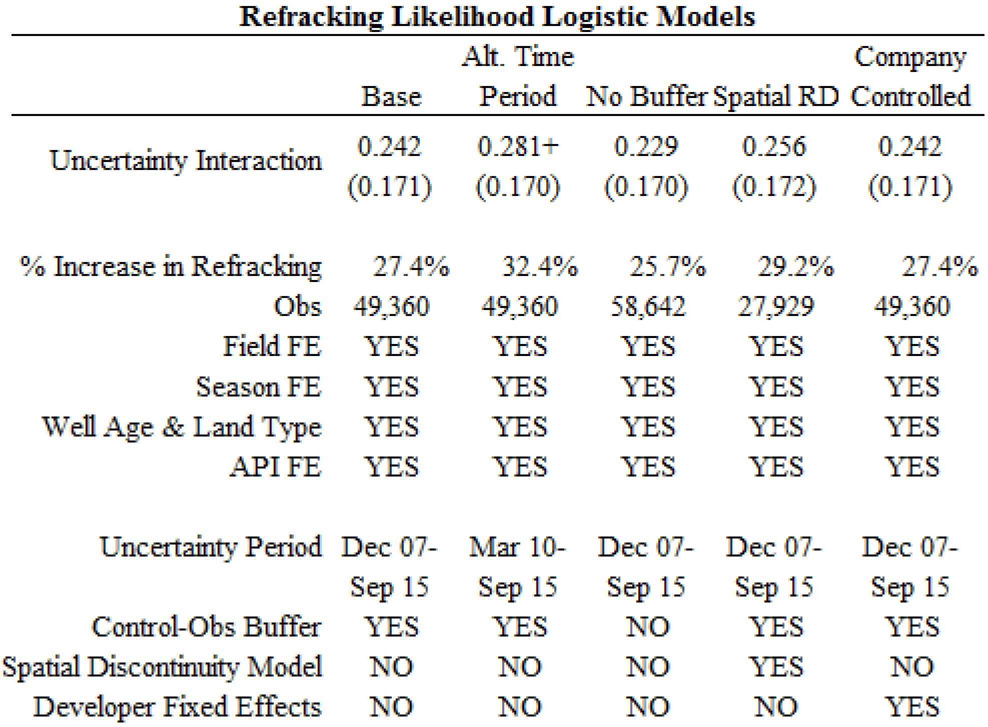
[162] https://www.reuters.com/article/us-energy-refracking-insight/refracking-brings-vintage-oil-and-gas-wells-to-life-idUSKBN0GK0CC20140820, https://www.hartenergy.com/exclusives/citi-refracks-clearly-work-29659

Table 48: Refracking Results



Refracking Likelihood Logistic Models

	Base	Alt. Time Period	No Buffer	Spatial RD	Company Controlled
Uncertainty Interaction	0.242 (0.171)	0.281+ (0.170)	0.229 (0.170)	0.256 (0.172)	0.242 (0.171)
% Increase in Refracking	27.4%	32.4%	25.7%	29.2%	27.4%
Obs	49,360	49,360	58,642	27,929	49,360
Field FE	YES	YES	YES	YES	YES
Season FE	YES	YES	YES	YES	YES
Well Age & Land Type	YES	YES	YES	YES	YES
API FE	YES	YES	YES	YES	YES
Uncertainty Period	Dec 07-Sep 15	Mar 10-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15
Control-Obs Buffer	YES	YES	NO	YES	YES
Spatial Discontinuity Model	NO	NO	NO	YES	NO
Developer Fixed Effects	NO	NO	NO	NO	YES

