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VALUATION OF UNCONVENTIONAL OIL AND GAS DEVELOPMENT

BY

ANDREW J. BOSLETT

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

IN

ENVIRONMENTAL AND NATURAL RESOURCE ECONOMICS

UNIVERSITY OF RHODE ISLAND

2016

DOCTOR OF PHILOSOPHY DISSERTATION

OF

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UNIVERSITY OF RHODE ISLAND

2016

ABSTRACT

Valuation of Unconventional Oil and Gas Development

By

Andrew J. Boslett

Doctor of Philosophy of Environmental and Natural Resource Economics

University of Rhode Island

Public discourse regarding the local economic, environmental, and socio-cultural impacts of unconventional oil and gas development has been intense, especially in those areas of the country that are relatively unfamiliar with extractive industry. At the center of this debate is the contrast between the economic and financial benefits that accrue to local governments and landowners versus the environmental and socio-cultural costs borne by the public-at-large. Understanding how local citizens value unconventional oil and gas development is an important policy consideration for federal, state, and local governments.

The overarching theme of this work, consisting of three manuscripts, seeks to contribute to the debate regarding the impacts of energy consumption and development. In two manuscripts, I use the hedonic valuation approach to value the benefits and costs of shale gas and oil development. I do this through the context of a statewide moratorium on development in New York and a long-standing severance between the surface and mineral estates in the western Colorado property market.

My results indicate that homebuyers significantly value both the financial benefits and environmental costs of unconventional oil and gas development. In Manuscript 1, I

find that New York properties that were most likely to experience the financial and environmental impacts of Marcellus Shale development decreased in value by 23% as a result of the moratorium, which under certain assumptions indicates a large and positive net valuation of development. In Manuscript 2, I find that the homebuyers have large and significant valuations of the environmental costs of development on the order of 35% of sale prices for those properties that have an unconventional well within a mile of the property's extent.

In my third manuscript, I again apply hedonic valuation and value the benefits and costs of silica sand mining in western Wisconsin. The great increase in the application of hydraulic fracturing in oil and gas production has led to an increase in demand for silica sand. This type of sand is an important ingredient in hydraulic fracturing. Silica sand mining has a number of local benefits and external costs. I use the hedonic valuation methodology to value sand mining's impacts, focusing on property views and local air quality. I find strong evidence that both changes in view and air quality are negatively capitalized into housing prices. I also find evidence of appreciation for those properties that are not as subject to those environmental quality changes.

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The last four years have been a time of both personal and professional development. I'd like to make some acknowledgements.

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I would also like to thank other faculty and staff at URI: Corey Lang, for his teachings in applied econometrics and for our collaborations; Peter August, for his helpful videos on ArcGIS and his open-door policy with related-questions; Jim Opaluch, for helpful dialogue about economics throughout my time at URI (especially towards the end); Stephen Atlas, for inviting me into his lab group and giving me insights on behavioral economics and mental processing; Professor Emi Uchida, for bringing me here to Rhode Island, for funding me for my first three years in the program as part of her ecosystem services project in Rhode Island, and for many helpful conversations along the way; Professor Tom Sproul, for many interesting conversations and for first encouraging me to think about problems from an experimental framework; and Denise Foley and Judy Palmer, for their help and patience over the last four years.

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Words cannot express my appreciation to my Mom and Dad. Every day I am reminded of how blessed I am to be their son. They have supported in every area of my life.

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Last but not least, I should thank the State of Rhode Island and the USDA for funding my time here in Rhode Island.

PREFACE

This dissertation is written in three-manuscript form. The first manuscript is co-authored with Todd Guilfoos and Corey Lang. It has been published in the *Journal of Environmental Economics and Management*. The second manuscript is also co-authored with Todd Guilfoos and Corey Lang. It is in review at the *Journal of the Association of Environmental and Resource Economists*. The third manuscript is solo-authored and is being prepared to submit to *Land Economics* or *Resource and Energy Economics*.

Manuscript 1: Valuation of Expectations: A Hedonic Study of Shale Gas Development and New York's Moratorium

Manuscript 2: Valuation of the External Costs of Unconventional Oil and Gas Development: The Critical Importance of Mineral Rights Ownership

Manuscript 3: A Bucket or a Sieve? A Valuation of Views and Air Quality around Silica Sand Mining in Wisconsin

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Manuscript – 1

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**Valuation of Expectations:
A Hedonic Study of Shale Gas Development and New York's Moratorium**

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Environmental and Natural Resource Economics, University of Rhode Island

Abstract

This paper examines the local impacts of shale gas development (SGD). We use a hedonic framework and exploit a discrete change in expectations about SGD caused by the New York State moratorium on hydraulic fracturing. Our research design combines difference-in-differences and border discontinuity, as well as underlying shale geology, on properties in Pennsylvania and New York. Results suggest that New York properties that were most likely to experience both the financial benefits and environmental consequences of SGD dropped in value 23% as a result of the moratorium, which under certain assumptions indicates a large and positive net valuation of SGD.

Keywords: shale gas development; hydraulic fracturing; hedonic valuation; expectations; rational expectations; moratorium; difference-in-differences; border discontinuity

1. INTRODUCTION

Shale gas development (SGD) has dramatically changed the US energy landscape in the last decade. The Energy Information Administration (2013) predicts that the US will shift from being a net importer to a net exporter of natural gas by 2020 and domestic production will increase 44% by 2040. Much of the attention on SGD has been on the Marcellus Shale, which extends over 95,000 square miles across New York, Ohio, Pennsylvania, and West Virginia (Kargbo et al., 2010). Marcellus drilling began in 2005 and has been the source of considerable extraction. From 2005 to 2014, 7,797 unconventional wells have been drilled in Pennsylvania alone.

While the macroeconomic benefits to the US economy are clear, there is uncertainty surrounding the local benefits and costs to households and communities impacted by SGD. Property owners with mineral rights can receive substantial gas lease and production royalties (Pennsylvania Department of Environmental Protection, 2012); however, little is known about the magnitude of payments due to the private nature of the contracts. Potential costs of SGD could include various health and environmental impacts such as water pollution, air pollution, and traffic congestion. The impacts from the health and environmental externalities are also highly uncertain.

Given the current scale of SGD and expected growth in the future, it is critical to understand to the local valuation of SGD. This paper seeks to answer this question using a hedonic framework, as housing prices should reflect the future stream of benefits and costs tied to the property. Empirically, this is hindered in two ways. First, the location of wells may be endogenous. Second, expectations about SGD form in advance of actual drilling, and if expectations are capitalized into housing prices, then a

simple before-after comparison may lead to incorrect inference about the valuation. We mitigate these confounding factors by specifically focusing on expectations and using an exogenous shift in expectations to reveal valuation.

Just as hydraulic fracturing was beginning its exponential increase in Pennsylvania, New York State implemented a de facto moratorium on hydraulic fracturing on July 23, 2008, citing uncertainty about health and environmental impacts (State of New York's Executive Chamber, 2008).¹ The state extended the moratorium multiple times between 2010 and 2014 (e.g., Wiessner, 2011) and, on December 17, 2014, the New York Department of Environmental Conservation implemented a permanent ban (Kaplan, 2014). These decisions were highly contentious, as evidenced by several dozen towns in New York passing resolutions in support of SGD in the spring and summer of 2012 and 15 towns are currently considering secession (Mathias, 2015).² To date, there has been no hydraulic fracturing in New York.

This paper exploits changes in expectations that resulted from New York's moratorium on drilling and measures this event's impact on housing prices. Importantly, the moratorium did not mark a change in the amount of hydraulic fracturing in New York – expectations about future SGD are the only thing that changed.

We estimate the effect of the statewide moratorium using a difference-in-differences methodology. We use Pennsylvania as a counterfactual because

¹ There is considerable heterogeneity in state regulation on shale gas development as a result of different political, hydrological, and geological dynamics (Kulander, 2013; Richardson et al., 2013). Some states have used a more lenient approach to regulation. For example, Pennsylvania had no specific regulations concerning hydraulic fracturing until early 2010 (Kulander, 2013). Since then, Governor Tom Corbett's signed Act 13, prohibiting any local regulation or restrictions on shale gas well production (Begos, 2012). Like New York, New Jersey and Maryland have enacted regulations to restrict or ban hydraulic fracturing.

² These resolutions could not supersede state law, but were meant to send a signal to state politicians in Albany and were in contrast to the more common local bans and moratoria implemented elsewhere in the state.

expectations about future SGD were likely similar to those in pre-moratorium New York, but in contrast with New York, those expectations were realized. Our aim is to identify the change in prices for properties in New York that are most likely to be impacted by SGD (both positively and negatively), relative to price changes for similar properties in Pennsylvania. We use private well water use as a proxy for properties likely to experience SGD.³ These are essentially rural properties outside of municipal water supply boundaries, meaning they have the space requirements for drilling. Further, contaminated well water is one of the most common and serious environmental costs.

The design of our preferred sample is motivated by a border discontinuity and underlying shale geology. We begin with property transactions data for two Pennsylvania and three New York counties along the border. In the vein of recent border discontinuity designs (e.g., Grout et al., 2011; Turner et al., 2014) and specifically those that use state borders (Holmes, 1998; Rohlin et al., 2014), we restrict observations to be within five miles of the border in order to minimize unobserved differences in price determinants and best model the counterfactual for New York residents. Even after these restrictions, there are still substantial shale geology differences across the border. Thus, we further restrict observations to be in a specific band of shale thickness, a geological characteristic that strongly affects the amount of gas or oil in a reservoir (Advanced Resources International, 2013). These restrictions are meant to improve the similarity of expectations about future SGD. Post-moratorium spillovers across the border are a threat to identification. However, we contend that

³ While we cannot predict exactly where SGD would occur in New York, 99.8% of drilling in our Pennsylvania sample occurred in private well water areas.

these effects are minimal due to pre-moratorium expectations about spillovers, the rapid pace of drilling stemming from high initial prices, the area comprising a single labor market, and southerly flow of surface water.

Using the 5-mile border and shale geology restrictions, our results suggest that the statewide moratorium decreased New York property values 23.1% for those properties most likely to experience SGD. Relaxing the sample restrictions leads to smaller estimates in the range of 10-21%, which suggests that effects are heterogeneous across our New York counties and that accounting for shale geology is critical for understanding expectations. We estimate a series of robustness checks that test additional shale geology restrictions, test for spillover effects across the state border, and use municipal water properties as an additional control, and results are consistent with point estimates in the range of an 18-26% drop in housing values.

We interpret these results as a positive net valuation of SGD by buyers and sellers in New York and Pennsylvania. However, this interpretation relies on two assumptions: the expected probability of SGD in pre-moratorium New York is 1 and the expected probability of post-moratorium SGD is 0 and New York and Pennsylvania property owners and buyers accurately valued the negative and positive aspects of SGD prior to the moratorium. We estimate several models that bolster our confidence in these assumptions. However, if either of these assumptions are false, we are still recovering the effect of the moratorium on property values, which is driven by expectations over financial benefits and environmental externalities of SGD, and this is an important estimate for areas considering bans on hydraulic fracturing. Further, the estimates serve as a validation that expectations are capitalized into property values.

One of the models we use to test the assumptions needed for an interpretation of net valuation is a more traditional model of the effect of proximity to drilling using only our Pennsylvania observations. The results suggest no price impacts of proximity. While one interpretation is that the impacts of drilling are small, we interpret this to mean that ex ante expectations established in the initial expansion of SGD in Pennsylvania were capitalized into property values and were accurate ex post leading property values not to change. These results corroborate our claim that New York households near the border have accurate expectations about SGD, which in turn supports a rational expectations assumption in hedonic valuation.

There are two major contributions of this paper. First, we provide new evidence of local impacts of SGD. Existing hedonic studies (Gopalakrishnan and Klaiber, 2014; Muehlenbachs et al., 2014) find negative impacts of nearby drilling for well-water dependent properties as large as -22%. However, Gopalakrishnan and Klaiber (2014) also find that negative effects dissipate to a statistical zero 6-12 months after a permit is issued. Our results lead to very different conclusions. One reason may be that both of these studies either use data exclusively from western Pennsylvania or derive most of their identifying variation from western Pennsylvania. A concern is that split estates, where mineral rights are sold separately from the property, are common in western Pennsylvania due to the area's more extensive history of resource extraction (Kelsey et al., 2012). In contrast, split estates are relatively uncommon in our focus area of eastern Pennsylvania and south-central New York. Thus, our data are more likely to recover net effects of SGD because property owners hold mineral rights and will benefit from royalties and lease payments. Our interpretation of Gopalakrishnan and Klaiber (2014)

and Muehlenbachs et al. (2014) is that their estimates capture the negative externality of SGD near private well water, which is critical to understand, but mostly exclude the financial benefits because of the area of study. Consistent with this interpretation are recent survey findings that indicate a majority of property owners that do not hold the mineral rights to their property are dissatisfied with local drilling, whereas a majority of property owners holding mineral rights are satisfied (Collins and Nkansah, 2013).⁴

While the split estate issue is perhaps the most critical, there are other differences between our study and others that could lead to different estimates of the local impact of SGD. We incorporate physical attributes of shale geology into the analysis, which existing valuation studies have not utilized. This appears to be important to creating valid counterfactuals in a difference-in-differences framework. Further, our treatment group has no direct experience with SGD, though they seemingly would learn about it as SGD expanded right across the border. Additionally, we are estimating area-level impacts that capture impacts occurring to whole areas, as opposed to a proximity analysis that captures differential impacts for properties nearby drilling. This focus may average away some of the negative effects of SGD if property owners in NY expect that they would be minimally impacted by negative externalities since the placement of future shale gas wells is unknown.

The second contribution is to add to our understanding of how expectations are capitalized into property values. While many hedonic papers implicitly assume expectations exist and recent structural models have incorporated expectations (e.g., Bishop and Murphy, 2011; Ma, 2013), we offer a particularly clean, reduced-form

⁴ A survey by Brasier et al. (2013) found that landowners that hold their property's underlying mineral rights have generally lower risk perceptions of SGD.

illustration of how expectations factor into prices. The effect of the New York moratorium is to change expectations, whereas the results of the proximity analysis using only Pennsylvania properties support the idea of rational expectations because no price changes occur once drilling commences. This work also complements hedonic studies that show new information can cause capitalization of dis-amenities, even when levels of dis-amenities do not change (e.g., Pope, 2008; Guignet, 2013).

2. BACKGROUND

The first objective of this section is to catalog various estimates of benefits and costs of SGD, which is critical for putting our estimates of the net valuation of SGD in context. Given the private and dispersed nature of financial benefits, it is a contribution of this paper to compile these estimates. The second objective is to give a timeline of SGD in Pennsylvania and SGD regulation in New York.

2.1 Financial benefits

During shale gas extraction, owners of sub-surface mineral rights may sign a mineral lease contract with energy production companies, granting them the right to develop mineral deposits underneath their property (Pennsylvania Department of Environmental Protection, 2012). The two primary monetary benefits associated with shale gas production are lease signing bonuses and royalty payments. A lease signing bonus is an initial payment, based on acreage, for signing a gas lease contract (Weidner, 2013). Due to the uncertainty of natural gas production, this is perhaps the most important element of the lease (Hefley et al., 2011). The payment level is based on a

number of variables, including geological factors, landowner-stipulated restrictions, nearby drilling results, and the current state of the natural gas market (Weidner, 2013). The average per acre signing bonus is \$2,700 (Hefley et al., 2011), though this can vary from \$50 to almost \$6,000 (Humphries, 2008; Green, 2010; Eichler, 2013; Rieley, 2014).

The other major monetary benefit is royalty payments, which are recurring payments on a proportion of natural gas production. The minimum royalty rate, set by law, is 12.5% of the value of extracted natural gas (Pennsylvania Department of Environmental Protection, 2012). However, the negotiated rate can be much higher, depending on the same factors that determine lease payments (Weidner, 2013). According to a Penn State University Extension associate, Marcellus Shale gas production has generated a cumulative total of \$160 million in royalties for landowners in Bradford County, Pennsylvania as of late 2012 (Loewenstein, 2012).

SGD infrastructure-related benefits can also serve as economic windfalls for landowners. Surface rights owners can receive monetary payments for allowing pipeline, compressor station, and water impoundment construction on their properties. These are often one-time payments. A payment for pipeline easement construction is based on the length of the constructed pipeline and can range from \$5-25 per linear foot (Messersmith, 2010). Due to the nuisance factor associated with compressor stations (e.g., Litovitz et al., 2013), payments for their construction can range from hundreds of thousands to millions of dollars (Clark, 2014). Payments for water impoundment construction can range from \$40,000-70,000, but could potentially be lower or higher given their intended size and permanency (Clark, 2014).

Lastly, governments have the ability to raise revenue through taxing shale gas

development, which in turn would have public finance implications. These public finance measures could then be capitalized in housing prices through improvements to public goods and services in local municipalities, such as schools. Pennsylvania did enact an “impact fee” in 2012 through Act 13, retroactive to 2011 activity, which charged a fee on a per-well, per-year basis.⁵ As SGD expands these impact fees could be a considerable source of income for local government; in 2012 impact fees in Pennsylvania brought in \$202 million (Rabe and Hampton, 2015). The distribution of the fees can go to a variety of sources, such as county and municipal governments, various environmental and non-environmental state government agencies, and the state’s legacy fund (Powelson, 2013). These various estimates of monetary benefits highlight the variation and uncertainty of the how much revenue could be expected from future SGD. For additional details, see online appendix Table A1.

2.2 Costs

There are also a number of potential landowner costs of nearby shale gas development, which are primarily driven by environmental impacts. The hydraulic fracturing process is highly water intensive, so much of the focus on the environmental costs of SGD revolve around water quantity and quality impacts. Shale gas development has led to large increases in wastewater management needs (Rahm et al., 2013). In Pennsylvania, regional wastewater generation has increased by 540% since 2004 (Lutz et al., 2013). In terms of water quality, Jackson et al. (2013) find increased levels of

⁵ This source of income for Pennsylvania municipalities appears to be significant, but likely not to our study. Our main results rely on 2006 to 2011 data, we contend that this mechanism would have a minimal effect on housing prices and our estimates.

methane contamination in groundwater in heavy-SGD areas, while Olmstead et al. (2013) find evidence of surface water pollution as a result of SGD waste disposal and management processes. In 2014, the Pennsylvania Department of Environmental Protection released a list of more than 250 instances where SGD operations impacted water quality in the state.

In addition, recent research has shown increased air pollution in areas close to shale gas extraction and processing infrastructure (e.g., Litovitz et al., 2013; Rich et al., 2014). Increased air pollution associated with shale gas development may have significant public health implications (e.g., McKenzie et al., 2012). Although the mechanisms are unclear, Hill (2012) finds significant impacts of shale gas extraction on the birth weight of children born in nearby homes. Additional environmental costs have been identified as concerns such as seismicity (Frohlich, 2012), forest loss and fragmentation (Drohan et al., 2012), and ecosystem services and local biodiversity (Evans and Kiesecker, 2014; Kiviat, 2013). For additional details regarding environmental and social impacts of SGD, please refer to Table A2 in the online appendix.

2.3 Timing of drilling and regulation

Figure 1 presents a timeline of SGD and regulatory activity in New York and Pennsylvania. Marcellus shale development commenced in 2005 with the horizontal drilling and hydraulic fracture of a previously-drilled vertical well in Washington County, identified as the “Renz No. 1” well (Carter et al., 2011). Positive results from this and other early wells spurred development. Starting in 2008, around the same time as the New York moratorium, unconventional well development rapidly transpired in

Pennsylvania, and as of late 2014 a total of 7,797 wells have been drilled. Figure 2 shows the spatial distribution of the 1,468 unconventional wells drilled from 2006 to 2011 in Bradford and Tioga counties.

In early 2008, the NY DEC received well permits to drill into the Marcellus Shale from multiple companies. These actions were preceded by 1-2 years of activity from industry land men, who would approach landowners about signing oil and gas leases. In May 2008, a group of landowners in Broome County struck a multi-million dollar contract with XTO Energy to lease over 50,000 acres. Landowners in other NY towns close to the Pennsylvania border received significant lease offers as well (Wilber, 2014). Online forums and discussions by property owners and landowner coalitions (e.g., Natural Gas Forum For Landowners) suggest that landowners expected significant drilling. This growing excitement was shared by those in the NY DEC's Division of Mineral Resources, which organized a presentation titled "Marcellus Shale Gas Well Development in New York State" in May 2008 that positively reviewed the state government's current capacity to regulate development and that additional environmental regulations were not needed. Clearly, during the years 2006-2008, residents were forming expectations about the probability of SGD in their area, as well as expectations about associated benefits and costs. All available information suggests that New York residents expected SGD, particularly in the southern part of the state near Pennsylvania.

Although excitement regarding the economic benefits of SGD grew as reports of lease activity became public, there were still significant concerns regarding the environmental, social, and public health aspects of drilling (Wilber, 2014). Citing the fact that the state was relying on a previous environmental impact statement of oil and gas

drilling from 1992 that did not address the many unique environmental issues associated with SGD (Lustgarten, 2008), Governor David Paterson passed a measure on July 23, 2008 that effectively blocked SGD for the near future. The primary intent of this measure was to postpone development in order to study the environmental and public health impacts of SGD, as well as New York's capacity to regulate it (State of New York's Executive Chamber, 2008).

In late 2009, the New York City's Department of Environmental Protection published an assessment of the potential impact of SGD within the city's water supply area in the Catskills Mountain region. The report highlighted the water contamination risk associated with rapid development within the watershed. In the interest of further study of the environmental impacts of SGD, the NY state legislature or governor passed legislation to extend the moratorium multiple times from 2010 to 2013 (Hoye, 2010; New York Senate, 2010; Wiessner, 2011; New York Senate, 2012; New York State Assembly 2013). During this time period, a potential policy was floated that would allow SGD in southern counties bordering Pennsylvania, but only in towns that explicitly approved it (Hakim, 2012). However, this policy was never enacted.

After six years of legislative and executive order action, the situation culminated in a permanent statewide ban on SGD in December 2014 (Kaplan, 2014), driven largely by lingering public health concerns (NY Department of Health, 2014). As a result of this series of policies, no unconventional natural gas development has occurred in New York, which is reflected in Figure 2.

Despite the statewide nature of the moratorium, New York is a home rule state that grants legislative authority to local governments to enact local legislation that may

limit state-level intrusion into local matters (Stinson, 1997). Given this history and the discontent with the moratorium, 45 New York towns passed resolutions in support of SGD in the spring and summer of 2012 (FracTracker, 2014). Fourteen of these towns are in our sample counties and are shown in Appendix Figure A3. These resolutions were passed by town councils and were not voted on by residents, but likely reflect residents' sentiments. The resolutions had no impact on the ability for gas companies to operate in New York, but were intended to apply political pressure to state policy makers and signal to industry that these towns are supportive of SGD. One of the major landowner groups driving the passage of the resolutions, the Joint Landowners Coalition of New York, sued Governor Cuomo in order to expedite the state's environmental and public health review of SGD (De Avila, 2014).