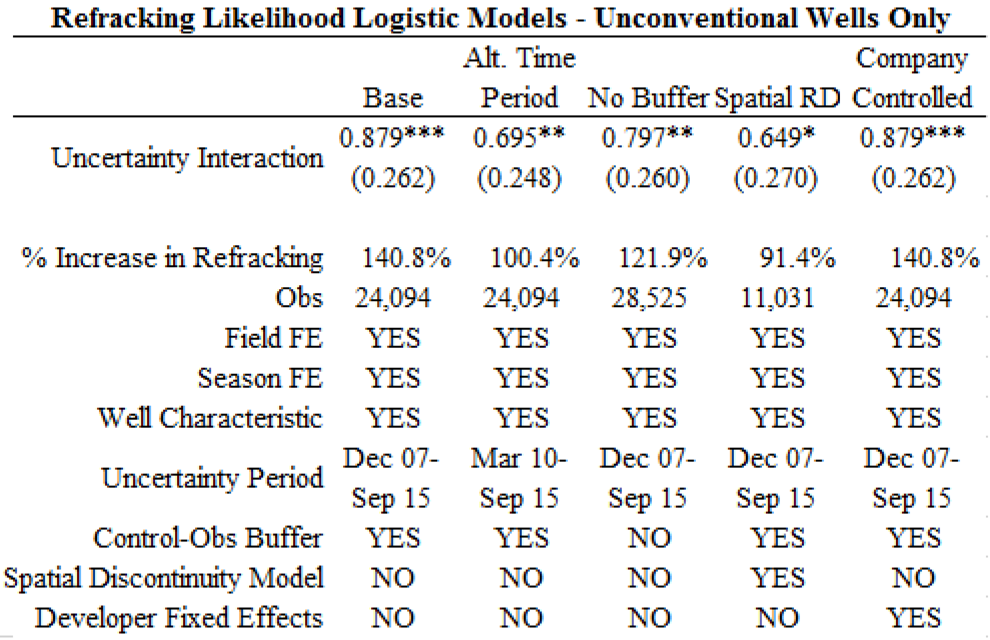
dataset comprises a well/season panel through the life of all oil wells, with a binary indicating whether or not in a given season i the well w in township-range s was re-fracked. I then run a logistic difference in differences model to determine whether developers are more likely to refrack under uncertainty, after controlling for well, time period, and innate township-range characteristics:

$$Refrack_{w,s} = Age_{w,s} + Age^2_{w,s} + API_w + Interaction_{w,m} + Season_s + Field_i + \epsilon_{m,w}$$

Well controls like depth, elevation, direction, and land type are not included because they do not vary across the same API. $Refrack_{w,s}$ takes on a value of 1 when the developer refracks well w in season s, and is otherwise 0. Errors are clustered at the field level.

Results across all specifications do not show evidence that firms are more likely to re-frack, except for the alternative time period which had a coefficient significant at the 10% level:

Table 49: Refracking Results: Unconventional Wells Only



Refracking Likelihood Logistic Models - Unconventional Wells Only

	Base	Alt. Time Period	No Buffer	Spatial RD	Company Controlled
Uncertainty Interaction	0.879***	0.695**	0.797**	0.649*	0.879***
	(0.262)	(0.248)	(0.260)	(0.270)	(0.262)
% Increase in Refracking	140.8%	100.4%	121.9%	91.4%	140.8%
Obs	24,094	24,094	28,525	11,031	24,094
Field FE	YES	YES	YES	YES	YES
Season FE	YES	YES	YES	YES	YES
Well Characteristic	YES	YES	YES	YES	YES
Uncertainty Period	Dec 07-Sep 15	Mar 10-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15	Dec 07-Sep 15
Control-Obs Buffer	YES	YES	NO	YES	YES
Spatial Discontinuity Model	NO	NO	NO	YES	NO
Developer Fixed Effects	NO	NO	NO	NO	YES

Just as in the production regressions, a result would be more expected in the unconventional wells than in vertical wells. Although vertical wells can be refracked, refracking usually occurs in horizontally drilled wells. Indeed, results change substantially when only horizontal wells are considered. Table 49 shows results for the same regression only using data from unconventional wells.

All specifications show roughly a doubling of refracking likelihood under uncertainty. These results show that it is likely firms are re-fracking wells in order to spur and speed production, as it is one adjustable tool after well completion still available to the developer.

C.2 Sage-Grouse Spatial Regression Discontinuity Balance Tests

For all sage-grouse empirical analyses, I include an alternative specification of my base model leveraging a spatial regression discontinuity. In this alternative, I only consider wells or parcels within 10 miles of the border between core habitat and other territory. My concern with this specification is that a developer could relocate just across the border of core sage-grouse territory in order to evade regulation while still taking advantage of the same quality land. Thus, the expectation of the RD model was that it would *overstate* the effect of uncertainty.

However, I see the opposite. In 5 of the 6 empirical analyses[163] in which I found statistically significant results with the effect going in the expected direction, the uncertainty treatment effect is smaller in magnitude for the RD model than for the base model. Perhaps even more suprising is that the location selection model does not meet any threshold of statistical significance in the RD specification, whereas it is significant at the 0.1% level in the base specification (the 4 other models with a smaller effect under RD maintain their statistical significance under RD). One possibile explanation for these diminished effects is that the territory near the border is fundamentally different than other land across the state.