On the other side of the debate, 176 New York towns implemented local bans or moratoriums on hydraulic fracturing in the event that the statewide moratorium was lifted (FracTracker, 2014). Most of these townships were located in areas of the state that were unlikely to experience significant SGD from the Marcellus Shale due to geological limitations (e.g., low thickness). In our three NY counties, there were only two towns – Owego (Tioga County) and Wayne (Steuben County) – that passed moratoria on shale gas development, both in 2012.

3. CONCEPTUAL FRAMEWORK

In this section we present a hedonic property model that incorporates the phenomena of interest, the valuation of expected shale gas development through the enactment of a moratorium. The hedonic valuation methodology, originally presented by

Rosen (1974), posits that the price of a heterogeneous good can be decomposed into implicit prices associated with its individual characteristics. By separating the price of the good into its implicit prices, the technique can help illuminate the value of each characteristic. The standard hedonic model assumes that all negative and positive discounted cash flows will be capitalized into the transaction price if there is full information about those attributes that derive benefits and costs.

We apply the hedonic valuation concept to shale gas development through housing prices. The price function is given as $P_h = P_h(L, S, N, Q(D), G(D))$ where L is a vector of lot characteristics, S is a vector of structural characteristics, N is a vector of neighborhood characteristics, Q is a vector of environmental characteristics, and G are geological characteristics that allow for possible shale gas development (e.g., land overlying shale with retrievable gas). Shale gas development is represented by D . Geological attributes, $G(D)$, derive value from financial amenities such as lease and royalty payments that gas companies pay to homeowners to gain access to the shale. The dis-amenities are represented by the effect on environmental characteristics, $Q(D)$. We assume that development of the shale would also reduce environmental quality.⁶ A homebuyer derives utility from these attributes and a composite good Y , and is expressed as $U(Y, L, S, N, Q(D), G(D))$. The homebuyer maximizes utility with respect to a budget constraint and the expected utility gained from these attributes in relation to the composite good Y .

Prior to development, the expected flow of benefits and costs coming from shale

⁶ This also represents other dis-amenities that are not environmental in nature but are costs of shale gas development that are born through damage caused by noise pollution, damaged roads, and increased demands on other public infrastructure. We restrict ourselves to this simplified notation for ease of discussion.

gas development are uncertain and ambiguous in sign. The expected effect of shale development through lease and royalty payments is positive, $\partial G/\partial D > 0$. Geological attributes related to shale are considered a normal good and a positive attribute to the hedonic price function, $\partial P_h/\partial G > 0$. Thus, if households expect SGD to happen, prices will increase for those properties likely to benefit, all else equal. The expected effect of shale development on environmental quality is negative, $\partial Q/\partial D < 0$. Since environmental quality is a normal good, $\partial P_h/\partial Q > 0$, expectations about SGD will decrease prices, all else equal. The expected implicit value, P_D , derived from shale gas development is

$$E[P_D] = E \left[\frac{\partial P_h}{\partial Q} \frac{\partial Q}{\partial D} + \frac{\partial P_h}{\partial G} \frac{\partial G}{\partial D} \right] \quad (1)$$

(predicted sign) + - + +

Equation 1 defines the expected value of shale gas development, which contains uncertainty of the magnitude of the negative and positive effects of shale gas development. This uncertainty is derived from the fact that information about financial benefits and risks to environmental amenities is imperfect.

Individuals adjust their expectations of the likelihood of SGD when a moratorium is put in place, and this affects prices. This change in expectations is what we will focus on to identify the net valuation of SGD. Without a moratorium, the probability of shale gas development occurring may be high and bounded at 1, and individuals expect to receive the full value of the shale gas development; when there is a moratorium, the probability of shale gas development is 0, and individuals expect to receive zero value of the shale gas development. The change in the expected value of shale gas development is captured by examining the differences in hedonic price functions with and without a

moratorium, ceteris paribus. This is the case in Equation 2, where $M = 0$ when there is no moratorium and $M = 1$ when there is a moratorium.

$$\text{Expected SGD Net Benefits} = (P_h(\cdot)|M = 0) - (P_h(\cdot)|M = 1) \quad (2)$$

The change in expectations reveals the value of shale gas development to the area with a moratorium and provides an event that can uniquely identify this change in expectations. This valuation of expectations implicitly includes the negative and positive local amenities of shale development in Equation 1.

Two assumptions are required to interpret the change in prices as net valuation. First, we assume that the probability of SGD is one without the moratorium and zero with it. As discussed in Section 2.3, given that leasing contracts were being signed and drilling permits were being applied for in New York and given the eventual well density in Pennsylvania near the border with New York (Figure 2), we think that residents believed that drilling would come to New York with certainty, especially those areas near the border with Pennsylvania. It is less clear whether expectations dropped to zero following the moratorium, given that it was initially temporary and then made permanent. If the perceived probabilities of the SGD are strictly within the bounds of one and zero, before and after a moratorium, then our model would underestimate the net value of shale gas development. We detail in Section 6.2 two robustness checks that allow for expectations to change slowly or change in the years after the moratorium and results are similar.

Second, we assume that positive and negative impacts of SGD are accounted for equally through expectations. However, it is possible that expectations of negative externalities are discounted, i.e., $E[\partial Q/\partial D] < \partial Q/\partial D$, even if the probability of SGD is 1. Several reasons for why this would exist, such as hyperbolic discounting of longer

term environmental and health impacts, discounting of external consequences of neighbors' actions, and uncertainty about well placements. If this assumption does not hold, our estimate may reflect financial benefits more than costs. Still, this estimate reveals valuation of expectations about SGD for a population that has not experienced it, which is policy relevant for other areas considering bans. We detail in Section 6.3 a hedonic model that tests for proximity effects of drilling. The results indicate no price effect, which we interpret as buyers and sellers forming accurate expectations prior to drilling, and thus prices do not change once drilling begins.

4. METHODOLOGY

We develop a model that identifies the impact of the New York statewide moratorium on housing prices, and thus reveals the net valuation of expectations about SGD. We employ a difference-in-differences model, which compares properties in New York before and after the moratorium to similar properties in Pennsylvania. As discussed in more detail in the next section, our preferred sample is comprised of properties within five miles of the state border with similar shale geology and only includes private well properties, which are most likely to experience SGD. This choice is motivated by intuition and prior findings; Gopalakrishnan and Klaiber (2014) and Muehlenbachs et al. (2014) find that private water properties are most price responsive to proximate drilling. We define the treatment group to be New York properties and the treatment is the moratorium.

Equation 3 is our main specification:

$$\ln(p_i) = \beta_1 NY_i + \beta_2 PostMoratorium_i + \beta_3 NY_i \cdot PostMoratorium_i$$

$$+X_i'\delta + \varepsilon_i \quad (3)$$

where p_i is the sales price of property i , NY_i is a binary variable equal to one if the property is located in New York, $PostMoratorium_i$ is a binary variable equal to one if the transaction occurs after the New York State moratorium on SGD, and X_i is a set of housing, location, and temporal controls. X_i also includes a constant to capture the omitted group of properties located in Pennsylvania that transact before the moratorium. Finally, ε_i is the error.

The interpretation of the model coefficients is as follows. β_1 is the pre-moratorium price difference between properties in New York relative to Pennsylvania. β_2 is the price change from pre-moratorium to post-moratorium for Pennsylvania properties. The key coefficient in Equation 3 is β_3 , which is the double difference estimate. This term identifies the effect of the moratorium on New York properties, relative to Pennsylvania properties. As discussed in Section 3, our expectation about the sign and magnitude of this coefficient is ambiguous. It could be positive if New York households are concerned about the environmental dis-amenities of SGD and value the delay or ban of SGD. Alternatively, β_3 could be negative if households anticipated economic gains from SGD and house prices had already capitalized that expectation. Lastly, β_3 could be zero if the moratorium did not change expectations or perceived benefits and costs of SGD are small.⁷

While the prior section laid out assumptions required to interpret coefficients as

⁷ One might think this type of specification and data could also be used to estimate the area level net value of SGD for Pennsylvania. However, we feel this is untrue precisely because expectations in both Pennsylvania and New York would muddle the comparison. A better comparison would be to compare Pennsylvania to some area with no possibility of SGD, with data prior to 2006 marking the pre-treatment time.

net valuation, there are also assumptions required for the difference-in-differences design to be valid. First, we assume that Pennsylvania serves as a good counterfactual for New York, in terms of house price dynamics. One potential concern is that areas in our study had different reactions to the US housing market collapse, which is correlated with the timing of the moratorium. In the Section 5, we show that our sample of Pennsylvania and New York homes follow a similar price trend pre-moratorium. Also, by focusing on observations close to the border, we hope to mitigate unobservable determinants of price trends.⁸

Our sample choice of five border counties was meant to improve the treatment-control comparison. Our refinement to focus in particular on properties within 5 miles of the border with similar shale thickness furthers the strength of the good counterfactual assumption. However, using bordering counties implicitly assumes that spillover effects are minimal. Spillover effects could be either environmental or economic. Environmental spillovers would occur if water or air pollution from SGD were to travel into New York from Pennsylvania. Evidence from Gopalakrishnan and Klaiber (2014) and Muehlenbachs et al. (2014) suggests that effects of water pollution are localized at about 2km. SGD in our study area is limited to the Susquehanna River Basin, which flows south. Thus, any surface water contamination is also likely to flow south further into Pennsylvania rather than north into New York.⁹ Economic spillovers are increases in

⁸ Kuminoff and Pope (2013) find that lower value properties experienced larger boom-bust swings than higher value properties. Given the differences in price levels between the two states (see Table 1 and Figure 4), it is possible that our Pennsylvania sample experience a larger bust. However, if this was the case, our estimates would be upward biased, suggesting the impact of the moratorium to be even more negative for New York prices. To test whether differential boom-bust trends may be impacting our results, we estimate models that include a series of \$100,000 sale price bin fixed effects interacted with year fixed effects to allow differential boom-bust evolution by price tier. Results are consistent with our main results.

⁹ An additional possibility is that property owners in pre-moratorium Pennsylvania formed expectations about environmental spillovers from New York into Pennsylvania in the event of SGD in New York. If

employment and spending across the border that indirectly or directly affect the housing market. Our estimates are unlikely to be affected by any economic spillover because our sample is restricted to a small area of just five miles on either side of the border, and thus can be thought of as a single labor market.¹⁰ An additional argument that applies to these two types of spillovers is that New York residents and potential buyers would have formed expectations about drilling in Pennsylvania and those expectations would be capitalized into prices prior to the moratorium. Thus, while spillovers may occur, they should be expected and already accounted for in house prices.

Second, we assume that the treatment (moratorium) had no effect on the control (Pennsylvania). The main concern here is whether the moratorium on drilling in New York increased drilling in Pennsylvania. We argue that the pace of development in Pennsylvania (and elsewhere) was so rapid in the 2008-2011 timeframe that the lack of drilling in New York had no effect on prices or scarcity in Pennsylvania. Another way for drilling to be impacted would be if horizontal drills could cross state boundaries and extract New York gas from Pennsylvania, but this is in fact illegal.¹¹

Third, we assume that the implementation of the New York statewide moratorium was exogenous to the counties in this study. We believe this is a safe assumption for two

true, then the New York moratorium may have increased prices in Pennsylvania. We argue that this effect would have been minimal given the evidence of highly localized environmental impacts of drilling from Gopalakrishnan and Klaiber (2014) and Muehlenbachs et al. (2014).

¹⁰ We additionally examined cross border migration to see if individuals relocated from New York to Pennsylvania after the moratorium. The results, presented in Figure A1 of the appendix, suggest no changes in migration patterns.

¹¹ It is highly unlikely that horizontal well drilling across state lines has occurred along the NY-PA border. New York has restrictions on how close one can drill to the state boundary (New York State Regulations – Environmental Conservation Law 553.1; personal correspondence with Thomas Noll, Section Chief of the Bureau of Oil & Gas Permitting and Management in the NY DEC Division of Mineral Resources). Though Pennsylvania does not have an analogous law outlining state border proximity issues, Pennsylvania Department of Environmental Protection officials note that it is unlikely that any horizontal laterals cross over into New York from Pennsylvania (personal correspondence with David Engle, Operations Manager in the Oil & Gas Division of the Pennsylvania Department of Environmental Protection).

reasons. One, it is a statewide moratorium, not just a moratorium for the three sample New York counties, and much of the support for the moratorium came from regions in New York outside of this sample. Two, many of the sample towns were and still are against the moratorium as evidenced by the fact that 14 of 37 towns in our New York sample passed resolutions in support of SGD during the spring and summer of 2012, while only two towns passed a moratorium.

5. DATA

This study was conducted with property transaction data from five counties along the New York – Pennsylvania border: Chemung, Steuben, and Tioga counties in New York; Bradford and Tioga counties in Pennsylvania. We specifically chose these five counties because 1) the two Pennsylvania counties constitute one of the major clusters of drilling in that state, 2) all five counties are primarily agricultural and rural in character and thus make for good comparison, and 3) they border each other so that unobservable determinants of house prices likely follow similar dynamics.

We obtained transactions and property characteristics data from January 1, 2006 through December 31, 2012 from each county's property assessment office and New York's Office of Real Property Tax Services. Sales prices are adjusted to 2011 levels using the CPI (U.S. Bureau of Labor Statistics, 2014). For each property in our dataset, we have information on the number of bedrooms, number of bathrooms, finished living area, acreage, and age of each property in our dataset. Three of the five counties in our dataset include multiple transactions per property. However, Bradford County (PA) and Steuben County (NY) could only provide us with information for the most recent

transaction for each property.¹²

In order to identify each property's water supply, we use data from Pennsylvania's Department of Environmental Protection and New York's Department of Taxation and Finance, Office of Real Property Tax Services. Pennsylvania's data contains public water supply area boundaries, making sold parcel water supply identification straightforward. However, New York's data on water supply access is in parcel centroid format, which represents every parcel in the state by its center point. Using parcel boundaries provided by county and regional planning departments, we connected sales data to water supply data using Geographic Information Systems (GIS). However, a portion of our sold parcels do not overlay a centroid. In order to identify the water supply for each parcel in our transaction set, we follow Muehlenbachs et al. (2014) and create buffers of 100 meters around all public water supply parcel centroids. Then, we assume that all parcels falling outside of these buffers are dependent on well water. Figure A2 in the Appendix presents all transactions in our five counties by water type. The figure makes clear several points. First, private water supply properties are almost exclusively outside of town boundaries. Second, Pennsylvania has a larger share of private water properties than New York. Further, there are very few public water properties within five miles of the border, especially in Pennsylvania.

In total, our original dataset includes 26,138 property transactions across all five counties from 2006 to 2012. We include only single-family residential and mobile homes

¹² We examined how this data limitation may affect results by only using the latest sale for all counties and coefficients were very similar to the main results presented in Section 6. The results are available upon request.

with private water, which leaves us with 8,466 observations.¹³ We drop all observations that sold for less than \$10,000 or more than \$1,000,000 in 2011 CPI adjusted dollars. Further, we hypothesize that lot size is a key property characteristic for forming expectations about benefits and costs to SGD. Pennsylvania has larger lot sizes on average, so we drop observations that fall outside of the 5% and 95% of the lot size distribution to ensure common support between our Pennsylvania and New York samples. Lastly, we drop eight Pennsylvania transactions that occur prior to the moratorium that are located within two miles of a permitted well. We do this such that all transactions pre-moratorium have expectations about SGD, but no realized impacts.

Our analysis of the moratorium uses sales in the time span 2006-2011. 2006 marks the beginning of exploration and lease signings in Pennsylvania and New York. At this point, both properties in Pennsylvania and New York will begin to capitalize expectations about the benefits and costs to hydraulic fracturing, but have yet to experience it. We use 2011 as a cutoff because local resolutions begin to be passed in early 2012. With these cuts, we are left with a sample of 4,976 transactions.

While choosing counties along the border goes a long way towards removing unobservable differences between New York and Pennsylvania observations, we develop four samples that further restrict observations. First, in the vein of a border discontinuity design, two samples are created that limit observations to be within 15 miles of the border and then within five miles of the border. These samples are intended to further minimize possible bias stemming from unobservable, time-varying processes

¹³ While mobile homes are often excluded in hedonic analyses such as this, we chose to include them because a substantial proportion is located on lots greater than half an acre. We present robustness checks in Section 6 removing mobile homes and results are similar.

that differentially affect housing prices across the state boundary. Second, we further restrict the 15- and 5-mile samples to only include properties that have similar shale geology. Figure 3 shows the thickness of shale deposits, which is a key driver of extraction potential.¹⁴ On average, our Pennsylvania counties have thicker shale deposits than in New York, with thickness increasing towards the southeast. In order to ensure that expectations about SGD are similar on either side of the border, we restrict observation to be in the 100-200 feet range of thickness. Our preferred sample, shown by the dashed region of Figure 3, satisfies both the 5-mile border restriction and shale thickness restriction and includes 1,018 observations.

Table 1 presents summary statistics for several variables of interest. The first column gives the means for all private water observations in our five counties. The second and third columns give differences in means for New York versus Pennsylvania for pre-moratorium samples for all counties (Column 2) and the preferred sample of observations within 5 miles of the border and of similar shale thickness (Column 3). The purpose of examining these differences is to determine the comparability of New York and Pennsylvania. Following Imbens and Wooldridge (2009), we divide the difference in means by the combined standard deviation to test for substantial differences and mark differences for which this statistic exceeds 0.25 with an asterisk. Table 1 shows there is strong statistical overlap between the samples, lending credence to the research design. We note that the only significant difference is in shale thickness between the samples which is dramatically reduced by using the restricted sample. There is also convergence of socioeconomic characteristics as we restrict our sample to tracts just along the border

¹⁴ Based on a Marcellus Shale thickness map from the Marcellus Center for Outreach and Research at Pennsylvania State University.

in our study counties, as shown in Appendix Table A4.

As discussed in Section 4, the critical assumption for our difference-in-differences design to be valid is Pennsylvania must be a good counterfactual for New York. The most common way to support this assumption is to compare pre-treatment price trends, and now having introduced the data, we can do just that. Figure 4 displays price trends for 2006 through July 2008 for the preferred sample. Price trends are similar between New York and Pennsylvania for private water properties, which further bolsters our confidence that the counterfactual created by the control counties is appropriate. In contrast, the pre-moratorium price trends for public water properties do not coincide, which motivated us to not use these properties in our difference-in-differences design. One reason for the non-parallel trends could be the small number of Pennsylvania public water properties near the border. We could expand the sample in order to include more public water properties (and this does indeed improve the alignment of pre-treatment trends), but that would defeat the purpose of the border discontinuity. In addition, we tested whether characteristics of transacted properties were different across states after the moratorium. The results presented in Table A3 of the online appendix show that most characteristics, most importantly lot size, are not statistically different across states.

6. RESULTS

6.1 The effect of the statewide moratorium

Table 2 presents the main results of our analysis of the effect New York's statewide moratorium on housing prices (Equation 3). We present the double difference

coefficients from five models, each with the same specification, but with progressively more stringent sample criteria. As controls, all models include a variety of property-specific characteristics, year fixed effects and township fixed effects. Column 1 includes all transactions in each of our five sample counties. Column 2 restricts transactions to be within 15 miles of the border, while Column 3 further restricts transactions to be within the 100-200 foot shale thickness band. Column 4 requires transactions to be within five miles of the border, while Column 5 further restricts transactions to be within the 100-200 foot shale thickness band. Column 5 is our preferred specification as differences in unobservable characteristics will be minimized with the border restriction and expectations about SGD should be very similar due to the common thickness.

The coefficient on *NY*PostMoratorium* in Column 1 is -0.101, which indicates that private well water properties declined in price 10.1% after the moratorium relative to similar properties in Pennsylvania. Restricting the sample to within 15 miles of the border increases the magnitude of the coefficient to -0.13, and the coefficient grows again to -0.151 when restricting for shale thickness. For the 5 mile sample, the coefficient is -0.209, and adding shale thickness the coefficient is -0.231. The results present a clear pattern that coefficients increase in magnitude as sample restrictions are imposed. This pattern indicates that both the border distance restrictions and the shale thickness restriction are important for minimizing unobservable variation and aligning expectations across the border.

Our estimates imply that taking away the expectation of SGD reduces property values and thus indicates a positive valuation of SGD for areas most likely to experience both the financial benefits and environmental consequences of SGD. Combining our

preferred estimate of -0.231 and the average, pre-moratorium, New York house price in our preferred sample (\$110,526 in \$2011), the moratorium reduced house values by \$25,531 on average relative to Pennsylvania. In turn, we interpret this number as the net present value of an expected stream of costs and benefits of SGD. If we annualize this present value for a 30-year productive well life with 5% interest, this result translates into an annual net benefit of \$1,649. One assumption underlying this interpretation is that the probability goes from 1 to 0 with the moratorium. Instead, if subjective probabilities were within the bounds of 1 and 0, then the net value would be larger and equal to \$25,531 divided by the change in probability. For example, if the probability of SGD changed from 0.9 to 0.4, then the estimated net present value of SGD would be $\$25,531 / (0.9 - 0.4) = \$51,062$.¹⁵ The second assumption necessary for our interpretation is that households have accurate expectations about the benefits and costs that will result from SGD. For instance, if households are accurate in their assessment of financial benefits, but discount the possibility of adverse health or environmental consequences, then our estimate may reflect lost benefits more than the net value. However, in Sections 6.2 and 6.3, we present results that bolster our confidence in these two assumptions.

6.2 Robustness checks and extensions

Table 3 provides a series of robustness checks that probe several key assumptions

¹⁵ Another way in which expectations can affect the calculation of net values is if households have a perceived duration of the moratorium. For example, many people (authors included) had the impression that the initial moratorium would last five years, and then the New York State government would make a decision. In this case, the house price reduction is not the lost value of SGD, but the cost of waiting five years for SGD. At a 5% interest rate, the annualized value of SGD would be \$7,618. Given results in Section 6.2 that households do not seem to be updating their beliefs, we think the assumption that people believed the moratorium to be temporary is inconsistent with the data. However, future work could examine more recent data to determine if the permanent ban in 2014 led to any price change.

of our difference-in-differences model and our interpretation of the results as revealing net value of SGD.¹⁶ Each column builds on our main result of Column 5 Table 2, and thus uses both the 5 mile border and shale thickness restrictions. Columns 1 and 2 address the assumption of expectations changing from 1 to 0 with the moratorium. Column 1 excludes transactions occurring in 2008. As there may have been a gradual slide from certainty of SGD to uncertainty to certainty of no SGD, removing the time period which this slide was likely to occur ensures a large discrete and complete change in expectations. The estimated coefficient is -0.244, which is nearly identical to the main result. Column 2 includes transactions from 2012, which were originally excluded because of the local resolution activity that occurred in New York in the spring and summer of 2012. The coefficient again stays consistent at -0.255, which suggests that expectations changed with the moratorium and did not change much after that with the multiple extensions.