To investigate this possibility, I ran balance tests on the wells and township-range-sections for the RD specifications. I split the statewide well and section data into buckets within 10 miles of the core habitat border and wells/sections further than 10 miles of the border (mimicking the observations included and excluded from the RD specification). Note that both core territory and non-core territory will comprise both buckets, as some core territory is further than 10 miles from the edge of core habitat. I tested all well characteristic controls I use in the drilling timing models and section chacterteristics I use in the location selection model, which are also informative for the lease price bidding models as the bidding tests use the same level of geographic controls. Because land type and soil type are

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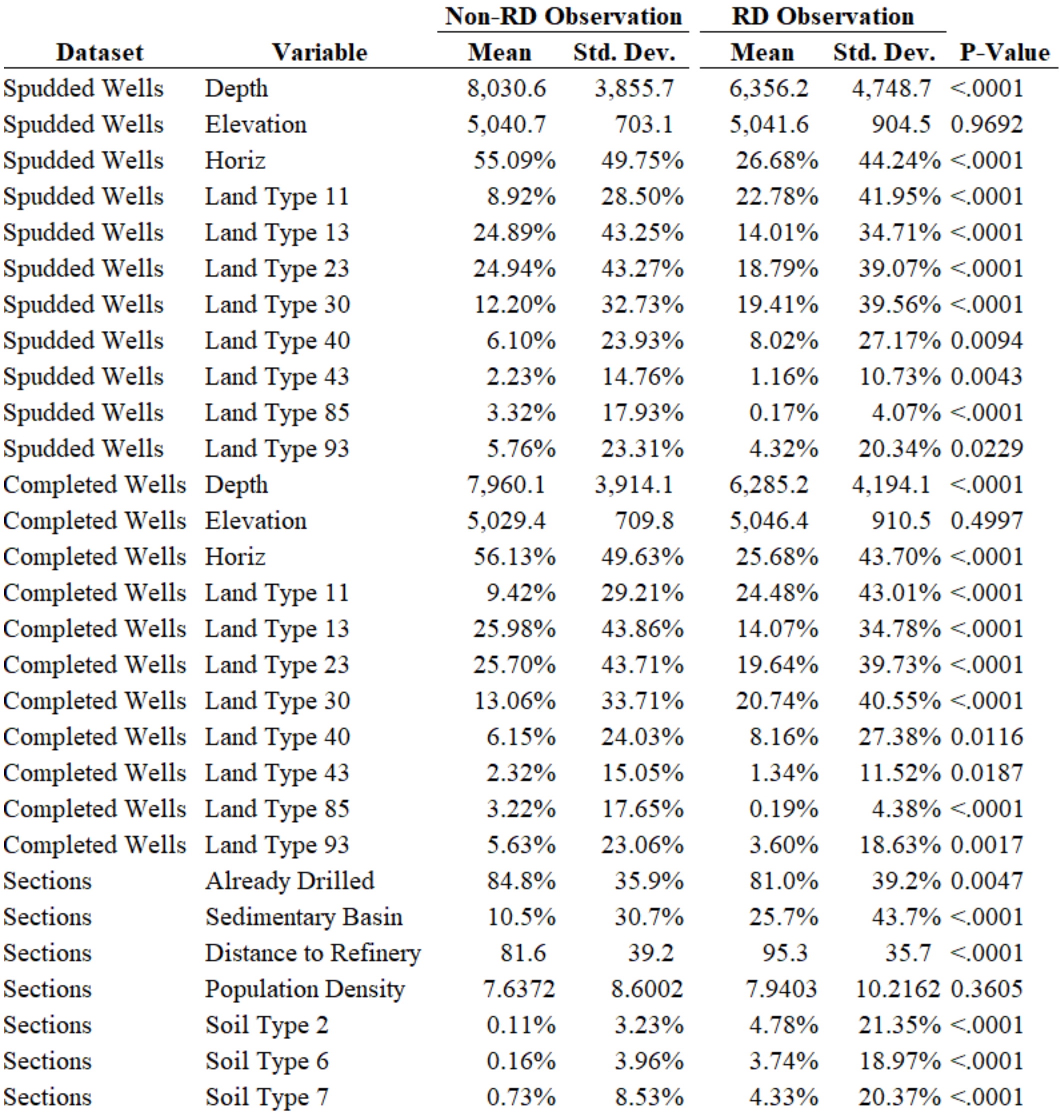
[163] These 5 models are location selection, drilling timing (APD to completion), drilling timing (spudding to completion only), lease price bidding, and likelihood to refrack unconventional wells. The model in which the RD specification shows the stronger effect is drilling timing (APD to spudding only).

Table 50: Balance Test



Dataset	Variable	Non-RD Observation Mean	Non-RD Observation Std. Dev.	RD Observation Mean	RD Observation Std. Dev.	P-Value
Spudded Wells	Depth	8,030.6	3,855.7	6,356.2	4,748.7	<.0001
Spudded Wells	Elevation	5,040.7	703.1	5,041.6	904.5	0.9692
Spudded Wells	Horiz	55.09%	49.75%	26.68%	44.24%	<.0001
Spudded Wells	Land Type 11	8.92%	28.50%	22.78%	41.95%	<.0001
Spudded Wells	Land Type 13	24.89%	43.25%	14.01%	34.71%	<.0001
Spudded Wells	Land Type 23	24.94%	43.27%	18.79%	39.07%	<.0001
Spudded Wells	Land Type 30	12.20%	32.73%	19.41%	39.56%	<.0001
Spudded Wells	Land Type 40	6.10%	23.93%	8.02%	27.17%	0.0094
Spudded Wells	Land Type 43	2.23%	14.76%	1.16%	10.73%	0.0043
Spudded Wells	Land Type 85	3.32%	17.93%	0.17%	4.07%	<.0001
Spudded Wells	Land Type 93	5.76%	23.31%	4.32%	20.34%	0.0229
Completed Wells	Depth	7,960.1	3,914.1	6,285.2	4,194.1	<.0001
Completed Wells	Elevation	5,029.4	709.8	5,046.4	910.5	0.4997
Completed Wells	Horiz	56.13%	49.63%	25.68%	43.70%	<.0001
Completed Wells	Land Type 11	9.42%	29.21%	24.48%	43.01%	<.0001
Completed Wells	Land Type 13	25.98%	43.86%	14.07%	34.78%	<.0001
Completed Wells	Land Type 23	25.70%	43.71%	19.64%	39.73%	<.0001
Completed Wells	Land Type 30	13.06%	33.71%	20.74%	40.55%	<.0001
Completed Wells	Land Type 40	6.15%	24.03%	8.16%	27.38%	0.0116
Completed Wells	Land Type 43	2.32%	15.05%	1.34%	11.52%	0.0187
Completed Wells	Land Type 85	3.22%	17.65%	0.19%	4.38%	<.0001
Completed Wells	Land Type 93	5.63%	23.06%	3.60%	18.63%	0.0017
Sections	Already Drilled	84.8%	35.9%	81.0%	39.2%	0.0047
Sections	Sedimentary Basin	10.5%	30.7%	25.7%	43.7%	<.0001
Sections	Distance to Refinery	81.6	39.2	95.3	35.7	<.0001
Sections	Population Density	7.6372	8.6002	7.9403	10.2162	0.3605
Sections	Soil Type 2	0.11%	3.23%	4.78%	21.35%	<.0001
Sections	Soil Type 6	0.16%	3.96%	3.74%	18.97%	<.0001
Sections	Soil Type 7	0.73%	8.53%	4.33%	20.37%	<.0001

categorical variables rather than binary or continuous variables, I tested for the balance of all land and soil types with greater than 50 observations by creating a binary for individual land or soil types.

Indeed, the covariates of my models are not balanced across the buckets as the balance test repeatedly fails. In the drilling timing models that were tested for both spudded and completed wells, only well elevation is balanced across populations. In the location selection model, only population density is balanced. All other variables (well depth, vertical vs. horizontal, all land types, distance to oil refinery, sedimentary basin binary, prior drilling binary, and all soil types) are unbalanced. In total, the balance test fails 16/18 times (27/29 times if spudded and completed wells are counted separately). This indicates that the lack of a strong effect in the RD specification may be due to idiosyncratic differences between territory near the border and land further from the border, suggesting these populations are fundamentally different. This means that the reduced effects of the RD specifications cannot be extrapolated across the whole state, and provides futher justification for not using the RD specification as my primary model.