Columns 3 and 4 return to the 2006-2011 timespan and test whether alternative shale geology characteristics may better match expectations across the border. Column 3 restricts the data set to only include those transactions that overlay shale that is 150 to 200 feet thick. The resulting parameter estimate -0.260 is similar to our Table 2 estimate. Column 4 additionally requires transactions to overlay shale with similar depth.¹⁷ Low depth areas of the shale have relatively lower reservoir pressure and higher water content, which may reduce potential oil and gas recovery. However, high depth areas of the shale

¹⁶ In the appendix, we present additional robustness checks. Table A5 shows the set of control variables. Table A7 estimates models similar to Table 2, but using the level of prices and results are similar. Table A8 tests for robustness of only including single family homes and using propensity score matching to trim the sample for covariate balance, and results are similar. Table A9 tests supports the robustness of our 15 mile border and shale thickness model estimate using models similar to those used in Table 3.

¹⁷ Depth is measured based on a Marcellus Shale depth map from the Marcellus Center for Outreach and Research at Pennsylvania State University.

may be less permeable and have higher drilling costs than low depth areas (Advanced Resources International, 2013). Though ambiguous, it could have an impact on expectations. The estimate from Column 4 is -0.240, very similar to our estimate without this additional requirement.

Our research design also assumes that environmental spillovers across the border are minimal. In Column 5, we remove observations within 1 mile of the border in hope that any expected or actual spillover is contained to that distance. The estimated coefficient is -0.231, identical to the main result.¹⁸

Our final robustness check, Column 6 in Table 3, further probes how well Pennsylvania serves as a counterfactual in terms of house price trends. Here, we use a triple difference specification and include properties that are served by municipal water supply. These properties are in towns and are unlikely to receive either the financial benefits or the main environmental damages associated with water contamination. Their purpose is to serve as an additional control for differential market trends in New York and Pennsylvania. However, our border discontinuity with a five mile distance requirement is designed to mitigate these types of unobservable variables. In addition, the pre-treatment trends did not run parallel (Figure 4), and there are very few public water properties on the Pennsylvania side (Appendix Figure A4). Thus, we do not believe this is the best research design, but investigate it as a robustness check. The triple difference term $NY*PostMoratorium*Private$, which is now the coefficient of interest, is interpreted as the change in price due to the moratorium for New York private water supply

¹⁸ If instead of a 1 mile exposure buffer of environmental effects, there is a 5 or more mile exposure buffer, all New York properties in our preferred sample would be exposed. Under this (extreme) assumption, our estimates would recover the option value of mineral rights.

properties, relative to Pennsylvania private water properties, and relative to the differential change between public water properties in New York and Pennsylvania. The coefficient estimate is -0.179, which is smaller than the main result and less statistically significant. While this result is broadly consistent with the main result, the reduced magnitude is consistent with a pre-moratorium downward trajectory of municipal water properties in New York relative to Pennsylvania. In sum, the range of estimates from Table 3 support our assumptions and suggest that the moratorium reduced property values between 18% and 26% for New York properties overlaying high-quality shale deposits.

In Table 4, we extend our analysis of the effect of the statewide moratorium by examining whether there were heterogeneous price impacts based on lot size and future resolution status of a property's township.¹⁹ Instead of using our preferred 5 mile distance band in this analysis, we apply a border distance band of 15 miles in order to include more towns that ultimately passed resolutions in 2012. Larger lots may be able to capture more financial benefits through leases and royalties. Owners and potential buyers may expect these financial benefits and so the price decline post-moratorium will be amplified for larger properties. The first column in Table 4 presents results from a specification that builds on our double difference framework by interacting lot size (log acres) with each of the three double difference variables. Resulting parameter estimates indicate that the double difference coefficient of interest is similar in magnitude to the results from Table 2, Column 3. The interaction with lot size is negative (as expected), but is statistically

¹⁹ We also estimate a model with only properties smaller than 10 acres to control for properties that have substantial differences in values due to quality and size of the land (due to being used for agriculture). We find our results do not qualitatively change with this restriction.

indistinguishable from zero.²⁰ We interpret these results as indicating that there is no heterogeneity across lot sizes, which we may be due to the high degree of uncertainty in financial benefits.

The second column of Table 4 explores whether the future resolution status of a town affects price impacts. As noted above, the statewide moratorium was unpopular in certain parts of New York. Towns that eventually pass resolutions likely supported SGD in the 2006-2008 range. Residents and homebuyers may have had larger expectations about the financial benefits, and thus may have a larger price decrease post-moratorium. We estimate a specification that is similar to the preferred specification, but additionally interacts *ResolutionTown* (= 1 if a property is located in a town that passes a resolution in 2012) with the double difference variable *NY*PostMoratorium*. The results indicate that residential property prices declined -12.8% post-moratorium, similar to the estimate found in Table 2, Column 3. However, we find that this effect does not change in resolution towns. Although the parameter estimate on the triple difference term is negative (-9.8%), it is not statistically significant. This result suggests that the underlying likelihood of SGD as viewed by homeowners and prospective buyers is no different in resolution towns versus other towns. However, this modeling approach is focused on selection and underlying characteristics, not the effect of the resolution itself. In the appendix, we present an analysis of the property value impacts of passing a resolution. Our results suggest no effect.

6.3 Proximity analysis

²⁰ We also estimated models with different assumptions about the functional form for lot size and results were similar.

In this section we develop a more traditional model that estimates the effect of proximity to drilling on house prices. Similar to Gopalakrishnan and Klaiber (2014), we estimate variations on the following model:

$$\ln(p_i) = \beta_1 Wells_i + \beta_2 Wells_i \cdot Private_i + X_i' \delta + \varepsilon_i \quad (4)$$

where $Wells_i$ is the number of wells within a given distance of a property, $Private_i$ is a binary variable equal to one if the property depends on well water, and X_i is a set of housing, location, and temporal controls. Gopalakrishnan and Klaiber (2014) estimate several specifications varying distance cutoffs and time windows, and we follow suit. We implement both a one mile and two mile cutoff for the measure of proximity, and estimate the impact of new wells six and 12 months prior to transaction, as well as any time prior to transaction. We interact the binary variable $Private_i$ with $Wells_i$ to allow for heterogeneous effects of proximity over private versus public water. We use all observations in our three counties of Pennsylvania from 2006 to 2012. Identification comes from comparing houses within a given distance band of a drilled shale well to houses further away and houses that predated the drilling.

While this model has a traditional interpretation of valuation of proximity, this model also estimates the accuracy of households' pre-drilling expectations. Because all transactions in this analysis occurred after households began signing leases with gas companies, we claim that expectations of SGD net benefits had already been capitalized into sales prices. Under this interpretation, a post-drilling change in house prices would suggest that expectations were incorrect. Specifically, if prices decline post-drilling, as is the case in prior studies, this would indicate that households' expectations had either overvalued the financial benefits or undervalued the environmental costs.

The results presented in Table 5 suggest that proximity to wells has no effect on house prices. Across all six specifications, neither the public nor private well water coefficients are statistically different from zero. These results are qualitatively robust to changes in functional form. We interpret this to mean that ex ante expectations established in the initial expansion of SGD in Pennsylvania were on average accurate ex post. In turn, these results support our claim that New York households near the border have accurate expectations about SGD. However, an alternative interpretation is there is no economically significant benefit or cost of living in proximity to drilling.

7. CONCLUSION

This paper proposes to view hedonic analysis through a different lens by focusing on the formation, realization, and change of expectations to inform environmental policy. We provide area-level impacts of the statewide moratorium on SGD for households living in New York. Under assumptions of rational expectations of benefits and costs of SGD and the statewide moratorium causing a 100% change in expectations about the probability of SGD, the results are interpreted as the net valuation of the local impacts of SGD. If expectations did not change 100%, then the estimates could be seen as a lower bound of SGD value. With loss of the rational expectations assumption, we are still recovering the effect of the moratorium on property values, which is driven by expectations over financial benefits and environmental externalities of SGD, and this is an important estimate for areas considering bans on hydraulic fracturing. Our preferred model suggests that the moratorium causes a 23.1% price decline for New York properties most likely to experience SGD, which indicates a positive and substantial

valuation of SGD. Our results measuring proximity effects of drilling in Pennsylvania suggest no price movement after drilling begins. This finding supports the rational expectations assumption, in that expectations of SGD are formed prior to drilling and ex post expectations were accurate in regard to the costs and benefits of SGD.

For our preferred border discontinuity sample, our point estimate translates into a \$25,531 loss in equity per house and an annualized loss of \$1, 649 per house. In order to estimate the total property market impact to these three counties, we performed the following back-of-the-envelope calculation. The average sales price 2006-2008 for a private water property in our three study counties in New York was \$117,283 (in \$2011). Using our -10.1% estimate derived using all properties, the average house lost \$11,846 in value due to the moratorium. From the 2000 Decennial Census, these three counties have a total of 99,402 housing units. Based on our transactions data, 30% (or 29,848) of these are likely to have private water supply. Putting these together, we estimate the total net loss in value for these three New York counties from the moratorium was \$354 million.

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Tables and Figures

Figure 1: Timeline of New York policies on shale gas development and the number of wells drilled in Pennsylvania from 2006 to 2014

Notes: NY DEC and DOH refer to the Department of Environmental Conservation and Department of Health, respectively. * 5 Wells were drilled in our PA study area in 2008 before the moratorium was implemented in NY on July 23rd, 2008

Figure 2: Unconventional well development in Bradford and Tioga counties from 2006 to 2011

Figure 3: Shale thickness and border restrictions across sample counties

Notes: Geological thickness data is digitized from maps from Pennsylvania State University's Marcellus Center for Outreach and Research (MCOR).

Figure 4: Pre-moratorium sale price trends

Notes: This sample includes all 1,225 single family residences and mobile homes sold from \$10,000 to \$1,000,000 (in 2011 CPI-adjusted dollars) from 2006 to the NY de facto moratorium on SGD (July 23, 2008). Observations are located within 5 miles of the NY-PA border, overlay Marcellus Shale that is 100 – 200 feet thick, and are not within two miles of a spud unconventional well.

Table 1: Summary statistics

Variable	Full Sample	Pre-Moratorium Differences: NY - PA	
		Full Sample	< 5 Mile Border & Shale Trim Restrictions
Price (000s)	108.09	24.18	25.67
Lot size (acres)	3.06	-0.54	-0.60
# of beds	2.79	0.17	0.20
# of baths	1.41	0.07	-0.12
Finished squared feet (000s)	1.52	0.10	0.01
Age at time of sale (years)	51.20	4.34	7.40
# of spud wells: 0 - 3 miles	2.33	-0.01	-0.004
Shale thickness (feet)	190.07	-63.54*	8.10*
% of mobile homes	0.08	-0.05	-0.08
Observations	4,976	2,349	449

Notes: Observations are single family residences and mobile homes located outside of public water supply areas. Housing prices are CPI-adjusted to 2011 levels. The 5 mile border restrictions includes only those observations that are located within 5 miles of the NY-PA state border. The shale trim restriction includes only those observations that overlay shale that is 100 - 200 feet thick. * if the differences in means divided by their combined standard deviation is greater than 0.25.

Table 2: Double difference estimates of the impact of the NY shale gas development moratorium on housing prices

	(1)	(2)	(3)	(4)	(5)
	Full Sample	15 Mile Border Restriction		5 Mile Border Restriction	
		Full	Shale Trim	Full	Shale Trim
NY * PostMoratorium	-0.101*** (0.036)	-0.130*** (0.039)	-0.151*** (0.045)	-0.209*** (0.074)	-0.231*** (0.077)
Property Variables	Y	Y	Y	Y	Y
Year Fixed Effects	Y	Y	Y	Y	Y
Township Fixed Effects	Y	Y	Y	Y	Y
Observations	4,976	2,829	2,260	1,072	1,018
R-squared	0.385	0.402	0.395	0.354	0.354

Note: Observations represent single family residence and mobile home property transactions from 2006 to 2011. All observations are located outside of public water supply areas and, thus, rely on private well water. The dependent variable is the natural log of sale price, CPI-adjusted to 2011 values. Property variables include number of beds and bathrooms, a quadratic in square feet of living area, a quadratic in property acreage, a cubic in property age, an indicator variable for mobile home, and an indicator variable for whether some property characteristics were imputed. Standard errors are shown in parentheses and are estimated using township-level cluster-robust inference. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Table 3: Robustness checks for the 5 mile border restriction and shale thickness model

	(1)	(2)	(3)	(4)	(5)	(6)
	Exclude 2008	Include 2012	Thickness Trim	Thickness & Depth Restrictions	1 Mile Border Cut	Triple Difference Approach
NY * PostMoratorium	-0.244*** (0.084)	-0.255*** (0.078)	-0.260** (0.088)	-0.240** (0.088)	-0.231*** (0.063)	-0.050 (0.061)
NY * PostMoratorium * Private						-0.179* (0.100)
Property Variables	Y	Y	Y	Y	Y	Y
Year Fixed Effects	Y	Y	Y	Y	Y	Y
Township Fixed Effects	Y	Y	Y	Y	Y	Y
Observations	856	1,193	826	817	805	2,353
R-squared	0.379	0.364	0.356	0.359	0.356	0.414

Note: Unless otherwise noted, observations represent single family residence and mobile home property transactions from 2006 to 2011. All observations are located outside of public water supply areas and, thus, rely on private well water. All observations are located within 5 miles of the border and overlay shale from 100 to 200 feet thick. The dependent variable is the natural log of sale price, CPI-adjusted to 2011 values. Property variables include number of beds and bathrooms, square footage of finished living area and its squared term, a quadratic in property acreage, and a cubic in property age. Model 1 excludes observations from 2008 for a cleaner break in expectations. Model 2 tests for the robustness of the results with an additional year's worth of sales data from 2012. Model 3 drops all observations in the shale thickness band from 100 - 150 feet, thus only leaving those in the 150 - 200 feet thickness band. In Model 4, we add shale depth trim to our main model (4,000 - 5,000 feet of shale depth) to better control for potential geological differences between the two states. Model 5 drops all properties that are located within a mile of the state border. Model 6 applies a triple difference approach, using properties in both private and public areas. Private is a variable that indicates whether a property is located in a private water supply area. Standard errors are shown in parentheses and are estimated using township-level cluster-robust inference. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Table 4: Heterogeneous impacts of the moratorium by acreage and for resolution towns

	(1)	(2)
	Acreage Interaction	Local Resolution Interaction
NY * PostMoratorium	-0.120** (0.055)	-0.128*** (0.046)
NY * PostMoratorium * ln(Acreage)	-0.031 (0.040)	
NY * PostMoratorium * ResolutionTown		-0.098 (0.064)
Property Variables	Y	Y
Year Fixed Effects	Y	Y
Township Fixed Effects	Y	Y
Observations	2,260	2,260
R-squared	0.400	0.395

Note: Observations represent single family residence and mobile home property transactions from 2006 to 2011. All observations are located outside of public water supply areas and, thus, rely on private well water. All observations are located within 15 miles of the border and overlay shale from 100 to 200 feet thick. The dependent variable is the natural log of sale price, CPI-adjusted to 2011 values. Property variables include number of beds and bathrooms, square footage of finished living area and its squared term, a quadratic in property acreage, and a cubic in property age. The first model interacts the DD with the natural log of acreage and replaces the quadratic in property acreage with the natural log of acreage. The second model interactions the DD with a binary variable that indicates whether an observation was located in a town that passed a local resolution in support of shale gas development in 2012. Standard errors are shown in parentheses and are estimated using township-level cluster-robust inference. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Table 5: Impact of unconventional well density on residential property prices in Pennsylvania

Variables	Model Specification - Spatial-Temporal Buffers					
	(1)	(2)	(3)	(4)	(5)	(6)
	One Mile Buffer			Two Mile Buffer		
	Six Months	Twelve Months	All Pre-Sale	Six Months	Twelve Months	All Pre-Sale
# of Spud Wells	-0.020 (0.029)	-0.013 (0.024)	-0.015 (0.019)	0.002 (0.011)	0.009 (0.007)	0.002 (0.006)
# of Spud Wells * Private	0.036 (0.034)	0.027 (0.027)	0.020 (0.019)	0.009 (0.011)	0.0004 (0.007)	-0.001 (0.006)
Property Variables	Y	Y	Y	Y	Y	Y
Year * Town FE	Y	Y	Y	Y	Y	Y
Observations	6,248	6,248	6,248	6,248	6,248	6,248
R-squared	0.402	0.402	0.402	0.403	0.403	0.402

Notes: All observations are single family residences and mobile homes sold in Pennsylvania from 2006 to 2012 for \$10,000 to \$1,000,000 (in 2011 CPI-adjusted dollars). Property characteristics include # of beds, # of baths, quadratics for acreage and finished square footage, a cubic in age, and binary variables that indicate whether or not the property is in a private water supply area, whether it is a mobile home, and whether it is missing values for beds, baths, finished square footage, or age. Standard errors are shown in parentheses and are estimated using township-level cluster-robust inference. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Appendix

This appendix provides information, data, and results that supplement, but are not critical to, the analysis in our main paper.

Tables A1 and A2 provide information regarding the monetary benefits and environmental costs, respectively, which may accrue to landowners in areas with active shale gas development. These supplement the discussion in Sections 2.1-2.2 of the main text. Although we focus on environmental costs, other costs from SGD could be social in nature, such as increased inequality and vulnerability of poor community members (Schafft et al., 2014), strains on local road infrastructure (Miller and Sassan, 2014), and community cultural changes (Jacquet and Kay, 2014).

Table A3 gives summary statistics for housing characteristics post-moratorium. This table is identical in structure to Table 1 from the main text. The purpose of this table is to test whether characteristics of transacting properties differed after the moratorium. If the types of properties did change, then this would discredit our main difference-in-differences estimates. The table shows that transacting New York properties are older than Pennsylvania properties. The table also shows that shale thickness is greater in the New York sample, as it is pre-moratorium, and the distance to spud wells is greater in New York than in Pennsylvania, which is expected. Most importantly, lot size is not significantly different between the states. Thus, we see no reason to believe that changes in the types of properties that transact will affect our estimates.

Table A4 highlights differences in means for a variety of census tract-level variables between New York and Pennsylvania (U.S. Census 2000). The table tests for

whether New York and Pennsylvania are significantly different from each other in terms of demographic, economic, and social characteristics. We break up the states into three subsets: (i) full state, (ii) study counties, and (iii) all census tracts in our study counties that are adjacent to the state boundary. By testing for statistical differences across different subsets of the states, we identify whether these characteristics converge as we move closer to our primary study area adjacent to the border. Results indicate that there are significant differences in demographic, economic, and social characteristics between New York and Pennsylvania at the state level. Although the absolute differences start to decrease when we restrict the census tract subset to only include those within our five study counties, we still observe significant differences in racial characteristics, rental occupancy percentage, and the unemployment rate. Once we restrict our sample to include only those census tract observations along the state border, we find that the only statistically-significant difference between the two states is median age. This is an important result, as it strengthens our argument that by focusing our analysis along the state border, we improve the comparability between our treatment and control groups.

Table A5 uses our preferred sample from Column 5 of Table 2 (properties within five miles of the border with shale geology overlap) and tests how functional form assumptions affect estimates. Results are consistent across specifications.

Table A6 provides our comprehensive model results including parameter estimates on all covariates included in our models. All estimates have the expected sign.

In Table A7, we estimate Table 2 from the main paper using Linear-Linear models with the understanding that the value of shale development is likely to be similar across the spectrum of sale prices. Our model estimates indicate that New York

properties that are most likely to experience shale development value it in the range of \$10,000 to \$28,000. Given mean sale price values for our subsample, the results are qualitatively similar whether you use a Log-Linear or Linear-Linear, making the average effect of the moratorium the same regardless of using logs or levels.

Table A8 provides a series of robustness checks on our results from Table 2, Column 5 (additional to those found in Table 3), while Table A9 tests the robustness of our results from Table 2, Column 3 (by estimating a similar series of models from Table 3). Results from both tables provide additional support to those found in the main text.

Figure A1 examines household movement across the border. One threat to our identification strategy is spillovers across the border caused by the moratorium. Using IRS migration data from our five sample counties, we compare the number of people moving from New York to Pennsylvania and vice versa. Figure A1 shows parallel trends both before and after the moratorium, giving credence to our identification assumptions.

Figure A2 shows the locations of residential property sales in our study area from 2006 to 2011 by water type.

Figure A3 shows the locations of towns in our study area that have passed SGD-supporting townships, while Figure A4 shows shale depth across our study area with an outlined 5-mile state border restriction buffer.

Analysis of Property Price Impacts of Local Resolutions in Favor of SGD

In addition to examining the effect of the statewide moratoria, we explore the effect of town-level resolutions in support of SGD on housing prices. While local resolutions had no direct effect on actual drilling activity, it is possible that passing a

resolution did affect expectations about the future likelihood of local SGD, especially in light of the state's position on home rule authority and the proposal floated in 2012 that would allow drilling only in communities that support it. In addition, bans were more popular in New York as a whole and towns in several counties north of our sample counties were very active with bans and moratoria (e.g., Livingston, Ontario, Tompkins and Yates counties).

Similar to the moratorium, these resolutions mark a potential change in expectations, especially when seen in the context of the greater number of local bans occurring elsewhere in the state and the floated policy to allow SGD in southern NY counties that expressed support, and this change in expectations could be capitalized into housing prices. Figure A3 shows the geographic distribution of local resolutions in our sample counties.

Like our moratorium analysis we work in a difference-in-differences framework, but now we use only transactions occurring in New York after the statewide moratorium, still restricting the sample to private well water properties. The dimensions of comparison now are location within a town that passes a local resolution versus location within a town that did not pass a local resolution and pre- versus post-resolution passage.

Treatment is passage of the local resolution. Equation 4 is the model we estimate:

$$\ln(p_i) = \gamma_1 ResolutionTown_i + \gamma_2 PostResolution_i + \gamma_3 ResolutionTown_i \cdot PostResolution_i + X_i' \theta + \mu_i \quad (1)$$

where p_i is sales price, $ResolutionTown_i$ is a binary variable equal to one if the property

is located in a town that passes a resolution in support of SGD, and $PostResolution_i$ is a binary variable equal to one if the transaction occurs after July 31, 2012. Because resolutions were being passed at various times March – July 2012 and it often took multiple meetings of discussion before passing, we exclude observations January – July 2012 so that the pre-post comparison is clean.

The coefficient of interest in Equation 1 is γ_3 , which is the double difference estimate. This term identifies the average change in prices for properties in resolution towns from before to after the resolution, relative to price changes for other New York properties located in towns that do not pass a local resolution. As discussed above, we expect this coefficient to be either zero or positive. It could be zero if passing a resolution does not change expectations about the likelihood of SGD in these areas. γ_3 will be positive if expectations do change and residents of the resolution towns feel the net benefits of SGD are positive, which seems likely since the residents passed the resolution in the first place.

The assumption of exogeneity may not hold with local resolutions as it does with the statewide moratoria. There could be characteristics of towns that pass resolutions that are correlated with house price changes.²¹ While estimates from Equation 4 cannot be interpreted as causal, we still feel there is value in investigating the correlation of prices and resolution decisions.

For the analysis of local resolutions, we use FracTracker Alliance maps to determine which townships have passed resolutions in support of SGD (FracTracker

²¹ Of the seven wells permits submitted (but never drilled) in our three NY Counties pre-moratorium, four occurred in Candor, NY, which passed a resolution. The other two permitted wells were outside of towns that passed resolutions (Erin in Chemung County; Tuscarora in Steuben County).

2014). We contacted township administrators regarding resolution dates. All confirmed dates range from early spring to the middle of summer of 2012. For the townships that we could not confirm timeline data, we assume the resolutions were passed in the same time frame as the others.

We use sales in the time span from July 24, 2008 to December, 31 2013 in New York. Further, we drop transactions occurring January-July 2012, as this was the period during which resolutions were being proposed, considered, and passed.²² There are very few properties in our preferred sample for the moratorium analysis that are located in towns that pass resolutions. Thus, we pull back from the 5-mile restriction and estimate models using 1) all New York observations, 2) only transactions in the 100-200 feet range of shale thickness, 3) within 15 miles of the border, and 4) within 15 miles of the border and shale thickness in the 100-200 feet range.

Table A10 presents results using the four different samples of data from estimates of Equation 4, which examines the house price impact of passing a resolution in support of SGD. Across the four models, coefficients are statistically insignificant and switch signs. We hypothesize that much of this noise could be due to the importance of covariates, especially town fixed effects as a result of self-selection into treatment. In Model 1, the double difference coefficient estimate is 0.094. This estimate implies that private water properties in towns that passed resolutions appreciated after resolutions were enacted. In conjunction with the earlier statewide moratorium results, this estimate suggests that the resolutions may have increased expectations about future SGD among buyers, which led to a subsequent price rebound. This result is consistent with the

²² From interviews with local clerks and township board representatives, it appears that the decision to ratify a local resolution in support of SGD was discussed across multiple township board meetings.

moratorium results in that it indicates positive valuation of SGD. Again, as argued in Section 2.3, these resolutions occurred in the backdrop of the more popular local bans and moratoria. While the resolutions are meaningless in that they do not affect SGD, they may influence expectations about what will happen in the town in the event that the statewide moratorium is eventually lifted.

However, restricted subsets of the data indicate negative double difference coefficient estimates in the range of -0.074 to -0.183. With the caveat that these coefficients are not statistically different than zero, the point estimates suggest that properties located within resolution towns depreciated post-resolution, relative to similar properties elsewhere. The contradiction in results between Model 1 and Models 2-4 and large standard errors suggest that the relationship either is ambiguous or cannot be measured with our sample counties.

Figure A1: Household movement across the NY-PA border

Notes: Data are from IRS county-to-county migration records. Only our five sample counties are included.

Figure A2: Observed transactions from 2006 to 2011 in sample counties

Figure A3: New York townships that have passed pre-emptive resolutions in support of shale gas development

Note: Townships classified as having passed pre-emptive resolutions in support of shale gas development are based on information provided by the Joint Landowners Coalition of New York.

Figure A4: Shale depth and border restrictions across our study area counties

Notes: Geological depth data is digitized from maps from Pennsylvania State University's Marcellus Center for Outreach and Research (MCOR).

Table A1: A review of potential landowner monetary benefits from shale gas development

Benefits	Description	Monetary Range
<i>Production-Related Benefits</i>		
Lease Signing Bonus	An initial payment, based on acreage, for signing a gas lease contract (Weidner, 2013); Most important element of lease given uncertainty of natural gas production (Hefley et al., 2011)	\$2700 per acre is average signing bonus amount, though this can vary considerably (Hefley et al., 2011); Average per acre payments can range from \$50 to almost \$6,000 (Green, 2010; Eichler, 2013; Riely, 2014)
Royalty Payments	Recurring payments on a proportion of natural gas extracted from the property (Weidner, 2013)	State law guarantees minimum 12.5% royalty rate, though the negotiated rate may be higher (Weidner, 2013); Royalty rates can range from 12.5% to 25%; Estimated average values of a landowner's share of royalties, per well, is \$2.5 million (Kelsey and Murphy, 2011)
Improved Public Services	Financed through tax and fee mechanisms on production or well development (e.g., Impact Fee in Pennsylvania, enacted in 2012)	In 2012, Pennsylvania received over \$200 million from an impact fee, some of which was distributed to local townships impacted by development (Rabe and Hampton, 2015)
<i>Infrastructure-Related Benefits</i>		
Pipeline Easement Payment	One-time contract payment to allow pipeline development on property; Based on length of constructed pipeline (Messersmith, 2010)	\$5-25 per linear foot (Messersmith, 2010)

Compressor Station Payment	One-time contract payment, potentially including an early exploration payment to allow the firm to assess the suitability of the land for the infrastructure (Attorney Douglas Clark, personal communication, 2014)	Range of compensation varies considerable, from hundreds of thousands into potentially millions of dollars (Attorney Douglas Clark, personal communication, 2014)
Water Impoundment Payment	Structure of payment varies, as the infrastructure could be a part of a well site agreement or a separate contract (Attorney Douglas Clark, personal communication, 2014)	Typical payment ranges from \$40,000 to \$70,000, though payment could be lower or higher (Attorney Douglas Clark, personal communication, 2014)

Table A2: A review of potential environmental impacts of shale gas development

Description	Spatial Range of Impact	Expected Sign
<i>Air Quality Impacts</i>		
Conventional air pollution increases associated with shale gas extraction and processing (e.g., Litovitz et al., 2011)	Local, Regional	-
Changes in overall greenhouse gas emissions due to natural gas displacement of coal use in energy production (e.g., Howarth et al., 2011; Cathles et al., 2012)	Global	N/A
<i>Water Impacts</i>		
Groundwater pollution due to shale gas development activities (e.g., Osborn et al., 2011; Jackson et al., 2013)	Local, Regional	-
Surface water contamination due to shale gas development waste disposal and management processes (Olmstead et al., 2013)	Local, Regional	-
Significant pressure on wastewater management capacity (e.g., Rahm et al., 2013)	Local, Regional	-
<i>Miscellaneous Effects</i>		
Shale gas infrastructure-driven forest and farmland fragmentation (e.g., Racicot et al., 2014)	Local, Regional	-
Decreases in wildlife habitat availability and quality in and around shale gas infrastructure (e.g., Kiviat, 2013)	Local, Regional, Global	-
Increased seismicity in and around unconventional wells and wastewater injection sites (Frohlich, 2012)	Local, Regional	-

Table A3: Summary statistics

Variable	Full Sample	Post-Moratorium Differences: NY - PA	
		Full Sample	< 5 Mile Border & Shale Trim Restrictions
Price (000s)	108.09	14.16	-5.56
Lot size (acres)	3.06	-0.12	-0.43
# of beds	2.79	0.10	0.16
# of baths	1.41	0.06	-0.10
Finished squared feet (000s)	1.52	0.07	0.05
Age at time of sale (years)	51.20	2.80	16.18*
# of spud wells: 0 - 3 miles	2.33	-7.78	-2.44*
Shale thickness (feet)	190.07	-64.06*	9.05*
% of mobile homes	0.08	-0.02	-0.05
Observations	4,976	2,627	567

Notes: Observations are single family residences and mobile homes located outside of public water supply ares. Housing prices are CPI-adjusted to 2011 levels. The 5 mile border restrictions includes only those observations that are located within 5 miles of the NY-PA state border. The shale trim restriction includes only those observations that overlay shale that is 100 - 200 feet thick. * if the differences in means divided by their combined standard deviation is greater than 0.25.

Table A4 - Demographic, Economic, and Social Characteristics

Variables	New York - Pennsylvania		
	Full State	Study Counties	Border Census Tracts
Median Age (Years)	-2.5***	-1.0	-1.6**
% of Population - Black	6.5***	3.4***	1.2
% of Population - Hispanic	11.5***	0.8**	0.7
Household Poverty Rate (%)	3.5***	-0.3	-0.7
Household Rental Occupancy (%)	16.6***	1.5*	-0.6
Median Household Income (000s)	3.9***	2.9	3.7
Unemployment Rate (%)	1.0***	0.7**	0.7
Bachelor Degree or Higher (%)	-3.5***	0.1	0.4

Notes: Data is from the U.S. Census 2000 and indicate differences in variable values between New York and Pennsylvania. The Border Census Tracts column includes data from census tracts that are adjacent to the NY-PA border. *** indicates significant difference at the 1% level, ** at the 5% level, * at the 10% level using a two-tail T-Test assuming unequal variances.

Table A5: Robustness checks (5 mile border & shale trim restrictions)

	(1)	(2)	(3)	(4)	(5)	(6)
NY * PostMoratorium	-0.256** (0.102)	-0.233*** (0.074)	-0.236*** (0.073)	-0.236*** (0.075)	-0.230*** (0.075)	-0.238*** (0.075)
Property Characteristics	N	Y	Y	Y	Y	Y
County FE	N	N	Y	N	N	Y
Year FE	N	N	N	Y	N	Y
Town FE	N	N	N	N	Y	N
Observations	1,018	1,018	1,018	1,018	1,018	1,018
R-squared	0.023	0.320	0.322	0.325	0.350	0.327

Note: Unless noted, observations represent single family residence and mobile home property transactions from 2006 to 2011. All observations are located outside of public water supply areas and, thus, rely on private well water. The dependent variable is the natural log of sale price, CPI-adjusted to 2011 values. Property variables include number of beds and bathrooms, square footage of finished living area and its squared term, a quadratic in property acreage, and a cubic in property age. Standard errors are shown in parentheses and are estimated using township-level cluster-robust inference. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Table A6: Comprehensive results from Table 2

	(1)	(2)	(3)	(4)	(5)
Variables	Full Sample	15 Mile Border	15 Mile Border & Thickness	5 Mile Border	5 Mile Border & Thickness
NY	0.275*** (0.025)	0.268*** (0.032)	0.273*** (0.038)	0.096 (0.087)	0.128 (0.096)
PostMoratorium	0.071 (0.047)	0.075 (0.062)	0.098 (0.069)	0.264** (0.099)	0.293*** (0.102)
NY * PostMoratorium	-0.101*** (0.036)	-0.130*** (0.039)	-0.151*** (0.045)	-0.209*** (0.074)	-0.231*** (0.077)
Acres	0.059*** (0.011)	0.059*** (0.014)	0.055*** (0.017)	0.049** (0.022)	0.051** (0.024)
Acres ²	-0.002*** (0.0005)	-0.002*** (0.000659)	-0.002** (0.000786)	-0.001 (0.001)	-0.001 (0.001)
LivingArea	0.485*** (0.075)	0.441*** (0.099)	0.414*** (0.121)	0.523** (0.193)	0.529** (0.209)
LivingArea ²	-0.053*** (0.019)	-0.039* (0.023)	-0.033 (0.028)	-0.050 (0.051)	-0.051 (0.055)
Beds	-0.017 (0.014)	0.005 (0.017)	0.012 (0.020)	-0.0001 (0.030)	0.003 (0.032)
Baths	0.200*** (0.022)	0.170*** (0.027)	0.188*** (0.028)	0.150*** (0.049)	0.156*** (0.051)
Age	0.0144*** (0.003)	0.010*** (0.003)	0.012*** (0.004)	0.014** (0.005)	0.015*** (0.005)
Age ²	-0.000228*** (3.07e-05)	-0.000179*** (3.86e-05)	-0.000202*** (3.96e-05)	-0.000218*** (5.47e-05)	-0.000227*** (5.54e-05)
Age ³	8.39e-07*** (1.09e-07)	6.70e-07*** (1.34e-07)	7.33e-07*** (1.37e-07)	7.66e-07*** (1.72e-07)	7.89e-07*** (1.73e-07)
Mobile	-0.340*** (0.055)	-0.391*** (0.093)	-0.374*** (0.101)	-0.332* (0.189)	-0.272 (0.208)
Imputation	0.005 (0.064)	0.045 (0.107)	0.136 (0.127)	0.144 (0.211)	0.158 (0.232)
Observations	4,976	2,829	2,260	1,072	1,018
R-squared	0.385	0.402	0.395	0.354	0.354

Note: All models include property characteristics, year fixed effects, and township fixed effects.

Table A7: Double difference estimates of the impact of the NY shale gas development moratorium on housing prices, Linear Model

	(1)	(2)	(3)	(6)	(7)
Variables	Full Sample	15 Mile Border	15 Mile Border & Thickness	5 Mile Border	5 Mile Border & Thickness
NY * PostMoratorium	-10,696*** (3,889)	-16,945*** (4,553)	-19,029*** (5,183)	-23,988*** (8,532)	-25,917*** (8,851)
Property Characteristics	Y	Y	Y	Y	Y
Year Fixed Effects	Y	Y	Y	Y	Y
Township Fixed Effects	Y	Y	Y	Y	Y
Observations	4,976	2,829	2,260	1,072	1,018
R-squared	0.426	0.509	0.506	0.442	0.446

Note: Observations represent single family residence and mobile home property transactions from 2006 to 2011. All observations are located outside of public water supply areas and, thus, rely on private well water. The dependent variable is the natural log of sale price, CPI-adjusted to 2011 values. Property variables include number of beds and bathrooms, square footage of finished living area and its squared term, a quadratic in property acreage, and a cubic in property age. The Shale Thickness restriction includes only those observations that overlay Marcellus Shale that is 100 - 200 feet thick. The Shale Depth restriction includes only those observations that overlay Marcellus Shale that is 4000 - 5000 feet below the surface. Standard errors are shown in parentheses and are estimated using township-level cluster-robust inference. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Table A8: Robustness checks for the 5 mile border restriction and shale thickness model

	(1)	(2)	(3)	(4)	(5)
	Single Family Only	PSM	1 Mile Border Cut		Shale Depth Restriction
			NY	PA	
NY * PostMoratorium	-0.236** (0.092)	-0.211** (0.095)	-0.272*** (0.076)	-0.192*** (0.065)	-0.206** (0.081)
Property Characteristics	Y	Y	Y	Y	Y
Year Fixed Effects	Y	Y	Y	Y	Y
Township Fixed Effects	Y	Y	Y	Y	Y
Observations	900	918	924	899	870
R-squared	0.309	0.366	0.351	0.360	0.358

Note: Unless otherwise noted, observations represent single family residence and mobile home property transactions from 2006 to 2011. All observations are located outside of public water supply areas and, thus, rely on private well water. All observations are located within 5 miles of the border and overlay shale from 100 to 200 feet thick. The dependent variable is the natural log of sale price, CPI-adjusted to 2011 values. Property variables include number of beds and bathrooms, square footage of finished living area and its squared term, a quadratic in property acreage, and a cubic in property age. Model 1 includes only observations classified as single family residences (no mobile homes included). Model 2 applies propensity score matching, where we use a probit model of all property characteristics listed above and 100-150 v. 150-200 shale thickness bins to predict NY. We then cut all observations outside of the 5% and 95% of the distribution of the propensity score. We then run our main specification on the reduced dataset. In Models 3 and 4, we cut all observations within a mile of the border from NY and PA, respectively. This is done to test for the effect of environmental spillovers (see Model 6 in Table 3 in the main text for an analogous regression where both sides are cut from the model). Instead of using a shale thickness restriction, Model 5 keeps only those observations that are 4,000 - 5,000 feet below the surface, which is in the common support of both states (see Marcellus Center for Outreach and Research at Pennsylvania State University for maps). Standard errors are shown in parentheses and are estimated using township-level cluster-robust inference. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Table A9: Robustness checks for the 15 mile border restriction and shale thickness model

	(1)	(2)	(3)	(4)	(5)	(6)
	Exclude 2008	Include 2012	Shale Thickness Trim	Shale Depth	1 Mile Border Cut	Triple Difference Approach
NY * PostMoratorium	-0.184*** (0.044)	-0.171*** (0.045)	-0.157** (0.058)	-0.183*** (0.063)	-0.140*** (0.043)	-0.064 (0.044)
NY * PostMoratorium * Private						-0.086 (0.064)
Property Characteristics	Y	Y	Y	Y	Y	Y
Year Fixed Effects	Y	Y	Y	Y	Y	Y
Township Fixed Effects	Y	Y	Y	Y	Y	Y
Observations	1,926	2,623	1,486	1,361	2,047	5,807
R-squared	0.399	0.399	0.322	0.366	0.400	0.499

Note: Unless otherwise noted, observations represent single family residence and mobile home property transactions from 2006 to 2011. All observations are located outside of public water supply areas and, thus, rely on private well water. All observations are located within 15 miles of the border and overlay shale from 100 to 200 feet thick. The dependent variable is the natural log of sale price, CPI-adjusted to 2011 values. Property variables include number of beds and bathrooms, square footage of finished living area and its squared term, a quadratic in property acreage, and a cubic in property age. Model 1 excludes observations from 2008 for a cleaner break in expectations. Model 2 tests for the robustness of the results with an additional year's worth of sales data from 2012. Model 3 drops all observations in the shale thickness band from 100 - 150 feet, thus only leaving those in the 150 - 200 feet thickness band. In Model 4, we use a shale depth trim instead of a shale thickness trim (4,000 - 5,000 feet of shale depth). Model 5 tests for the impact of environmental spillovers by cutting all NY and PA observations that are located within a mile of the state border. Model 6 applies a triple difference approach, using properties in both private and public areas. Private is a variable that indicates whether a property is located in a private water supply area. Standard errors are shown in parentheses and are estimated using township-level cluster-robust inference. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Table A10: The effect of local resolutions in support of SGD on housing prices

	(1)	(2)	(3)	(4)
	Full Sample	Shale Trim	15 Mile Border	Shale Trim + 15 Mile Border
ResolutionTown *	0.0939	-0.074	-0.079	-0.183
PostResolution	(0.627)	(0.770)	(1.102)	(1.192)
Property Characteristics	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Township FE	Y	Y	Y	Y
Observations	1,834	1,338	1,170	998
R-squared	0.244	0.190	0.246	0.216

Note: Observations represent single family residence and mobile home property transactions sold in NY from the NY moratorium in 2008 to late 2013. All observations are located outside of public water supply areas and, thus, rely on private well water. Due to the uncertainty of actual resolution dates, we cut all observations from January to July of 2012, which is in the range of all resolution passages that we have information on. The dependent variable is the natural log of sale price, CPI-adjusted to 2011 values. Property variables include number of beds and bathrooms, square footage of finished living area and its squared term, a quadratic in property acreage, and a cubic in property age. ResolutionTown indicates whether a sold property was located in a township that eventually passed in a resolution, while PostResolution indicates whether the property was sold after July 2012. Standard errors are shown in parentheses and are estimated using township-level cluster-robust inference. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

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Manuscript – 2

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**Valuation of the External Costs of Unconventional Oil and Gas Development:
The Critical Importance of Mineral Rights Ownership**

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Abstract

This paper seeks to quantify the negative externalities associated with unconventional extraction of oil and gas using hedonic valuation and residential property transactions. One complication in determining local impacts is the fact that some but not all properties are tied with mineral rights, which enable the residents to benefit financially from nearby drilling. To overcome this issue, we exploit the mineral severance legacy of the Stock-Raising Homestead Act of 1916 to identify properties in Western Colorado that with certainty do not have mineral rights and thus are only impacted negatively by proximate drilling. Our regression results suggest that housing prices decline about 35% when drilling occurs within one mile. This estimate of local costs is substantially larger than prior results found elsewhere in the literature, which demonstrates the critical importance of mineral ownership.

Keywords: unconventional oil and gas development; hydraulic fracturing; horizontal drilling; federal mineral ownership; mineral severance; hedonic valuation

JEL codes: Q3, Q5

1. Introduction

Shale and tight oil and gas basins have emerged as important sources of energy in the United States through innovations in hydraulic fracturing and horizontal drilling. This development has led to significant impacts on residents and landowners that are close to drilling activities. There are environmental and health risks associated with unconventional oil and gas development related to groundwater contamination (Osborn et al., 2011), surface water pollution (Olmstead et al., 2013), wastewater management (Rahm and Riha, 2012), and infant health (Hill, 2013; McKenzie et al., 2014). However, there are positive impacts as well, especially for those residents that lease their mineral rights to drilling companies in return for royalty payments and lease signing bonuses (Fitzgerald, 2014; Hardy and Kelsey, 2015).¹ Royalty payments can be paid as high as 20% of the value of production and lease signing bonuses can reach into the thousands of dollars per acre leased (e.g., Brasier et al., 2011; Kelly-Detwiler, 2013).

There is a growing body of literature in economics that seeks to estimate the local impacts of unconventional oil and gas development through hedonic valuation, with remarkable variation in estimates. Gopalakrishnan and Klaiber (2014) examine price responses in southwestern Pennsylvania and find that prices can decline by as much as 22% for private well-water dependent properties, but generally are smaller and short lived. Muehlenbachs et al. (2015) use data from across Pennsylvania and find that shale development can lead to depreciation as high as 17% for well water properties within 1.5

¹ The United States is unique in that private citizens can own the minerals underneath their property. In most countries, it is the government or the crown that owns all subsurface rights (Kulander, 2013). Since U.S. citizens can own their properties' minerals, they can financially benefit from drilling through leasing. The possibility of financial benefits has led to more public support for unconventional oil and gas development in the United States than in other countries (e.g., Stevens, 2010; Gény, 2010). Private mineral rights ownership has been crucial in driving development in the United States (Wang and Krupnick, 2013).

kilometers of an unconventional drill site. They also find that drilling can have a small positive impact on property sale prices in public water supply areas. Delgado et al. (2016) use data from Northeastern Pennsylvania and find no robust impact of nearby drilling. Boslett et al. (2016) examine the impact of the New York State moratorium on unconventional drilling and find New York properties most likely to be impacted by shale gas development declined 24% in value relative to comparable Pennsylvania properties after the moratorium. They interpret this finding as a positive expected value of shale gas development. Weber and Hitaj (2015) find evidence of appreciation in farm property values in both Pennsylvania and Texas, especially during leasing periods. Importantly, their estimates are attenuated in areas with significant mineral severance. In Colorado, Bennett and Loomis (2015) find mixed results that are often not statistically significant. Also in Colorado, James and James (2015) find that a one kilometer decrease in distance away from an unconventional well is associated with a 7 to 20% decrease in sale price. However, this effect can be mitigated if the property is above a horizontal well lateral, which suggests royalty payments from leasing are capitalized into prices. Using zip code level aggregate data from Texas, Weber et al. (2016) find evidence of both appreciation and depreciation due to shale development. There remain large variations in estimates of shale gas development on property prices without sufficient explanation.

One potential reason for the contrasting results is that mineral right ownership is not accounted for explicitly in these studies. Mineral ownership is important because it firmly demarcates property owners who financially benefits from unconventional gas development versus those who do not. Without mineral ownership information, it is not known whether the recovered valuation is a net impact of financial positives and

environment/health negatives, purely the negatives, or a weighted average of the two. In Pennsylvania, which is the focus of several of the above studies, mineral right ownership varies substantially and systematically across the state. In Western Pennsylvania, where there is a legacy of energy extraction, mineral rights are more often severed from surface rights than in northeastern Pennsylvania, where energy extraction only started recently (Kelsey et al., 2012). The valuation studies focused on Eastern Pennsylvania estimate less negative (or even positive) impacts of shale gas.² While the important distinction between private well water and public water properties has been identified by the existing hedonic valuation literature, the critical issue of mineral rights ownership has not been resolved. This has not been a lack of foresight or understanding by researchers of the importance of mineral ownership in how people are impacted by drilling. Rather, this information is extremely difficult for researchers to obtain.³

In this paper, we resolve the issue of unknown mineral rights by exploiting a historical severance in mineral rights ownership, the Stock-Raising Homestead Act of 1916 (SRHA1916). Over the course of the 19th century, the United States expanded its boundaries through territorial acquisition, often exchanging land rights for homesteading starting with the Homestead Act of 1862. In the late 1800s and early 1900s, the federal

² Consistent with this interpretation of the valuation results, homeowners that do not own mineral rights have an increased perception of environmental risk (Brasier et al., 2013) and frustration (Collins and Nkansah, 2015).