C.3 Bidding Regressions

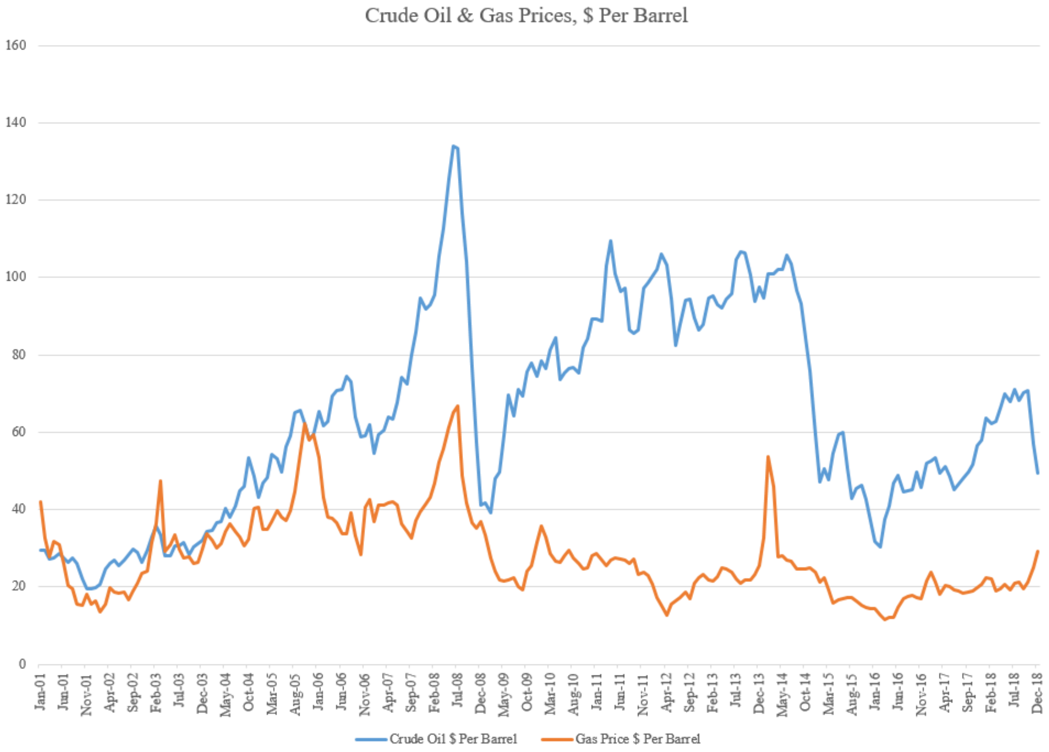
C.3.1 Bidding Parallel Trends Discussion

The parallel trends charts of bid price indicates there is only an upward response in non-core territory, rather than a depression in core territory.

Oil & gas are often described as homogeneous goods, meaning that a supply interruption in one region shouldn't impact world prices so long as that region is small enough. While Wyoming is certainly a major player by U.S. standards, it is not large enough to affect the global market. Thus any increase in demand for parcels out of the sage-grouse region should theoretically be dispersed throughout the world, making any local increase imperceptibly small. The local increase is notable, meaning that some other explanation is at play.