³ Mineral right ownership information is held in county deeds offices and is not commonly included in property deeds. The chain of title can be unclear, especially when the mineral estate was historically separated from the surface estate. One may need to go back to the original land grant to confirm the title of the mineral estate. Charting mineral rights ownership over time is the full-time job of a title abstractor (Wilson, 2014). Suffice it to say, it would be difficult for researchers to successfully obtain mineral rights ownership information for a large property transaction database. One of the authors of this study spent a day at Pennsylvania's Bradford County's Register and Recorder office researching mineral rights transfers and can attest to this. See Table 1A in the Appendix on a review of the previous literature and how each paper contextualized the issue of mineral rights ownership.

government recognized both the increasing value of energy for economic growth and the government's inability to properly identify "mineral" lands, which they kept in federal ownership, and "nonmineral" lands, which they disbursed for homesteading. In response, the federal government passed the SRHA1916, which continued the tradition of land disbursement, but the federal government retained ownership of minerals in all land disbursed after 1916 (Gates, 1977; Harrison, 1989).

To build our dataset of transactions, we identify residential properties in Colorado located on land originally distributed under the SRHA1916. Thus, the federal government owns the mineral rights for each of these properties and current residents do not benefit financially from lease and royalty payments. Our study area is on the western slope of Colorado, centered in Garfield, Mesa, and Rio Blanco counties. Western Colorado was one of the major areas of post-1916 homesteading and this region is one of the primary locations of unconventional oil and gas development in the state.

Our hedonic analysis suggests that houses within one mile of an unconventional drill site sell for 34.8% less than comparable properties without proximate drilling. This result is robust across various subsets of the data and alternative regression specifications, including a repeat sales model and a matching model. When multiplied by the average house price of \$183,300, this discount translates to a price reduction of \$63,788, which equals \$3,952 when annualized by a 30-year mortgage and a 5% interest rate. We interpret this price difference as the household valuation of the external environmental and health costs associated with proximity to unconventional oil and gas development.

Our findings corroborate the negative valuations found in other papers, but are much larger – 60% larger in magnitude than the largest existing negative estimate. This

disparity demonstrates the importance of understanding mineral rights, as financial benefits of drilling are capitalized into housing prices and can adulterate estimates of external costs. Supporting this conclusion, we also estimate hedonic models using Western Colorado properties with unknown mineral rights ownership, mirroring the setup of prior studies, and find much smaller and statistically insignificant impacts of proximity.

Our paper is structured as follows. We start in Section 2 with a conceptual framework that discusses the issue of mineral rights ownership in valuation of unconventional oil and gas development. In Section 3, we outline the history of SRHA1916. In Section 4, we discuss our data set and how we obtained it. We then follow with a discussion our methodological approach and the assumptions we use in our interpretation of our model results. In Section 5, we present our results, and Section 6 concludes.

2. Conceptual Framework

In this section, we outline the potential biases in hedonic valuation of unconventional oil and gas development. The net benefits and costs of oil and gas development vary across mineral estate classifications. Only residential properties that are unified with their property's mineral estate can receive direct financial benefits, such as a lease signing bonus and production-based royalties. However, all properties receive the environmental costs of nearby oil and gas development. Previous hedonic valuation work has not incorporated the ownership of mineral rights into valuation frameworks due

to the lack of data. Thus, these studies have typically contextualized their estimates as *net* valuations of local oil and gas development.⁴

We define the price of property i as $P_i(\cdot)$, a function of environmental characteristics E_i , the financial benefits of oil and gas development F_i , and structural characteristics. The environmental quality of the property is influenced by the presence of local oil and gas development, D_i . These impacts could be associated with diminished water quality, air quality, forest and habitat fragmentation, or visual or noise disamenities. Additionally, the financial benefits of owning the property are impacted by the presence of local oil and gas development, D_i .

In this framework, mineral ownership is defined as a binary variable, M_i , equal to 1 if the property's surface estate is connected with its mineral estate and equal to 0 otherwise. The net valuation of unconventional oil and gas development for property i can be decomposed as follows:

$$(1) \quad \text{Valuation}_i = \frac{\partial P_i}{\partial E_i} \cdot \frac{\partial E_i}{\partial D_i} + M_i \cdot \frac{\partial P_i}{\partial F_i} \cdot \frac{\partial F_i}{\partial D_i}$$

Thus, the valuation of development, as capitalized by housing prices, is a net valuation of the environmental impacts of development (first term) and the financial benefits of development, contingent on ownership of the property's mineral estate (second term). For the sake of simplicity, we re-write the equation as:

$$(2) \quad \text{Valuation}_i = C + M_i \cdot B,$$

⁴ Muehlenbachs et al. (2015) note that their estimate of the adjacency effect is an overall effect of the financial benefits of nearby drilling minus its environmental costs, while Gopalakrishnan and Klaiber (2014) remark that their negative valuations are likely understated due to the fact that they cannot control for the potential benefits of mineral leasing.

where C and B refer to the true values of the capitalization of the financial benefits and environmental costs (Table 1). If a property has mineral rights, then the estimated valuation will be the net impact, $C + B$. However, if a property is a split estate, then the estimated valuation will be the external costs of being proximate to drilling.

In order for researchers to estimate valuation with real data, a residential property market level analysis is required. We define θ as the proportion of properties unified with their minerals. Using the terminology from Table 1, we have:

$$(3) \quad \textit{Estimated Valuation} = (C + B) \cdot \theta + C \cdot (1 - \theta)$$

The estimated valuation is conditional on the proportion of treated properties with mineral rights, which is unknown to the researcher. Knowing either $C + B$ or C is useful for understanding local impacts and for guiding policy. But a weighted average of the two with an unknown weight yields imprecise guidance.

In this paper, we take advantage of the historical split in mineral rights from surface rights caused by SRHA1916, which is detailed in the next section. Thus, in our sample, $\theta = 0$ and we can isolate the negative environmental costs, C , from the financial benefits of development. This framework assumes there are no area level impacts of oil and gas development on properties which differ by mineral rights ownership, which would impact the estimate of proximity to wells. This potential issue is easily addressed with information about mineral rights ownership over the entire population of sale, or restricting the sample to only those properties without mineral rights ownership, i.e. $\theta = 0$, as we do in this study.

3. The Stock-Raising Homestead Act of 1916

In the late 1800s and early 1900s, the federal government passed a series of homestead acts that encouraged immigration and development in the western United States. The exact mandate varied across the acts; typically, settlers received 160-640 acres in return for a promise of ranching, cropping, or timber management on the property (Bureau of Land Management, 2006).

Early homestead acts apportioned both surface and subsurface rights to homesteaders. This was the case for the original Homestead Act of 1862, signed by President Abraham Lincoln after the separation of the Confederacy from the United States. These lands were selected for disbursement due to their perceived “nonmineral” character, as delineated by General Land Office’s entrymen and surveyors. All lands with mineral potential were retained by the federal government; however, demarcation was imperfect due to technology limitations (Leshy, 1987).

Recognizing its limitations in mineral assessment, the federal government passed the SRHA1916. This policy effectively discontinued the mineral-nonmineral classification system (Harrison, 1989). Homesteading individuals were granted no more than a section of land for ranching and forage crop production, conditional on making permanent improvements on the land within three years of the entry date. However, the federal government would retain mineral ownership of all lands disbursed through the Stock-Raising Homestead Act:

“That all entries made and patents issued under the provisions of this Act shall be subject to and contain a reservation to the United States of all coal and other

minerals in the lands so entered and patented, together with the right to prospect for, mine, and remove the same.”⁵

In addition, homesteaders and other later surface right owners had to allow access to the land for subsurface exploration and production:

“Any person who has acquired from the United States the coal or other mineral deposits in any such land, or the right to mine and remove the same, may reenter and occupy so much of the surface thereof as may be required for all purposes reasonably incident to the mining or removal of the coal or other minerals, first, upon securing the written consent or waiver the homestead entryman or patentee; second, upon payment of the damages to crops or other tangible improvements to the owner thereof...or, third, in lieu of either of the forgoing provisions, upon the execution of a good and sufficient bond...to secure the payment of such damages to the crops or tangible improvements of the entryman or owner.”⁶

This condition precludes the surface owner from preventing mineral exploration. The intent of the act was to continue the practice of homesteading and agricultural development of the west without compromising the federal government’s interest in mineral exploration (Tanke and Putz, 1982). If the surface owner had the right to prevent production from the property, the mineral estate would have no value. More recent

⁵ The Statues at Large of the United States of America from December, 1915 to March, 1917. Session 2. Chapter 9. Section 9. Page 864.

⁶ The Statues at Large of the United States of America from December, 1915 to March, 1917. Session 2. Chapter 9. Section 9. Page 864.

legislation has maintained surface use access for mineral rights interests while providing some limited protection to surface owners through accommodation doctrine. This principle allows only “reasonable” use of the surface by the mineral owner. The mineral owner may only access the surface if there are no other alternatives that could avoid interference with the present surface uses (Johnson, 1998). However, mineral rights dominance has largely been kept in place, as it is difficult for surface owners to prove that the use of the surface by the mineral owner is not reasonable (Kulander, 2013).

On privately-owned lands with federal mineral ownership, the mineral lessee must make a “good faith effort” to secure surface owner consent to access the property (Bureau of Land Management, 2007). However, the surface estate owner is only entitled to compensation associated with damages to crops and agricultural-related improvements. Thus, in the context of shale gas extraction, a homeowner may be exposed to water contamination, air pollution, noise, and visual disamenities, but not be entitled to compensation.⁷

The SRHA1916 led to a significant amount of private land with federal mineral ownership in the western United States. Out of approximately 300 million acres conveyed to private individuals through the various homesteading acts (Loomis, 2002), nearly 60 million acres have been split from their underlying subsurface estates as a result of the SRHA1916. In Colorado alone, these lands total 5.2 million acres. Figure 1 shows lands with federal mineral ownership across Colorado.

In a split estate, the surface property owner cannot financially benefit from

⁷ If the mineral lessee cannot come to a surface use agreement with the land owner, the company must rely on a performance bond to indemnify against unforeseen damages to crops and agricultural improvements. However, this bond does not cover all damages that a surface owner may face from drilling.

drilling. This situation is common in areas of the country that have experienced historical energy development and mining (e.g., Kelsey et al., 2012; Pender et al., 2014; Railroad Commission of Texas, 2015). Surface ownership can be split from its mineral rights through the issuance of a severance deed, in which a private landowner sells the land but retains the minerals. This situation is analogous to mineral ownership law in other countries: private land owners neither control the course of oil and gas development, nor financially benefit from it. The mineral estate is essentially dominant, which means that the surface owner must allow access to the mineral owner for exploration.

4. Empirical Setting and Data

Colorado has a long history of oil and gas development. According to data from the U.S. Geological Survey (Biewick, 2008), most Colorado counties have experienced oil and gas exploration since the early 1900s. Some counties, especially those outside of the intermountain areas, have seen a large increase in oil and gas development since the 1940s.

More recently, the new technologies of horizontal drilling and hydraulic fracturing have been used for extraction in Colorado. According to Drillinginfo, over 11,000 horizontal wells were drilled in Colorado between 2000 and 2014. Figure 1 displays the spatial distribution of this drilling. There are generally three drilling hotspots: northwestern Colorado, Weld County on Colorado's Front Range, and La Plata and Montezuma counties in southwestern Colorado. Our study focuses on northwestern Colorado because there is extensive federal mineral ownership in this area. Bennett and

Loomis and (2015) and James and James (2016) examine impacts in Weld County, which is more densely populated, but has much less federal mineral ownership than northwestern Colorado. Montezuma County contains many tribal lands, which complicates analysis due to jurisdictional complexity of mineral development and policy (West, 1992).

In this study, we use residential property transaction data from Garfield, Mesa, and Rio Blanco counties in western Colorado. We received this data from each county assessor's office. All transactions in our analyses occurred from 2000 to the end of 2014. All transaction data contains property characteristic information including the number of bedrooms and bathrooms, living area, age of the property, and its classified property or land use. We include only those transactions that are defined as residential or agricultural with a residential building ($N = 55,114$). All mobile homes are dropped from the analyses ($N = 2,819$).⁸ The data allow us to observe multiple sales per property, not just the most recent. All transactions that had more than seven bedrooms were dropped out of concern that the properties were apartment buildings ($N = 16$).

In order to focus on properties without mineral rights, we use the federal mineral ownership data from the Bureau of Land Management's Colorado GIS office.⁹ We overlay federal oil and gas ownership data layers with parcel boundaries. We include properties in our final sample that are completely contained within the federal mineral ownership boundaries ($N = 871$).¹⁰ While this cuts 98% of the transactions in our

⁸ Results from our main models are robust to including mobile homes and are available in the online appendix.

⁹ "Statewide Federal Mineral Ownership" data product.

¹⁰ There were data scale and alignment issues between our parcel data and our mineral ownership data. As a result, our restriction is conservative. There are likely other properties that are severed from their oil and gas rights by the SRHA but are not fully within the federal mineral ownership extent. We test our results

database, this restriction is necessary to identify the subset of properties that do not benefit financially from nearby drilling. It is almost certain that some properties outside of the federal mineral ownership boundary do not own mineral rights, but it is unknown on a property basis. Thus, this is the sample that provides the best estimate of the external costs of local oil and gas development. As shown in the results section, our coefficient estimates change considerably when we include properties with unclear mineral rights ownership. Lastly, we cut all observations in the below the 5th and above the 95th percentile of the sale price distribution to remove the influence of outliers. Our final sample is 783 transactions.

We received directional and horizontal well development data from Drillinginfo. In our three counties, there were 4,374 horizontal wells drilled from 2000 to 2014. Figure 2 maps the distribution of these wells relative to federal mineral ownership. In ArcGIS, we calculate the distance to the closest well at the time of sale. In addition, we calculated additional spatial statistics associated with distance to the closest municipality (U.S. Census definition) and the percentage of the property in an agricultural use from the National Land Cover Dataset 2001 to use as control variables in our regression model.

Table 2 provides summary statistics for our preferred sample of split estate properties, as well as the complete set of properties. Properties with federal mineral ownership are less expensive, relative to the population of properties. Split estate properties typically are less expensive, are larger in lot size, and have relatively less agricultural land. Interestingly, split estate properties are also more likely to have a

using less restrictive definitions of a split estate (i.e., 75 and 90% of property within federal mineral ownership boundary) and find robust results (available in the online appendix).

nearby horizontal well.¹¹

As discussed in the introduction, prior hedonic valuation papers have focused on differences in impacts between municipal water and private well water properties (Gopalakrishnan and Klaiber 2014, Muehlenbachs et al. 2015, Boslett et al. 2016). In Colorado, data does not exist on which properties have private vs. public water supply. However, our primary sample of split estate properties are typically outside of municipal boundaries, which is the best proxy for public water supply.¹² Therefore, our estimates are applicable to households that face the risk of groundwater contamination and are comparable to studies that focus on private water properties.

5. Methodology

We use the hedonic price method to estimate the effect of drilling proximity on housing prices. Our basic specification is:

$$(4) \quad \ln(p_{ist}) = \beta \cdot Well_{ist} + X'_{ist} \delta + \gamma_s + \tau_t + \varepsilon_{ist}.$$

p_{ist} is the sale price of property i in spatial unit s in year t . Prices are adjusted to 2015 levels using the Consumer Price Index. $Well_{ist}$ is a binary variable that indicates whether property i has an unconventional well within a given distance buffer at the time of sale.

X'_{ist} is a vector of structural, locational, and environmental explanatory variables. γ_s are spatial fixed effects; we present specification using both county and census tract as the

¹¹ This may suggest that there is a relationship between well development and mineral right severance, but that is beyond the scope of this paper.

¹² Phone conversation with Scott McGowan, GIS Coordinator with the Colorado Department of Public Health and Environment).

spatial unit. τ_t are year fixed effects. Collectively, these fixed effects control for unobserved price determinants across space and time. ε_{ist} is the error.

β is our coefficient of interest and is interpreted as the impact of having an unconventional well within r miles of the property on residential sale prices. Since we are only analyzing properties with federal mineral ownership, it reflects the marginal value of the environmental costs of having an unconventional well within the given spatial buffer.

Our goal is to define the radius r so that it captures the full spatial extent of negative externalities, but this is *a priori* unknown. Following Linden and Rockoff (2008) and more recently Muehlenbachs et al. (2015), we estimate a version of Equation (4) that includes a series of binary variables for different distance bands and seek to determine empirically at what distance the impact is statistically zero.

Figure 3 graphically presents results of a model that regresses log sales price on half mile distance bandwidths out to two miles, as well as property characteristics, year fixed effects, and census tract fixed effects. Results suggest that parameter estimates for the 0-0.5 mile bin and 0.5-1 mile bin are negative and statistically significant. Coefficient estimates are statistically insignificant beyond one mile. This finding is robust across alternative distance bin classifications and similar to findings from Gopalakrishnan and Klaiber (2014) and Muehlenbachs et al. (2015), who use a one mile and a two kilometer buffer, respectively, in their analyses. The similarity in coefficient estimates between the 0-0.5 mile and 0.5-1 mile bins is at first surprising because we would expect greater externalities closer to the drill sight. However, Figure 3 also displays the frequency of observations by distance and we see clustering of observations around 0.5 miles, which is why it is difficult to discern differential impacts less than and greater than 0.5 miles.

Going forward, we define r equal to one, and hence $Well_{ist}$ is a binary variable equal to 1 if there was a well drilled within one mile of the property before its sale.

5.1 Assumptions

There are a number of assumptions needed to interpret our estimates as the valuation of the environmental costs of unconventional oil and gas development. First, we assume that the assignment to treatment – in this case, close proximity to a horizontal well – is exogenous. It is unlikely that split estate owners can strongly dictate whether drilling happens, as the surface owner cannot prevent the mineral estate owner from accessing subsurface resources. Impacted parties can protest the inclusion of a parcel in an oil and gas lease sale (Bureau of Land Management Regulation 43 CFR 3120.1-3), but we were unable to find any protests directly from homeowners in our three study counties.¹³ A potential concern is that early oil and gas development could influence the likelihood of severance. In our case, the likelihood of severance is not a concern because of our study area's historical severance of mineral rights.

Second, we assume that property buyers and sellers have full information about local drilling activity and its potential for environmental impact. This is reasonable given the scale of planning and land disturbance associated with well permitting and drilling (e.g., Moran et al., 2015) and significant local discussion regarding the impacts of drilling (e.g., Williams, 2008; Lustgarten, 2009; Harmon, 2014). This region of Colorado has

¹³ There are examples of homeowners protesting the inclusion of a parcel in a 2012 lease sale in Delta County, outside of our study area. Most protests submitted to the Bureau of Land Management concerned environmental and social issues associated with drilling on *publically-owned land*, not split estate concerns on *privately-owned land*.

also been the primary site for multiple assessments of the health risks associated with unconventional development (e.g., Kassotis et al., 2013). As a result, home buyers are likely conscious of the potential benefits and costs of unconventional oil and gas development.

Third, property buyers and sellers are informed of the property's mineral right status and they understand its ramifications. There has been significant mineral development in western Colorado over the last century (Biewick, 2008). As a result, citizens are likely familiar with both oil and gas development and mineral ownership laws. The state legislature also passed a law in 2001 that required pre-transaction notification of the potential for a split estate (Garfield County Energy Advisory Board, 2007). There has been much public discussion since 2000 regarding a law that would mandate disclosure of mineral severance prior to all real estate sales. Although this legislation has not been passed due to issues secondary to the disclosure requirement (Moreno, 2011), it has been a major point of policy discussion in the state legislature over the study's time period. Additionally, federally-owned minerals were never disbursed with the land, so a title search is relatively quick and the information is publically accessible on the Bureau of Land Management's website.

Fourth, we assume that our estimates are not impacted by positive spillover effects of unconventional oil and gas development, including labor opportunities and improved public finances. Although these can be important benefits of local oil and gas development (e.g., Weber, 2012; Newell and Rami, 2015), these benefits are likely to be received at the regional level and are unlikely to be related to drilling adjacency or to mineral rights ownership.

Fifth, we assume that the financial benefits that a split estate owner can receive from local development are negligible. Landowners who do not own mineral rights are unable to receive lease or royalty payments from on-site production. However, landowners *can* receive compensation through a surface use agreement, which formally outlines where drilling and surface disturbances can happen on the property. Drilling companies must make a “good faith effort” to come to a surface use agreement with a landowner in a split estate situation. If the two parties are unable to come to an agreement, then the drilling company can rely on a performance bond (Bureau of Land Management, 2007). This alternative option does not cover all damages that a surface owner may face from drilling, such as contaminated drinking water, drilling-related noise, air pollution, and visual changes to the landscape. Additionally, performance bonds are typically meant to compensate for damages to cropland, but not pastureland (Fitzgerald, 2010). Since lands subject to SRHA1916 were originally intended for ranching and were deemed largely unsuitable for cropping, it is unlikely that property owners are reliant on a performance bond to indemnify them against damages related to drilling. It is more often than not that the surface owner will come to a surface use agreement with the drilling lessee (Hill and Rippley, 2004; BLM, 2006; Fitzgerald, 2010). Anecdotal reports suggest that oil and gas developers have leverage in negotiations, as they can rely on a performance bond if they do not agree to the surface owner’s preferred terms (e.g., The Telluride Daily Planet, 2005; Powder River Basin Resource Council, 2010; Hancock, 2014). For these reasons, it is unlikely that the financial benefits accrued from signing a surface use agreement are significant.¹⁴

¹⁴ This was corroborated in an email conversation with Cameron Grant, a mineral law attorney (Lyons Gaddis Kahn Hall Jeffers Dworak & Grant, A Professional Corporation of Attorneys and Counselors).

5. Results

5.1 Main Results

In Table 3, we present results that estimate the parameters of Equation (4), defining $Well_{ist}$ as a binary variable equal to 1 if there was a well drilled within one mile of the property. We present four model specifications that sequentially add more control variables to the model. Column 1 only includes property and location variables (i.e., number of bedrooms, distance to closest municipality), Column 2 adds year fixed effects, Column 3 adds county fixed effects, and Column 4 replaces county fixed effects with census tract fixed effects. Across columns, the coefficient on proximity ranges from -0.211 to -0.362 and is always statistically significant. The coefficient increases in magnitude substantially when year fixed effects are included, which is intuitive given that drilling (and hence treatment) is correlated with time. The coefficient is stable across Columns 2-4. Our preferred model is Column 4 that includes both year and tract fixed effects. This specification indicates that houses within one mile of an unconventional well sell for 34.8% less than houses further away, all else equal. This discount for proximity when multiplied by the average house price of \$183,300 translates to price reduction of \$63,788. Converting this into an annual impact using a 30-year mortgage and a 5% interest rate yields \$3,952, which is our best estimate of the annual external impacts of unconventional oil and gas development.

5.2. *Robustness checks*

In Table 4, we test for the robustness of this general result across alternative specifications and subsets of the data. In Column 1, we include an additional control variable, which is the number of vertical (conventional) oil and gas wells drilled within a mile of a property between 1980 and 1999. The concern is that past drilling is likely correlated with unconventional drilling, and thus if there is a negative impact on prices of past drilling, our estimates in Table 3 could be misattributing the variation from past drilling to current drilling. Since recent vertical well development may be an exploratory precursor to later horizontal well development, we use pre-2000 data to avoid potential endogeneity issues. In Column 2, we restrict our sample to only properties that are within 20 miles of an eventual unconventional well site. One concern with our full sample used in Table 3 is that some observed sales are far from drilling and may be a poor control group. By restricting the spatial distance, we hope to mitigate any bias that results from distant control observations. Column 3 further restricts the sample to be within 10 miles of an eventual unconventional well site. In Column 4, we restrict observations to be within 2005 to 2014. No proximate drilling took place within one mile of any sample properties prior to 2005. In our full sample, these pre-2005 properties are purely control observations. If there are structural changes in the housing market not captured by year fixed effects, then these observations may not be a good control and our estimates may be biased. In Column 5, we exclude all observations that sold more than once over our time period. Although fifteen years is a long time, there may be unobservable differences in the price dynamics of properties that sold multiple times over the study's period. In

Column 6, we estimate a repeat sales model and include only properties that sold more than once. Including property-level fixed effects better controls for unobservable property characteristics that could be correlated with proximity to drilling.

The coefficient estimates across these six columns are largely consistent with the main results. Magnitudes range from -0.307 to -0.381 and all estimates are statistically significant. Table 4 indicates that our estimates of the effect of drilling with one mile of a residential property are largely robust to alternative specifications and subsets of the data.¹⁵

5.3. Matching analysis

In this section, we shift to a matching approach in order to better control for observable differences between our control and treatment groups (e.g., Abbot and Klaiber, 2013; Ghanem and Zhang, 2014; Ferraro et al., 2015). The main goal of matching is to avoid the issue of selection bias and to create valid treatment-control comparisons through pairing on observable covariates (e.g., Caliendo and Kopeinig, 2008; Angrist and Pischke, 2009). This occurs when the estimated relationship between treatment status and outcome is driven by inherent differences in covariate distributions between treatment and control groups.

We use matching to further test the robustness of our regression model results.

¹⁵ In the Appendix, we provide additional robustness checks. In Tables 2A and 3A, we find qualitatively similar results when we define our treatment variable as the number of wells drilled within one mile of the property's extent, or when we use a distance bin approach. At the suggestion of a reviewer, we estimate our models in levels, as opposed to logs, and find similar results (Table 3A). In line with the structure of Table 4, we provide additional robustness check in Table 5A. All results from the Appendix support our main findings.

We first estimate a propensity score model of the probability of treatment as a function of property-specific variables:

$$(5) \quad Well_{it} = X'_{it} \cdot \alpha + \varepsilon_{it}$$

where $Well_{it}$ is a dummy variable equal to 1 if property i has an unconventional well within r miles of the property. In this case, X'_{it} is a vector of structural and locational explanatory variables used in our regression models, along with the number of vertical oil and gas wells drilled within a mile of the property from 1980 to 1999, as in Column 1 of Table 4. Including year and tract fixed effects would be ideal to control for temporal price trends and spatial unobservables, but given our limited sample size these match criteria are infeasible.

The propensity score is calculated using estimated coefficients from Equation (5). We then match treated observation to control observations using nearest neighbor matching with replacement. We match each treatment observation to its closest three control observations (3 -1 nearest neighbor matching). We apply a 0.05 caliper on the propensity score. Figure 4 provides the propensity score distributions for our control and treatment groups, pre versus post-matching, and shows that matching significantly reduces the difference between the distributions.¹⁶

Table 5 presents estimates of the treatment effect for our matching models. In Column 1, we estimate the difference in means between our treated observations and our matched control observations. The estimated difference in log prices is -0.263 and is

¹⁶ Following Rosenbaum and Rubin (1985), Sianesi (2004), and Kassie et al. (2011), we test the balancing between our matched treatment and control groups through mean standardized differences and the pseudo R^2 and likelihood ratio test of joint significance. We find that the mean standardized differences in our variables are reduced, our Pseudo- R^2 is reduced, and that the joint significance of the matching covariates is rejected, post-matching. These results are available in Table 8A in the Appendix.

statistically significant. In Columns 2-4, we use the matched sample to ensure covariate balance, but we return to a least squares framework to account for price dynamics and spatial unobservable variables. Control observations can be used more than once, so we weight each transaction proportional to the number of times it is used in the matching process using weighted least squares.¹⁷

In Column 2, we control for the estimated propensity score in our regression. The coefficient on proximity is -0.241, quite similar to the matching estimate. In Column 3, we add year fixed effects. The coefficient here is -0.439, which is a substantial increase in magnitude over Columns 1-2. Adding year fixed effects had a similar impact on coefficient magnitude in Table 3. In Column 4, we lastly add tract fixed effects and the resulting coefficient is -0.353, nearly identical to the main results in Table 3. In conclusion, our matching model improves the similarity of our treated and control observations, but results are similar to the regression models.

5.4. The effect of proximity when mineral rights ownership is unknown

We now seek to understand how valuation estimates change when mineral rights ownership is unknown, as is the case in all prior papers in this literature. We now include properties that are not completely contained within the federal mineral ownership boundaries. It is uncertain whether the mineral rights are unified with the property or split and owned by another party.

In Table 6, we estimate Equation (4) with our expanded sample ($N = 47,073$).

¹⁷ All transactions not matched to another observation are given zero weight.

Column 1 presents a specification identical to our preferred specification of Column 4 in Table 3, which includes property characteristics and year and tract fixed effects. The coefficient estimate is -0.057 and is statistically insignificant. This is substantially smaller in magnitude than estimates using only split estate properties. We interpret the disparity in coefficients as resulting from inclusion of properties that are tied to mineral rights and thus are able to financially benefit from nearby drilling, which offsets the negative impacts. However, we are unable to recover a comparison of benefits and costs using these estimates because the distribution of mineral estate ownership is unobserved.

The second column in Table 6 estimates separate proximity effects for properties with federal mineral ownership (our main sample) and properties without federal mineral ownership. Federal mineral ownership is a binary variable equal to 1 if the property is completely contained within the federal mineral ownership boundaries. The estimated impact for properties with unknown mineral ownership is -0.031, similar to Column 1. The coefficient on the interaction between the indicator for within one mile and federal mineral ownership is -0.318, similar to the main result in Table 3. Further, the interaction coefficient is statistically significant meaning that the impact of proximity is statistically different for properties without mineral rights than properties with unknown mineral rights, and these are all properties in the same three counties.¹⁸

¹⁸ We again estimate similar models using count and distance bin-based treatment variables. These results are available in the Appendix. In Table A6, our results suggest that the impact of nearby unconventional oil and gas development on housing prices is statistically significant and negative. We estimate that each well drilled within a mile decreases sale price by -0.7 to -0.2%. This is a significant attenuation relative to properties split from their mineral rights by the federal government, where we find a much higher estimate of -2.0%. In Table A7, we find that the effects of development within different spatial rings around the property varies across models. We generally find negative effects within two miles of development, though they are only strong and statistically significant when using county fixed effects. When using our preferred model with census tract fixed effects, our results indicate that having a well within one mile of the property reduces sale price by -4.3%.

6. Conclusion

We seek to quantify the negative externalities associated with unconventional extraction of oil and gas using hedonic valuation of residential properties. We exploit the Stock-Raising Homestead Act of 1916 to identify properties that do not have mineral rights, and thus cannot benefit financially from lease payments or royalties to isolate the external costs of unconventional oil and gas development. This approach resolves a significant issue in the valuation of unconventional oil and gas development, which has caused uncertainty in the interpretation of estimates from previous studies.

The results of our hedonic analysis suggest that houses within one mile of an unconventional drill site sell for 34.8% less than comparable properties without proximate drilling. This discount translates to a price reduction of \$63,788, which equals \$3,952 when annualized by a 30-year mortgage and a 5% interest rate. We interpret this price difference as the household valuation of the external environmental and health costs associated with proximity to unconventional oil and gas development. Further, our findings are 60% larger in magnitude than the largest existing negative estimate. While there are differences across study areas and identification strategies across studies, we interpret the disparity resulting from our studies ability to identify split estate properties.

The results of this paper can inform how the United States and other countries proceed with energy development. The suite of energy options available to consumers have benefits and costs that are received at global, regional, and local levels. Our estimates of the local external costs of unconventional oil and gas development should be

considered with respect to those incurred from other forms of energy production, including coal-fired power plants (Davis, 2011), wind turbines (Lang et al., 2014; Gibbons, 2015), and nuclear power facilities (Gawande et al., 2013).

For those states that allow local regulation of oil and gas development, optimal local policy responses to unconventional oil and gas development should consider these results alongside others which find positive valuations of development (Boslett et al., 2016). Mineral rights ownership is clearly important to valuation of local energy development. Policy-makers should account for mineral rights in policy development. They can then take measures to further support or regulate development (e.g., Zirotiannis et al., 2015) as a function of the level of local ownership of the minerals.

Our findings are relevant and applicable to a broader geographic area than Colorado. Prior hedonic valuation research provides great insight on local valuation of unconventional oil and gas development, especially on its perceived water quality risks. However, external validity outside of the United States is limited in these studies because private citizens in European and many other countries do not own subsurface minerals. Our study may provide a better metric for external costs of unconventional oil and gas exploration in these cases because it accounts for the critically important issue of mineral rights ownership.

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Tables & Figures

Table 1: Financial benefits and environmental costs of oil and gas development, differentiated by mineral estate ownership classification

	Environmental Costs	Financial Benefits	Valuation
Unified			
$(M_i = 1)$	C	B	$C + B$
Split $(M_i = 0)$	C	0	C

Table 2: Summary statistics

Variable	Properties with Federal Mineral Ownership		All Properties	
	Mean	Std. Dev.	Mean	Std. Dev.
Sale price (\$000s)	183.3	81.4	250.6	109.9
Lot size (acres)	6.4	26.7	1.4	8.0
Property age (years)	17.8	16.4	18.3	24.1
Bedrooms	3.0	0.7	3.2	0.7
Bathrooms	2.0	0.6	2.0	0.6
Living area (000s of sq. feet)	1.6	0.7	1.8	0.7
Distance to municipality (in miles)	1.8	3.4	0.5	1.5
% agricultural	3.0	14.4	7.4	23.3
# of vertical wells < 1 mile	0.9	1.1	0.1	0.6
% of properties with horizontal wells				
< 1 mile	12.5		2.2	
< 2 miles	34.6		7.4	
< 3 miles	38.2		10.6	
# of Observations	783		47,033	

Notes: We received residential property transaction, structural, and parcel data from Garfield, Mesa, and Rio Blanco county assessment and geographic information systems (GIS) offices. We received location data for all horizontal wells drilled from 2000 to 2015 and all vertical wells drilled from 1980 to 1999 in Colorado from Drillinginfo. We calculated the percentage of each property in an agricultural use using National Land Cover Dataset 2001 data. We calculated the distance to the closest municipality using U.S. Census Bureau TIGER data from 2010.

Table 3: The effect of unconventional development on residential properties with federal mineral ownership

	(1)	(2)	(3)	(4)
= 1 if Wells < 1 Miles	-0.211*** (0.033)	-0.343*** (0.025)	-0.362*** (0.064)	-0.348*** (0.059)
R-Squared	0.397	0.499	0.513	0.547
Property & Location Vars.	Y	Y	Y	Y
Year F.E.	N	Y	Y	Y
County F.E.	N	N	Y	N
Track F.E.	N	N	N	Y

Notes: Observations represent single family residential properties sold from 2000 to early 2015 in Garfield, Mesa, and Rio Blanco counties (N = 783). We truncate the data set to exclude the 5 and 95 percentiles of sale price. The dependent variable is the natural log of sale price (CPI-adjusted to 2014 values). Property variables include quadratics of # of bedrooms and bathrooms, parcel acreage, property finished living area, and property age. Location variables include quadratics of distance to the closest municipality and the percentage of the property in an agricultural use. Census tracts are based on U.S. Census 2010 boundaries. Standard errors are shown in parentheses and are estimated using tract-level cluster-robust inference: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 4: Robustness checks

	(1)	(2)	(3)	(4)	(5)	(6)
	Vertical well control	Well Distance Restriction		2005 - 2014	Sold Once	Repeat Sales
		20 miles	10 miles			
= 1 if Wells < 1 Miles	-0.348*** (0.060)	-0.350*** (0.064)	-0.333*** (0.067)	-0.308*** (0.072)	-0.307*** (0.083)	- 0.381*** (0.101)
# of Observations	783	771	616	523	241	545
R-Squared	0.560	0.551	0.539	0.551	0.609	0.799
Property & Location Vars.	Y	Y	Y	Y	Y	N
Year F.E.	Y	Y	Y	Y	Y	Y
Tract F.E.	Y	Y	Y	Y	Y	N

Notes: In Model 1, we include a control for the # of vertical oil and gas wells drilled from 1980 to 1999. In Models 2 and 3, we restrict our analyses to only those observations that are within 20 and 10 miles, respectively, of a well drilled pre or post-sale. In Model 4, we restrict our analysis to only those observations sold from 2005 to 2014. In Model 5, we only include those observations that were sold once between 2000 and 2015. In Model 6, we use a panel approach and only use those properties that were sold more than once from 2000 to 2015. We use property-level and year fixed effects. Standard errors are shown in parentheses and are estimated using tract-level cluster-robust inference: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 5: The effect of unconventional development on split estate properties using matching techniques

	Nearest Neighbor Matching	Weighted Regression		
	(3 - 1)	Only P.S.	+ Year FE	+ Property Variables
	(1)	(2)	(3)	(4)
= 1 if Wells < 1 Miles	-0.263*** (0.051)	-0.241*** (0.049)	-0.439*** (0.057)	-0.353** (0.137)
R-Squared		0.074	0.410	0.618

Notes: In Columns 1, we use nearest neighbor matching (3 - 1) and match on the # of bedrooms and bathrooms, living area, property age, and acreage, as well as the distance to the closest municipality, the percentage of the property in an agricultural use, and the number of vertical wells drilled within a mile from 1980 to 1999. We match with replacement and with a caliper of 0.05. In Column 2 through 4, we use our treatment observations and matched control observations from our Nearest Neighbor matching in Column 1 and estimate weighted regression models (in line with Equation 1 and Table 3). We weight based on the number of times each control observation was matched to a treatment observation. In Column 2, we only control for the estimated propensity score. In Column 3, we add year fixed effects. In Column 4, we add the structural and locational variables defined above. Census tracts are based on U.S. Census 2010 boundaries. Standard errors are shown in parentheses and are estimated using tract-level cluster-robust inference: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 6: The effect of unconventional development on all residential properties (N = 47,139), binary treatment

	(1)	(2)
= 1 if Wells < 1 Miles	-0.057 (0.054)	-0.031 (0.051)
Federal Mineral Ownership		0.054 (0.065)
Wells < 1 Miles * Federal Mineral Ownership		-0.318*** (0.080)
R-Squared	0.446	0.447
Property & Location Vars.	Y	Y
Year F.E.	Y	Y
Track F.E.	Y	Y

Notes: Observations represent single family residential properties sold from 2000 to early 2015 in Garfield, Mesa, and Rio Blanco counties. We truncate the data set to exclude the 5 and 95 percentiles of sale price. The dependent variable is the natural log of sale price (CPI-adjusted to 2014 values). Property variables include quadratics of the # of bedrooms and bathrooms, parcel acreage, property finished living area, and property age. Location variables include quadratics of distance to the closest municipality and the percentage of the property in an agricultural use. Federal Mineral Ownership is a binary variable equal to 1 if the property is completely within the boundaries of federal mineral ownership. Census tracts are based on U.S. Census 2010 boundaries. Standard errors are shown in parentheses and are estimated using tract-level cluster-robust inference: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Figure 1: Map of unconventional oil and gas development in Colorado

Notes: Unconventional well location data was provided by Drillinginfo. Data on federal mineral ownership is from the Bureau of Land Management Colorado's GIS department.

Figure 2: Map of Western Colorado

Notes: Unconventional well location data was provided by Drillinginfo. Data on federal ownership of oil and gas is from the Bureau of Land Management Colorado's GIS department. We created our private lands estate classifications using federal mineral ownership and statewide surface ownership data. *Unknown Mineral Ownership* is the intersection between "Private" surface ownership and mineral ownership categories that do not include the federal ownership of the oil and gas estate, while *Federal Mineral Ownership* is the intersection between "Private" surface ownership and federal mineral ownership categories that do include the oil and gas estate. Properties indicated as *Unknown Mineral Ownership* may be split estate properties if the mineral rights were at one point severed due to alternative mechanism (e.g., a severance deed).

Figure 3: Distance bin parameter estimates and histogram of well distance

Notes: In the LHS graph, we highlight parameter estimates for distance bins in line with Equation 4. We define our treatment variable as a bin variable (see Equation 5). Each estimate reflects the impact of the closest well from the property drilled within the distance bin range, relative to the omitted category of having the closest well drilled beyond two miles. In the RHS graph, we highlight the distribution of distance to closest unconventional well. We only include those wells that were drilled before the sale of the home.

Figure 4: Propensity score distributions for one mile treatment, pre versus post matching (Nearest Neighbor 3 – 1)

Notes: These graphs highlight the difference in propensity score distribution, pre versus post-matching. Variables included in the propensity score estimation include the # of bedrooms and bathrooms, parcel acreage, property finished living area, property age, distance to the closest municipality, the percentage of the property in an agricultural use, and the number of vertical oil and gas wells drilled within a mile from 1980 to 1999.

Appendix

This Appendix provides information that is supplementary but not critical, to the analyses that included in the main paper.

Table 1A includes a brief literature review of the literature on hedonic valuation of unconventional oil and gas development. In this review, we focus on how mineral rights ownership was discussed in each of the papers, especially in respect to how it influenced their valuation. We do not summarize the results contained within each of studies. The literature is discussed in greater detail in the main paper and all References made in the table are listed in the Works Cited.

Table 2A provides a more comprehensive list of our parameter estimates in our main specifications from Table 3 in the main text. The signs on the variables generally match our expectations. Property price increases in acreage and living area but with diminishing returns. Older houses sell for a discount. Property price decreases in the number of bedrooms and bathrooms. This is unexpected, but this is not a concern given correlation between both variables and living area. We generally find that property price decreases as one moves further away from municipalities, though at a diminishing rate. This is somewhat expected given the amenities associated with living in or near towns.

In Table 3A, we define treatment as the number of wells drilled within 1 mile. The structure of the table is similar to that of Table 3 in the main paper. We find qualitatively similar results when using this alternative treatment definition. Each well drilled within a mile is associated with a decrease in sale price of 2%.

At the advice of an informal reviewer, we estimate Equation 4 in levels instead of logs in Table 4A. We again find qualitatively similar results. In our preferred

specification in Column 4, we estimate that having an unconventional well within a mile of a property decreases sale price by \$52,000. This is similar to an analogous estimate using the mean sale price in our study area and our estimate from Table 3, Column 4.

In Table 5A, we test for the robustness of our results in Table 3 of the main paper across a number of additional models. In Column 1, we include only those properties that are within three miles of a well drilled from 1980 to 1999. This model tests whether or not our treatment effect estimates are associated with differing levels of historical oil and gas development. In Columns 2 and 3, we relax our definition of a split estate – those properties with federal mineral ownership – to allow properties with 90% and 75% coverage, respectively, within federal mineral ownership boundaries. In Columns 4 and 5, we use alternative well distance restrictions to our 20 and 10 mile distances used in Columns 2 and 3 from our robustness table in the main text. In Column 6, we cut observations below the 5% and above the 95% distribution in acreage. We do this to avoid the influence of outlying observations based on property size. Lastly, in Column 7, we include mobile homes while also controlling for them using a binary indicator.

Our results from our additional models suggest that our results are robust. Our results are similar when we relax our definition of the split estate. Although these definitions are still restrictive and are likely including observations with federal mineral ownership, they suggest that we could increase our sample size and still obtain similar results. Our results are also similar to our main results when we use alternative restrictions based on distance to the closest well and when we cut outlying observations by acreage.

In Table 6A, we provide a brief summary of pre and post-matching statistics from Table 5 in the main text. Mean standardized differences in the matching covariates are reduced. Also, the Pseudo- R^2 is reduced and the p-value of the likelihood ratio test of joint significance of the matching covariates is significantly higher, post-matching. These results suggest that there are no differences in observed characteristics between control and treatment observations, post-matching.

In Table 7A, we use our full sample in line with Table 6 in the main text. Instead of only including properties with federal mineral ownership, we now include properties with unknown mineral ownership. However, we now define treatment as the number of unconventional wells drilled within a mile of the property. In Column 1, we find that each well within a mile is associated with a 0.3% decrease in property sale price. This effect is not significant and is much smaller than the estimates found in Table 2A (1.7 to 2.0%). In Column 2, we differentiate the effect of well development by whether or not the property is within federal mineral ownership boundaries. We find that the effect of well development is much larger for those properties with federal mineral ownership (-1.6%). For those properties with unknown mineral ownership, the effect is close to zero and insignificant. These findings support those from Table 6 in the main text. Since those properties with unknown mineral ownership are likely to include properties with unified mineral rights, our treatment effect for these properties is likely to be a net effect of financial benefits and external costs of development.