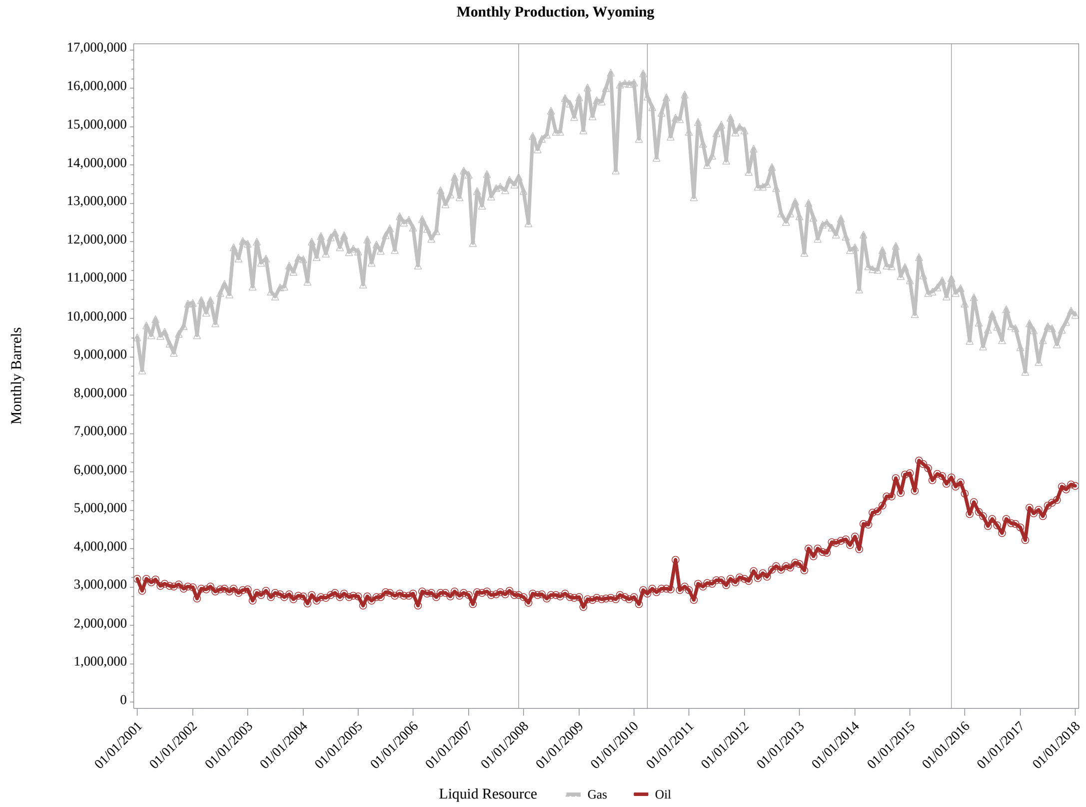
One possibility is that the actual counterfactual narrative is that in the absence of the expropriation uncertainty, there would be a price 'bubble' in *both* sage-grouse habitat and other territory due to some oil boom due to favorable world market conditions, new technology that is especially well-suited to Wyoming geology, or unexpected positive signals about Wyoming oil potential (examples of this could be local wells producing unexpectedly favorable oil & gas quantities or encouraging seismic tests). In this scenario, the control territory serves as a valid counterfactual and the effect of the uncertainty was simply to smooth out the bubble in the treatment habitat. I investigated each of these explanations, and neither adequately explain the price 'bubble'. There is a price increase only in crude oil during the uncertainty period relative to before or after the uncertainty period.

Figure 16: Oil & Gas Prices Over Time



However, this price spike did *not* correlate with increased production in Wyoming. Statewide production of oil was virtually flat until 2011, when it began increasing steadily until mid-2015. Wyoming gas steadily increased until February 2010 and then steadily declined until about January 2017, and exhibits no correlation with the price of gas.

Figure 17: Wyoming Production



Source: Wyoming Oil and Gas Commission Production Data

These charts indicate that energy-producing firms are insensitive to price increases, which is sensible given the erratic nature of gas and especially oil prices, and also matches the results of Anderson, Kellogg, and Salant (2018)[1]. It is also interesting to note that the period of highest 'sage-grouse uncertainty' coincided with completely flat statewide oil production, providing further evidence that firms have shifted production to local areas without risk of expropriation.

There was also a minor local boom due to new horizontal drilling techniques allowing developers to reach new pools[164], rather than extremely localized seismic testing or unexpectedly productive pools. The advent of horizontal drilling should

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[164] https://opengov.com/article/the-anatomy-of-an-oil-boom-and-bust , https://www.wyomingnews.com/news/local_news/energy-industry-recovery-likely-to-be-slow-in-laramie-county/article_a1db1ad4-150e-11e7-b9ab-2bb1ad9f239a.html

reasonably be expected to affect the entire state, and the sage-grouse is not limited to just one area - it is spread all across the state of Wyoming.

Instead, what appears to be happening is a statewide ‘flight-to-certainty’. Developers are relocating production to habitat not affected by sage-grouse regulations, even though oil and gas are examples of global markets. This has been documented in the literature before. Falk and Shelton (2018)[19] study the impact of political uncertainty on manufacturing investment by analyzing states with close gubernatorial elections following cases of the prior governor being term limited or dying/becoming incapacitated in office. They find that political uncertainty in specific states causes an *increase* in investment in nearby states that do not experience political uncertainty. The authors call this behavior a ‘flight-to-certainty’ and contrast their story with the traditional ‘wait-and-see’ narrative of Stokey (2016)[58]. The implication of the ‘flight-to-certainty’ is that the bidding regressions may have biased causal results. If the control group is impacted by the uncertainty, then the coefficient will be biased upwards in absolute value. Thus the coefficients might represent a ceiling on the true causal impact.

D Sources of Images Used

- Figure 1: Wikimedia Commons (royalty and copyright free image)
- Figure 3: Wyoming Game and Fish Department
- Figure 4: Enhanced Oil Recovery Institute - University of Wyoming
- Figure 10: American Geosciences Institute

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