Table 1A: Mineral rights ownership in the previous literature on unconventional oil and gas development

Authors and Year	Study Area	Mineral Rights
Gopalakrishnan and Klaiber (2014)	Washington County, Pennsylvania	Argue that their estimated valuation of the environmental costs is a lower bound due to the inclusion of properties with mineral rights ownership. Highlight the need for future work to differentiate the impacts of development on homebuyers by mineral rights ownership.
Muehlenbachs et al. (2015)	New York & Pennsylvania	Note that their estimated valuation does not capture positive impacts of development on nearby property prices if properties that are close to development are split from their mineral rights
Delgado et al. (2015)	Northeastern Pennsylvania	Argue that their estimated valuations capture both the positive effects and negative effects of development due to their choice in study area, which may have less severance.
James and James (2015)	Weld County, Colorado	Argue that their identification strategy avoids the mineral rights issue by controlling for both distance to the closest well and whether or not the property overlays the well's horizontal lateral
Bennett and Loomis (2015)	Weld County, Colorado	Argue that some of their estimated positive impacts are due to the potential that properties near wells are more likely to own their minerals
Boslett et al. (2016)	Border of New York & Pennsylvania	State that their study is recovering a net valuation of development due to relatively high mineral ownership by landowners in the study region
Weber and Hitaj (2015)	Pennsylvania and Texas	Argue that the larger appreciation in farmland values found in Pennsylvania are likely associated with greater mineral rights ownership in the state relative to Texas
Weber et al. (2016)	Dallas & Forth Worth, Texas	Note that there is relatively low local ownership of mineral rights in the study area, which suggests that the estimated appreciation in housing prices after development is likely due to the expansion of the tax base (rather than expected financial benefits of drilling)

Table 2A: Comprehensive results of our models from Table 3 in the main text

	(1)	(2)	(3)	(4)
= 1 if Wells < 1 Miles	-0.211*** (0.033)	-0.343*** (0.025)	-0.362*** (0.064)	-0.348*** (0.059)
Beds	-0.143 (0.107)	-0.129 (0.135)	-0.152 (0.146)	-0.104 (0.119)
Beds * Beds	0.019 (0.015)	0.013 (0.018)	0.018 (0.020)	0.011 (0.016)
Baths	-0.023 (0.208)	-0.070 (0.138)	-0.083 (0.130)	-0.084 (0.117)
Baths * Baths	0.024 (0.035)	0.034 (0.023)	0.041* (0.021)	0.042** (0.018)
Age	-0.004 (0.004)	-0.004 (0.004)	-0.004 (0.004)	-0.004 (0.004)
Age * Age	-3.00e-05 (5.95e-05)	-3.56e-05 (5.71e-05)	-3.70e-05 (5.61e-05)	-5.38e-05 (5.58e-05)
LivingArea	0.073*** (0.007)	0.074*** (0.010)	0.070*** (0.010)	0.065*** (0.012)
LivingArea * LivingArea	-1.12e-05*** (1.12e-06)	-1.12e-05*** (1.41e-06)	-1.06e-05*** (1.51e-06)	-9.99e-06*** (1.92e-06)
Acres	0.005* (0.002)	0.006* (0.003)	0.004 (0.003)	0.002 (0.005)
Acres * Acres	-2.11e-05*** (6.31e-06)	-2.25e-05*** (6.70e-06)	-1.77e-05* (8.03e-06)	-1.12e-05 (1.13e-05)
Municipality	0.0009 (0.014)	0.001 (0.008)	-0.040* (0.021)	-0.097*** (0.026)
Municipality * Municipality	0.0006 (0.001)	0.0004 (0.0007)	0.002** (0.001)	0.005*** (0.0009)
Agr %	-0.003 (0.002)	-0.004 (0.004)	-0.005 (0.004)	-0.007 (0.006)
Agr % & Agr %	0.005 (0.004)	0.005 (0.005)	0.006 (0.005)	0.009 (0.007)
R-Squared	0.397	0.499	0.513	0.547
Property & Location Vars.	Y	Y	Y	Y
Year F.E.	N	Y	Y	Y
County F.E.	N	N	Y	N
Track F.E.	N	N	N	Y

Notes: Notes: This table displays coefficient estimates from our control variables in our models highlighted in Table 3. Beds is the number of bedrooms in the property's house. Baths is the number of bathrooms in the property's house. LivingArea is the square footage of finished area in the property (in 00s). Acres is the property's acreage. Age is the property's age (years). Municipality is the distance to closest municipality (U.S. Census Bureau 2010). Agr % is the percentage of the property in an agricultural use (National Land Cover Dataset 2001).

Table 3A: The effect of unconventional development on the residential properties with federal mineral ownership, count treatment

	(1)	(2)	(3)	(4)
# of Wells < 1 Miles	-0.017*** (0.0009)	-0.020*** (0.003)	-0.020*** (0.003)	-0.020*** (0.003)
R-Squared	0.455	0.535	0.545	0.583
Property & Location Vars.	Y	Y	Y	Y
Year F.E.	N	Y	Y	Y
County F.E.	N	N	Y	N
Track F.E.	N	N	N	Y

Notes: Observations represent single family residential properties sold from 2000 to early 2015 in Garfield, Mesa, and Rio Blanco counties (N = 783). We truncate the data set to exclude the 5 and 95 percentiles of sale price. The dependent variable is the natural log of sale price (CPI-adjusted to 2014 values). Property variables include quadratics of # of bedrooms and bathrooms, parcel acreage, property finished living area, and property age. Location variables include quadratics of distance to the closest municipality and the percentage of the property in an agricultural use. Census tracts are based on U.S. Census 2010 boundaries. Standard errors are shown in parentheses and are estimated using tract-level cluster-robust inference: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 4A: The effect of unconventional development on the residential properties with federal mineral ownership in levels of sale price

	(1)	(2)	(3)	(4)
= 1 if Wells < 1 Miles	-27,531*** (6,890)	-53,853*** (5,887)	-54,272*** (12,977)	-52,290*** (11,486)
R-Squared	0.398	0.499	0.513	0.576
Property & Location Vars.	Y	Y	Y	Y
Year F.E.	N	Y	Y	Y
County F.E.	N	N	Y	N
Track F.E.	N	N	N	Y

Notes: Observations represent single family residential properties sold from 2000 to early 2015 in Garfield, Mesa, and Rio Blanco counties. We truncate the data set to exclude the 5 and 95 percentiles of sale price. The dependent variable is sale price (CPI-adjusted to 2014 values). Property variables include quadratics of # of bedrooms and bathrooms, parcel acreage, property finished living area, and property age. Location variables include quadratics of distance to the closest municipality and the percentage of the property in an agricultural use. Census tracts are based on U.S. Census 2010 boundaries. Standard errors are shown in parentheses and are estimated using tract-level cluster-robust inference: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 5A: Additional robustness checks

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Vert. Well Restriction	Split Estate Definition		Well Distance Restriction		Acres Cut	+ Mobile Homes
		> 90%	> 75%	15 miles	5 miles		
= 1 if Wells < 1 Miles	-0.347* (0.116)	-0.363*** (0.062)	-0.352*** (0.069)	-0.351*** (0.068)	-0.325** (0.101)	-0.382*** (0.084)	-0.354*** (0.064)
# of observations	558	860	882	701	589	703	804
R-Squared	0.561	0.528	0.521	0.522	0.540	0.579	0.563
Property & Location Vars.	Y	Y	Y	Y	Y	Y	Y
Year F.E.	Y	Y	Y	Y	Y	Y	Y
Tract F.E.	Y	Y	Y	Y	Y	Y	Y

Notes: In this table, we provide additional robustness checks to those shown in Table 3. In Column 1, we restrict our sample to only include those observations that are in historic oil and gas drilling areas, measured by being within a distance of 3 miles to the closest vertical well drilled from 1980 to 1999. In Columns 2 and 3, we ease the split definition to include those properties that have 90% and 75%, respectively, of their acreage within the federal mineral ownership boundaries. In Columns 4 and 5, we restrict our observations to those within 15 and 5 miles, respectively, of a pre or post-sale horizontal well. In Column 6, we cut off the 5% tails of the acreage distribution. In Column 7, we include mobile homes and control for this type of property with a binary indicator. Standard errors are shown in parentheses and are estimated using tract-level cluster-robust inference: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 6A: Pre and post-matching statistics

	Pre-Matching	Post-Matching
Mean Normalized Bias	23.2	5.4
Pseudo R ²	0.094	0.021
Likelihood Ratio Test P-Value	< 0.001	0.756

Notes: We used Nearest Neighbor Matching (3 - 1) with replacement a 0.05 caliper. We matched on the # of bedrooms and bathrooms, living area, property age, distance to municipality, percentage of the property in an agricultural use, and the number of vertical wells drilled within a mile from 1980 to 1999.

Table 7A: The effect of unconventional development on all residential properties
(N = 47,139), continuous treatment

	(1)	(2)
# of Wells < 1 Miles	-0.003 (0.002)	-0.001 (0.002)
Federal Mineral Ownership		0.048 (0.063)
# of Wells < 1 Miles * Federal Mineral Ownership		-0.016*** (0.002)
R-Squared	0.446	0.447
Property & Location Vars.	Y	Y
Year F.E.	Y	Y
Track F.E.	Y	Y

Notes: Observations represent single family residential properties sold from 2000 to early 2015 in Garfield, Mesa, and Rio Blanco counties. We truncate the data set to exclude the 5 and 95 percentiles of sale price. The dependent variable is the natural log of sale price (CPI-adjusted to 2014 values). Property variables include quadratics of the # of bedrooms and bathrooms, parcel acreage, property finished living area, and property age. Location variables include quadratics of distance to the closest municipality and the percentage of the property in an agricultural use. Federal Mineral Ownership is a binary variable equal to 1 if the property is within the boundaries of federal mineral ownership. Census tracts are based on U.S. Census 2010 boundaries. Standard errors are shown in parentheses and are estimated using tract-level cluster-robust inference: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Figure 1A: Close-up view of unconventional well development in southern Garfield County and northwestern Mesa County

Manuscript – 3

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A Bucket or a Sieve?

A Valuation of Views and Air Quality around Silica sand mining in Wisconsin

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Abstract

Silica sand mining has increased significantly since the beginning of the boom in unconventional oil and gas development. This increase in mining has had economic, environmental, and socio-economic impacts on local citizens. Yet, there has only been limited work exploring these issues in the academic literature. In this study, I explore how residential property buyers value the benefits and external costs of silica sand mining in Wisconsin. To my knowledge, this is the first hedonic valuation of silica sand mining in the academic literature. Evidence suggest that silica sand mining can decrease residential property sale prices through viewshed and air quality impacts. These effects are economically and statistically significant. I estimate stronger effects for those properties that are subject to both viewshed impacts and air pollution from silica sand mining. I find additional evidence that properties that are not subject to viewshed and air quality impacts appreciate in value post-mining. This suggests that there is potential for post-mining appreciation, perhaps associated with expectations of leasing-derived benefits from future on-property mining or price premiums associated with property sales to mining companies.

Keywords: silica sand mining; hydraulic fracturing; hedonic valuation; viewshed; air quality

1. Introduction

The demand for silica sand has increased measurably since the beginning of the boom in unconventional oil and gas development. Silica sand is one of the key ingredients in hydraulic fracturing, a process that has spurred significant oil and gas production from previously inaccessible shale resources. This type of sand is the most often-used proppant in hydraulic fracturing. A proppant is injected to maintain the fractures created during hydraulic fracturing (Benson and Wilson 2015). Hydraulic fracturing can require over 450 tons of proppant per well (King 2016). Although sand mined in the Midwest United States has historically been used in a variety of applications, most often in glass-making, the proportion of sand purchased by the oil and gas industry has increased over time. It comes as no surprise that silica sand mining is increasingly known as ‘frac’ sand mining.

Though the academic literature has explored many of the impacts of the unconventional oil and gas boom, there has been considerably fewer studies on local impacts associated with silica sand mining. These impacts can be both a blessing and a curse. In terms of positive impacts, the increase in demand for silica sand from the oil and gas industry has led to employment and income creation, a welcome boost for rural communities that have not recovered from the great recession (Prengaman 2012). Sand mining may also lead to growth in other sectors of the economy, including the rural rail economy (Davies 2012a). Local landowners and farmers may also receive significant signing bonuses and royalty payments from leasing their land to mining companies. Others have sold their land outright to mining companies for prices above and beyond assessed value (e.g., Davies 2012b; Lenker and Auch 2013; Dirr 2014; Mertens 2014).

Yet, these positive benefits are juxtaposed against environmental quality concerns. Despite its name, ‘frac’ sand mining involves no hydraulic fracturing and is instead extracted using surface mining techniques. This type of mining can take a significant toll on the landscape by leveling hills and causing habitat fragmentation. These mines can be very large; the average (maximum) size of permitted or operational frac sand mines in Wisconsin is 341 (4000) acres (Wisconsin Department of Natural Resources 2016). There are potential health concerns associated with increased local air pollution and ambient silica dust (e.g., Pierce 2011). Sand mines also use a significant amount of water and chemicals for sand processing (Wisconsin Department of Natural Resources 2012; Minnesota Department of Health 2014). This may lead to local water quality and quantity concerns for nearby farm owners and residents (Mundahl et al. 2014; Verburg 2014). Many stakeholder groups have petitioned silica sand mining over these environmental concerns (Pearson 2013) and some towns have passed short-term moratoria on silica sand mining (Kennedy 2013).

The focus of this paper is on the residential property market in western Wisconsin. As of 2016, there are over a hundred silica sand mines in the state, most of which are located in counties along the Mississippi River. The growth in the industry has been rapid over the last five years. In 2011 alone, the number of active sand mines doubled in the state. From 2002 to 2013, total production of sand and gravel in Wisconsin increased by around 1,100% (United States Geological Survey 2016). Figure 1 provides a map of the current extent of silica sand mining in Wisconsin. Other states that have frac-quality silica sand basins include Illinois, Iowa, Michigan, and Minnesota (Benson and

Wilson 2015), though as of 2014, Wisconsin produces over half of the United States' total production of silica sand (Content 2015).

In this paper, I use hedonic pricing theory to value the local impacts of silica sand mining in Wisconsin. This technique has a wide history of use in the economic literature and has recently been applied to understand how people value unconventional oil and gas development (e.g., Muehlenbachs et al. 2015). To my knowledge, this is the first economic study to use hedonic valuation to understand how citizens value silica sand mining's impacts.

My approach relies on regression models that relate the level of local silica sand mining to residential property sale prices. I first estimate a series of preliminary models exploring how general proximity to silica sand mining has influenced residential property sale prices from 2011 to 2016. I then explore the potential for heterogeneous impacts by impact of mine. I focus on the capitalization of viewshed impacts and air quality impacts associated with mining. These are two of the major environmental costs of sand mining. I differentiate the effect of mining by whether or not it is in view of the residential property. I hypothesize that having to view mining activity may negatively influence sale price beyond the effect of mere proximity. My approaches are similar to those used in the hedonic valuation of the impact of wind turbine views on housing prices (e.g., Heintzelman and Tuttle 2012; Gibbons 2015).⁴¹

⁴¹ This work builds on an extended literature incorporating property views into hedonic valuation models. Much of this literature has focused on views of environmental amenities or natural land uses (see Bourassa et al. 2004 for an extensive review). More recent work has focused on viewshed impacts associated with energy infrastructure, including wind turbines and nuclear energy stations (e.g., Heintzelman and Tuttle 2012; Dickes et al. 2013; Lang et al. 2014; Gibbons 2015).

Following this analysis, I explore how air pollution and dust from mines influence the sale price of residential properties. Given the rural character of my study area, I do not have spatially-explicit air pollution data. Instead, I use an indicator of cardinal direction away from each mine as a proxy for likelihood of air pollution associated with mining. I argue that those properties on the eastward side of sand mines are more likely to be impacted by dust and particulates from mining activity. An estimated differential effect between properties in opposite directions away from the mine is likely to be connected with greater air pollution effects on the eastward side of mines.

In my preliminary models, I find only weak evidence that silica sand mining has a significant impact on residential property prices. When I differentiate by whether a property is in-view or out-of-view of a mine, my results suggest that sand mining has a negative impact on sale prices for those properties in-view of a mine. Each in-view frac sand mine within two to four miles of the properties is associated with a 6 to 11% decrease in property sale price. However, I do not find a significant impact of sand mining that occurs within one mile of the property. Out-of-view sand mining generally has positive effects on sale price, but these are not significant.

My hypothesis regarding air quality impacts is supported by my findings. Sand mining from the west can have a negative impact on sale prices of downwind residential properties. At the same time, I find significant evidence of appreciation for properties that are upwind of mining activity. Each eastward sand mine within a mile of a property is associated with an increase in property sale price of 12%. This effect decreases to around 10% for mines within one to two miles and to 3-4% for mines within two to four miles. These effects are much stronger than the effects for corresponding westward mines.

Given the above results, I examine how silica sand mining influences residential properties across indicators of both views of and the direction of mining activity.

Estimates suggest that silica sand mining from the west significantly reduces residential property sale price, though the effect is considerably stronger for those properties that are in view of a sand mine. I also find sale price appreciation for residential properties that are out-of-view of eastward sand mining.

My results are suggestive of highly-localized positive capitalization of mining, as well as significant negative capitalization of viewshed and air quality impacts for those properties that are close but not adjacent to sand mining. Appreciation associated with silica sand mining makes sense, as Wisconsin sand mines have expanded outward over time⁴² and mining companies have been active in leasing or buying land outright for mining (e.g., Davies 2012b; Dirr 2014). Appreciation may be linked to (1) property sales to mining companies at prices above assessed values, or (2) expectations for this type of sale price premium in the future (especially for those properties that are in close proximity to mining activity but have not been sold to mining companies yet). It may also be linked to property price compensation packages used by frac sand mine companies to alleviate concerns from local residents regarding property price impacts. These packages are used to compensate property owners for any losses in value, post-mining. According to an unnamed county councilman in western Wisconsin, a sand mining company will typically pay a premium over the listing price if a nearby residential property is unsold six months after listing. It is currently unclear how often this type of transaction occurred

⁴² Based on aerial footprints of mines across time from Ted Auch, FracTracker Alliance.

in our data set. If it happened often, it may contribute to my findings of no change in price or appreciation for certain properties.

At the same time, depreciation associated with silica sand mining appears to be driven by both view and air quality changes. This is especially true for those properties that are close but not adjacent to mining activity. Since I do not find any significant evidence of environmental costs being capitalized within one mile, it seems as though the benefits of mining are highly localized around mines but the costs are diffused outwards from the mine to at least four miles away.

To my knowledge, this is the first economic study to explore the economic impacts related to silica sand mining (concurrent with Kalinin et al. 2016). Although Parker and Phaneuf (2013) provide a discussion of the potential impacts of silica sand mining on property prices, their insights were based on price impacts associated with other types of industrial activity. My results provide additional context of the mining-driven changes that have occurred in rural areas of Wisconsin. I move beyond the literature review and provide estimates of the impact of silica sand mining on nearby property prices. Despite the recent slowdown in drilling, oil and gas development using hydraulic fracturing is expected to continue in the future (United States Energy Information Administration's Annual Energy Outlook 2015). As a result, 'frac' sand mining is likely to continue to be an issue in rural Wisconsin. Understanding how the impacts of this type of sand mining are valued by local homeowners will be an important topic into the foreseeable future. This study provides an important first step in understanding how and why silica sand mining is capitalized into housing prices and valued by homebuyers.

This paper is structured in the following manner. In Section 2, I provide background on silica sand mining and its economic, environmental, and socio-cultural implications. In Section 3, I discuss my study area of western Wisconsin and outline my data. In Section 4, I highlight my methodological approach. In Section 5, I present my empirical results and finish with some brief conclusions in Section 6.

2. Background

2.1. Silica sand mining in Wisconsin

Although sandstone basins are located in many areas of the United States, the sandstone deposits in Wisconsin have characteristics that make it ideal in hydraulic fracturing applications. This sand has a high silica content and mostly consists of quartz, which is very hard (7.0 on the Mohs scale). As a result, it is able to resist pressure and hold open fractures from hydraulic fracturing. The sand deposits in the region are also generally close to the surface. This is in part a result of the fact that this general area of Wisconsin avoided significant glaciation during the last ice age.⁴³ This anomaly has made it easier for companies to access and retrieve the sand through surface mining (Benson and Wilson 2015).

2.2. Silica sand mining and its impacts

Academic research on the economic and socio-cultural impacts of silica sand mining has been fairly limited. Deller and Schreiber (2012) explore the relationship between general mining activity and various economic and socio-cultural variables, though their methodology was unable to differentiate silica sand mining from other types of mining. They also use county-level data at the national scale. Other economic studies

⁴³ This is why this area of Wisconsin is known as the “Driftless Area” (Benson and Wilson 2015).

have been either non-academic or associated with stakeholder group funding. Power and Power (2013) raise caution over high expectations of economic impact from silica sand mining, but their suggestions are extrapolated from general mining activity across the United States and rest of the world. Using IMPLAN and data from Illinois' LaSalle County, Harger (2015) estimates large direct and indirect employment and income effects from local silica sand mining.⁴⁴ In a review of literature related to the economic and environmental impacts of industrial activity and mining, Parker and Phaneuf (2015) suggest that silica sand mining may negatively impact property values and tourism in Pepin County, Wisconsin. However, this conclusion was based on anecdote and insights from the hedonic valuation literature of general industrial activity.

In the sociology literature, Pearson (2013) highlights community expectations regarding the financial and employment benefits of silica sand mining versus the environmental costs received by the general public in the vicinity of the mines. Although some rural landowners may receive hundreds of thousands of dollars for selling their land to mining companies, he generally describes the local community as opposed to silica sand mining on environmental, public health, and socio-cultural grounds. In later work, Pearson (2016) argues that the rapid pace and intensity of silica sand mining can reduce residents' sense of place and community.

A number of studies have explored the environmental impacts of silica sand mining. Air pollution and increased silica dust in the local atmosphere is a prominent concern in public media, though studies have found mixed results regarding the magnitude of impact. Richards and Brozell (2015) were unable to detect differences in

⁴⁴ As a note, this work was funded by the LaSalle County Mining Coalition and the Illinois Associate of Aggregate Producers.

upwind/downwind respiratory crystalline silica levels. However, Walters et al. (2015) found PM_{2.5} levels above the Environmental Protection Agency's annual standard. Although each silica sand mine can use as much as 2.5 million gallons of water a day (Wisconsin Department of Natural Resources 2012) and silica sand mining may change groundwater aquifer recharge (Parsen and Gotkowitz 2013), there have been no studies that evaluated pre and post-mining water quality in areas around silica sand mines. However, in 2012, 20% of active mines and processing plants in Wisconsin were cited for environmental violations (Prengaman 2013). Locke (2015) argues that this is an increasing concern given that silica sand mines are often located in unzoned areas without formal planning procedures.

2.3. Related hedonic valuation literature

There is a relatively limited literature on the hedonic valuation of mining activity or its associated impacts. In early work, Hitzhusen et al. (1997) use lakeside property prices to estimate the economic cost of pollution associated with abandoned strip mines in Ohio. Their results indicate that close proximity to abandoned mines reduces the sale price of properties. In later work, Damigos (2006) describes a National Resource Damage Assessments that used hedonic valuation to value environmental costs of the Eagle Mine in Colorado. The mine reduced sale price by \$25,000 for those properties within six miles. Williamson et al. (2007) explore the property price impacts associated with acid mine drainage-impaired streams in West Virginia. They observe impacts of -\$4,800 for those properties located within a quarter-mile of an impaired stream.

To my knowledge, there are no studies using hedonic valuation to infer how residents value the impacts of silica sand mining. Although Parker and Phaneuf (2013)

discuss some of potential implications of mining on housing prices, their insights are based on a survey of the related literature on other types of mining and industrial activity.

3. Data

3.1. Study Area

My study area is focused in thirteen counties in western Wisconsin (Figure 2). These counties are primarily rural with some scattered larger cities and towns, including Chippewa Falls, Eau Claire, La Crosse, Marshfield, and Sparta. All counties overlay sandstone formations that are sources of ‘frac’ sand and have experienced recent mining. There are 95 ‘frac’ sand mines within the counties (out of 101 in the entire state). Many of these mines were permitted between 2011 and 2016. Only seven of the mines were permitted for reclamation prior to the mid-2000s, which is generally agreed as the starting point to the boom in unconventional oil and gas development (Bauer 2014). There is some limited evidence that another sixteen mines were in place in 2004, based on aerial imagery from the National Agriculture Imagery Program (NAIP). However, this evidence is highly subjective, as it is difficult to differentiate mining and agriculture in aerial imagery.

3.2. Data

I use real estate transfer data from the Wisconsin Department of Revenue. This data set includes all residential property transfers that occurred in Wisconsin since the beginning of 2011. I only include those properties where the buyer and seller have no prior relationship and where the seller has not retained any rights associated with the property (e.g., a life estate or conservation easement). I also exclude multi-family properties. To avoid using non-fair market value property sales, I cut all property

transactions with sale prices less than \$20,000. After these cuts, I have 33,843 property transactions in my study area.

Although this data set contains all residential property transactions since 2011, it includes only a limited amount of property information. It comprises no information on the structural characteristics of the property beyond whether it is a mobile or multi-family home. However, I did receive structural characteristic data for a limited number of properties from Chippewa, Eau Claire, Jackson, Monroe, and Trempealeau. This information was provided by some of the state's regional Multiple Listing Services. A limitation of this data is that only those observations that were listed through the Multiple Listing Service were included in their databases. For each county in my data set, only 30 to 60% of my observations have matching MLS data. Thus, I incorporate this data only as a robustness check for my main models.

Using each property's unique parcel identification code, I supplement my data from the DOR by creating a rich dataset of locational information. I calculate the distance to the closest perennial stream from the National Hydrography Dataset. I also calculate the distance to the closest railway line and interstate highway (from the U.S. Census Bureau, circa 2010). I calculate each property's average elevation using data from the Natural Resource Conservation Service's Data Gateway. I use land cover data from the National Land Cover Dataset (NLCD) 2011 to calculate the average agricultural and forest land cover in and around each parcel.⁴⁵

⁴⁵ The parcel data that I used was not amenable to calculating statistics within parcel boundaries due to some overlapping parcel boundaries. Thus, I used focal statistics in ArcGIS and calculated local statistics within 500 meters around each parcel's centroid. For example, instead of calculating the percentage of each parcel in an agricultural use, I calculated the percentage of land in an agricultural use within a 500m buffer of each parcel's centroid.

I received silica sand mining location data from the Wisconsin Department of Natural Resources.⁴⁶ This data set included 127 silica sand mining locations, including mines, processing and drying plants, rail stations, and resin coating facilities. I only consider those facilities classified as performing at least some mining activity (N = 101). All other facilities are dropped from the analysis.

The data set provides coordinate location and production status for all silica sand mines in the state. However, the data does not include any information on when the mines were first permitted or excavated. Most permitting and regulation of sand mining in Wisconsin is done at the local level (e.g., Schuessler 2015). Although sand mines must abide by state air and water regulations, all reclamation permitting is done either by the county or the township where the mine is located. In order to commence non-metallic mining, each company must receive a reclamation permit (Haines 2012). I received reclamation permitting dates for 93 frac sand mines in Wisconsin through correspondence with local county and township officials in zoning and land information departments.⁴⁷ I use this as my proxy for before-after status of mining for each property transaction. If a property is close to mining activity that was permitted for reclamation before the time-of-sale, then the property is considered “treated” by silica sand mining. If the mine was permitted for reclamation after the time-of-sale, then the property is considered a “control” observation since silica sand mining was not occurring at the time-

⁴⁶ Wisconsin’s Department of Natural Resources’ “Locations of industrial sand mines and processing plants in Wisconsin”, Microsoft Excel spreadsheet.

⁴⁷ There were eight frac sand mines from which I could not find associated reclamation permitting information. These eight mines were prospective mines as of January of 2016 that had only just applied for reclamation permitting.

of-sale. Thus, for all analyses in this study, properties that are “treated” with nearby sand mining are those that were sold after a mine was first permitted for reclamation.

I calculated the distance to and direction from all frac sand mines within twenty miles for all properties in my study area. I used this information to estimate the distance to the closest silica sand mine and the number of silica sand mines within different buffers of each property’s extent. Additionally, I used ArcGIS and digital elevation data to outline the viewshed of each sand mine in my study area. I estimated the local viewshed of each mine’s centroid. Unfortunately, I did not have surveyed mine boundaries that would better capture the extent of mining. The implication of this is that both my distance and viewshed estimates are likely conservative. Properties are likely closer to mining activity than what would be suggested by my distance measure and there are likely some properties that are incorrectly classified as being out of a mine’s viewshed. Future work will exploit mine boundaries aerial-digitized by Auch (2016).

4. Methodology

4.1. The effect of silica sand mining on local property prices

In my analyses, I estimate hedonic valuation models to value the impacts of silica sand mining as perceived by home buyers in western Wisconsin. This approach has a long history of use in applied economics research (see Rosen (1974) for an early outline of the model). The main idea underlying the approach is that the price of a heterogeneous good is associated with its attributes and characteristics. The price of the good can then be decomposed as a function of its characteristics. This approach is particularly useful in eliciting how homebuyers value the impacts associated with neighborhood amenities and disamenities.

My first models relate the sale price of a home to the number of silica sand mines that are within a series of distance bins away from the property:

$$(1) \ln(P_{ist}) = \beta_1 \cdot Mine(0-1)_{ist} + \beta_2 \cdot Mine(1-2)_{ist} + \dots + \delta \cdot X'_{ist} + \alpha_s + \tau_t + \varepsilon_{ist}$$

P_{ist} is the sale price of residential property i at time t in census tract s . $Mine(0-1)_{ist}$ and $Mine(1-2)_{ist}$ are equal to the number of frac sand mines within 0 – 1 miles and 1 – 2 miles, respectively, of property i at the time of sale, t (see Figure 3 for examples of frac sand mine buffers of one mile, two miles, and five miles). The β parameters reflect the percentage change of each sand mine within the given spatial area on the natural log of sale price. Although I only show counts for two rings, I also include a count of mines within 2 – 4 miles in my main specifications.

I control for property and location characteristics in X'_{ist} , as well as census tract fixed effects, α_s , and year fixed effects, τ_t . These fixed effects help control for unobservable factors that vary across space and time and may influence the likelihood of local sand mining and residential property sale price. This approach relies on the comparison of a group of properties with a nearby sale mine permitted or in operation before the sale of the property versus (1) those properties without a nearby mine at any time and (2) those properties with a nearby mine permitted only after the sale of the property.

I infer a valuation of the impacts of silica sand mining using my β parameters. In these models, I do not identify separate impacts so any valuation from these parameters is *net* of the benefits and costs of nearby mining. Given the possibility of both positive and

negative impacts associated with silica sand mining, I have no prior expectation of the signs of these parameters.

To test for the robustness of these results, I estimate the model with alternative subsets of the data. I describe each robustness check in Section 5.

4.2. The effect of silica sand mining's viewshed changes on local property prices

Next, I explore the possibility of heterogeneous impacts based on certain characteristics of the spatial relationship of each property to silica sand mining. I first estimate how changes in views associated with silica sand mining impact nearby residential property prices. The landscape and land use fragmentation impacts of silica sand mining may lead to greater property price impacts for those properties that are in sight of a nearby sand mine, *ceteris paribus*.

I estimate the following regression model:

$$(2) \quad \ln(P_{ist}) = \beta_1 \cdot \text{VisibleMine}(X - Y)_{ist} + \beta_2 \cdot \text{NonVisibleMine}(X - Y)_{ist} + \delta \cdot X'_{ist} + \alpha_s + \tau_t + \varepsilon_{ist}.$$

This distance bin-based approach is similar to that used in Tables 2 and 3 except I now differentiate these counts by whether the mines are in-view or out-of-view of the property. $\text{VisibleMine}(X - Y)_{ist}$ and $\text{NonVisibleMine}(X - Y)_{ist}$ are equal to the number of the in-view and out-of-view frac sand mines, respectively, within X and Y miles of property i at the time of sale, t . The β parameters now reflect the percentage change of each in-view or out-of-view sand mine within X to Y miles on the natural log of sale price. Although I only show counts for one arbitrary X – Y mile ring, I include multiple mine counts in my main regression models (i.e., 0 to 1 miles, 1 to 2 miles, and 2 to 4

miles). I control for property and location characteristics, census tract fixed effects, and year fixed effects.

I have no prior expectation of the sign of either β_1 or β_2 due to the potential for the environmental costs of silica sand mining to be offset by positive appreciation, perhaps due to expectations of a future sale premium from a mining company. However, I believe that these parameters may both be positive if the costs of mining are lower than any perceived financial benefits. On the other hand, they may both be negative if its costs are greater than its positive impacts. However, I hypothesize that β_1 will be attenuated if β_2 is positive or larger in absolute magnitude if β_2 is negative as a result of negative capitalization of viewshed changes due to silica sand mining.

For any given X – Y spatial area, I estimate the viewshed impact of silica sand mining by subtracting β_2 from β_1 . This value is the difference in housing price between those properties in sight of a frac sand mine versus those out of sight of a frac sand mine, post-permitting. For now, I argue that the only difference between these properties is the impact of the viewshed itself, though I relax this assumption in my discussion of later results.

To test for the robustness of my viewshed results, I estimate various alternatives of Equation 1. These models vary by different subsets of the data. I describe them in Section 5.

As an additional source of robustness, I follow Gibbons (2015) and use a slightly different approach to identification. My viewshed approach described above defines treatment using a bin framework, where I differentiate the effect of in-view and out-of-view silica sand mining across different spatial areas. I now use a strict r mile buffer

approach and limit my observations to only those within r miles of a mine at any time. I again include counts of both visible and non-visible frac sand mines, permitted prior to the sale of the property, within r miles.

$$(3) \ln(P_{ist}) = \beta_1 \cdot VisibleMines_{ist} + \beta_2 \cdot NonVisibleMines_{ist} + \delta \cdot X'_{ist} + \alpha_s + \tau_t + \varepsilon_{ist}$$

where $VisibleMines_{ist}$ is the number of visible frac sand mines located within r miles and $NonVisibleMines_{ist}$ is the number of non-visible frac sand mines located within the same distance for residential property i at time t in census tract s . β_1 and β_2 indicate the impact of each visible and non-visible sand mine, respectively, within r miles on residential property sale price. I estimate this model across alternative values of r , including integers from 1 to 4 miles.

For each buffer, I estimate two versions of Equation 3. The first model restricts the control group to only include those properties that are close to nearby mining that has not been permitted at the time-of-sale. Thus, these are properties that are close to future mining sites. By restricting my control observations to only those properties that are close to pre or post-sale mining, I avoid the potential issue of unobserved variability in housing and neighbor stock across my study area. I am more likely comparing observations in my control and treatment groups that are similar in characteristics and have experienced the same local economic and market trends.

The second version is more inclusive and does not use this restriction. This model incorporates control observations within twenty miles of present or future silica sand mining. This is the approach applied in the analyses in Tables 2 through 4. Our control observations are those properties that are either (1) close to future mining sites, as in the

first version of Equation 3, or (2) those residential properties that are outside of r miles but within twenty miles of a mine permitted before or after the time of sale.

4.4. Heterogeneity across cardinal direction

I then test for heterogeneity of impact by cardinal direction in order to get a first-order approximation of the impact of frac sand mine-driven air pollution on sale price. I use westerly and easterly cardinal direction away from the mine's meridian as a proxy for prevailing wind conditions. I hypothesize that wind blows more often to the east. Thus, those properties with westward frac sand mines are at a greater risk of air dust and pollution versus those with eastward frac sand mines.

I estimate a structurally similar model to Equation 2:

$$(4) \quad \ln(P_{ist}) = \beta_1 \cdot \text{Westward}(X - Y)_{ist} + \beta_2 \cdot \text{Eastward}(X - Y)_{ist} + \delta \cdot X'_{ist} + \alpha_s + \tau_t + \varepsilon_{ist}$$

$\text{Westward}(X - Y)_{ist}$ is the number of westward frac sand mines located within X and Y miles and $\text{Eastward}(X - Y)_{ist}$ is the number of eastward frac sand mines located within the same distance for residential property i at time t in census tract s . For each given $X - Y$ spatial area, β_1 and β_2 indicate the impact of each westward and eastward sand mine, respectively, on residential property sale price.

I again have no prior expectations of the sign of β_1 or β_2 . However, I hypothesize that β_1 will be attenuated or more negative relative to β_2 as a result of presumed higher levels of ambient dust and pollution for properties with westward-situated mining activity.

I use the difference between β_1 and β_2 as a first-order approximation of the capitalization of local air quality impacts in housing prices. The primary assumptions in this interpretation is that (1) air quality effects are felt predominately by those on the eastward side of mines, and (2) the only difference between properties on either side of the mine is the relative levels of air pollution and dust. However, a concern is that my control group - those mines with eastward mines - are likely to incur air quality impacts, as well. To the extent that my control group suffers from spillover effects associated with air quality impacts, my estimate is an underestimation of the valuation of air quality impacts of silica sand mining in housing prices.

4.4. *Heterogeneity across both viewshed and cardinal direction*

In my last series of models, I combine my indicators from Equations 1 and 3 and allow the impact of viewshed to vary based on cardinal direction from the mine. I now differentiate across two margins: (1) in-view or out-of-view of a mine, and (2) east or west of a mine (Equation 5):

$$(5) \quad \ln(P_{ist}) = \beta_1 \cdot \text{VisibleWestward}_{ist} + \beta_2 \cdot \text{NonVisibleWestward}_{ist} + \beta_3 \cdot \text{VisibleEastward}_{ist} + \beta_4 \cdot \text{NonVisibleEastward}_{ist} + \delta \cdot X'_{ist} + \alpha_s + \tau_t + \varepsilon_{ist}$$

Each variable is a separate count of frac sand mines within r miles of each potential combination of visibility and direction. Parameter interpretations are similar to those above. They represent the differential impacts of each type of mine, specified by visibility and direction, on residential property sale price.

Comparisons in parameters from β_1 through β_4 allow a more thorough exploration of the implications of air pollution and views of frac sand mines on prices for

residential properties near frac sand mines. Each combination of visibility and cardinal direction is associated with a different combination of impact. I hypothesize that β_1 will be the most negative or, if all parameters are positive, strongly attenuated parameter, due to the fact that these properties are subject to both the viewshed and air pollution impacts of silica sand mining. I also hypothesize that β_4 will be the most positive or, if all parameters are negative, strongly attenuated parameter, due to the fact that these properties do not face either the viewshed or the air pollution impacts of silica sand mining. I have no prior expectation of the relative differences between β_2 and β_3 since I do not know whether the air pollution impact (i.e., β_2) or the viewshed impact (i.e., β_3) will be more strongly valued in housing prices.

As a final note, this analysis allows us to estimate which properties are most impacted by the viewshed and air pollution impacts of silica sand mining. Although I can approximate the valuation of viewshed impacts by differencing my β_1 from β_2 or β_3 from β_4 , there may be concerns that those properties that are in view and to the east of silica sand mining are also more subject to air pollution costs than those out-of-view but also to the east of silica sand mining. This may be the case if topography serves as a source of deposition of dust for those out-of-view properties to the east of mining. In this case, the difference of β_1 and β_2 may capture viewshed impacts *and* the increased impact of air pollution based on viewshed.

With that concern acknowledged, however, I still believe that this is an important analysis. By controlling for both viewshed and cardinal direction, I obtain a more nuanced understanding of the differential impact of silica sand mining across spatial and topographical characteristics.

5. Results

5.1. *The effect of silica sand mining's viewshed changes on local property prices*

I estimate Model 1 with treatments across three different spatial areas: a 0 to 1 mile buffer, a 1 to 2 mile ring, and a 2 to 4 mile ring. I control for a quadratic function of property acreage, quadratic functions of a series of locational variables, year fixed effects, and census tract fixed effects. My locational variables include the proximities to the closest interstate highway and railroad and the percentage of land in an agricultural use within 500 meters of the parcel's centroid. I only use those observations above the 5th percentile and below the 95th percentile to reduce the potential for outlying sale prices (~\$30,000 to \$340,000).

Table 1 provides summary statistics for my main sample, as well as those properties that are within four miles of a frac sand mine, pre-sale. Properties share generally similar characteristics, though properties near silica sand mining are also closer to the interstate highway system and railroad system. This makes sense given the transportation needs of silica sand mining production and transportation.

My results in Table 2 suggest that nearby silica sand mining can have a significant and negative impact on residential property prices, though this effect seems to only exist for properties with mines located between two to four miles away. However, this effect is not statistically-significant when including census tract fixed effects. Across all models, I uncover no evidence that mining has an influence on price within two miles.

These results are somewhat surprising. The typical assumption in the literature is that environmental impacts diminish with increasing distance away from the source. In the mining context, one would expect attenuating effects of proximity to sand mining as one moves further away from mining activity. However, I find some limited evidence of

a significant effect of mining beyond two miles, but no effect of sand mining within two miles.

Since census tract fixed effects help control for unobserved differences in housing price across the study area, Column 4 in Table 2 is the preferred model. The estimate of this model suggests no significant effect of sand mining on nearby property prices. To test for the robustness of this non-result, I estimate models of Equation 1 with alternative subsets of the data. In Column 1, I relax our restriction on sale price to only exclude those observations sold for less than \$20,000. Columns 2 through 4 gradually restrict the dataset to avoid potential unobserved differences in spatially-varying characteristics that drive sale price. In Column 2, I only include observations from census tracts with sand mining activity at least within two miles away from the tract's borders. In Column 3, I exclude all observations that are outside of ten miles from the nearest sand mine. In Column 4, I only include observations from those counties from which we have structural characteristic information from the state's Multiple Listing Service databases. Lastly, I only include those observations with structural characteristic information in Column 5. In this model, I also control for quadratic functions of the number of bedrooms, number of bathrooms, and living area of the property.

My results in Table 3 provide further support for results in Column 4 of Table 2. I am unable to find any significant evidence that silica sand mining has a significant net effect on sale price. Although I find slightly larger estimates of some of our treatment effects, none of these differences are significant.

5.2. The effect of silica sand mining's viewshed changes on local property prices

My results from Tables 2 and 3 suggest that sand mining has at most a limited effect on the sale price of residential property prices. I now explore whether this finding of only a limited relationship is masking potential heterogeneity of valuation outside of a pure distance measure.

I first explore whether the impact of local silica sand mining is different for those properties that are in-view versus out-of-view of mining activity. In Table 4, I estimate four models of Equation 2. In each column, I control for property characteristics, year fixed effects, and census tract effects. In Columns 1 and 2, I restrict my control observations to be within 20 and 10 miles, respectively, of mining activity. In Column 3, I only include observations from those census tracts with sand mining activity or are within two miles of a sand mine. In Column 4, I only include those observations that have structural characteristic information from the MLS. I use these various subsets due to the fact that my study area is extensive, covering thirteen counties. There may be significant heterogeneity across the region, especially between those areas with silica sand mining and those without it.

My results in Table 4 suggest that silica sand mining can be negatively capitalized into residential properties prices if it is in-view of the property. This is especially true if the mines are located from 1 to 4 miles away from the property. I estimate that each in-view frac sand mine from 1 to 2 miles and 2 to 4 miles is associated with 5-7 and 10-11% decreases, respectively, in sale price. Most estimated effects in these two bins are statistically significant.

However, I find no statistically-significant impacts within 1 mile of the property. In fact, the magnitude of the effect of in-view silica sand mining seems to increase as one

moves further away from the property. This result is again surprising. One would expect that the impact of views would generally be smaller for properties that are further away from mining.

I find some limited evidence that out-of-view silica sand mining has a statistically-significant effect on nearby residential property prices. However, my estimates are only statistically significant for one subset of the data – only those properties in census tracts with silica sand mining – and only within the 1 to 2 mile ring. I find that effects of out-of-view mining attenuate with increasing distance away, which is the opposite of the relationship between estimated effect and distance away for in-view mining.

These results provide some insight as to why I find significant effects only beyond a certain distance away of mining activity. I find positive but statistically insignificant effects for properties within one mile of out-of-view silica sand mining. This may be driven by highly-localized expectations of financial benefits associated with silica sand mining. As one moves further away from mining, these expectations diminish, as suggested by out-of-view effects attenuating with increasing distance.

Yet, at the same time, I find that the effect of in-view mining increases with increasing distance. It is possible that those properties beyond a mile of a mine are not likely to receive financial benefits from leasing land for mining or selling land to mining companies. If this is the case, then these properties face viewshed impacts without a strong likelihood of compensation. For those properties that are in closer proximity to silica sand mining (i.e., within a mile), there may be a stronger likelihood of financial benefits, which may compensate for some of the viewshed impacts. This explanation is

speculative, but does make sense given the estimated relationships between in-view and out-of-view mining and distance away from mining activity.

As an additional form of robustness, I follow Gibbons (2015) in Table 5 and focus exclusively on those properties that are close to sand mining activity, pre or post-sale. In doing so, I differentiate those properties sold after mining occurs by visibility of the frac sand mines. Thus, I compare properties in-view and out-of-view of silica sand mining after it occurs versus properties sold in the same area, pre-mining. By focusing in such a small area, I remove the potential for omitted variable bias associated with differences between control areas without mining versus treatment areas with mining.

I estimate Equation 3 across four different buffers with radii of 1, 2, 3, and 4 miles. I include two models for each distance buffer: (1) a model that only includes a count of the visible sand mines at the time-of-sale, and (2) a model that includes counts of both visible and non-visible sand mines at the time-of-sale. I use the same control variables and fixed effects and sale price distribution from Tables 2 and 4.

All of these models suggest that visible sand mines have a negative impact on the sale price of nearby residential properties. My estimates are statistically-significant for the three and four mile buffers. I estimate that each visible sand mine within three miles is associated with a 6% decrease in sale price. This effect increases in magnitude to 7-8% at four miles.

However, I do not obtain statistically-significant effects for the one and two mile buffers. Estimates for these buffers are also smaller in magnitude than those found in the larger buffers. Although this is surprising, it matches up with what I found in Tables 2 through 4. There are two main reasons why this may be happening. First, I have a very

limited sample in these regions very close to mining activity. When I relax my econometric specification and only control for year and census tract fixed effects, I obtain stronger estimates in the -12 to -7% range that are close to statistical significance at the 10% level. Second, the potential financial benefits of silica sand mining that accrue to landowners may complicate any comparison between models across buffer sizes. In-view properties within one mile of a mine may have greater expectations of potential financial benefits from mining activity than those that are in-view of mines, but are further away. Those that are relatively far away from mining may have viewshed impacts without the potential for compensation.

5.3. Heterogeneity across cardinal direction

In Table 5, I estimate Equation 3 using the same spatial areas defined in Table 2 and 3. I follow the structure of Table 3 and use various subsets of the data in order to test for robustness of the result across different spatial restrictions. Instead of differentiating by view of mining activity, I now differentiate properties sold after mining occurs by the cardinal direction away from the frac sand mines. I hypothesize that properties with westward mines are more likely to be negatively impacts by air pollution impacts from silica sand mining than those properties with eastward mines.

Within the 2 to 4 mile ring away from the property, I generally find that each silica sand mine from the west is associated with a decrease in sale price on the order of 2 to 3%. However, I do not find significant effects for properties within two miles.

Importantly, close proximity to eastward frac sand mines is associated with an increase in property sale price, relative to pre-mining properties. This effect is statistically significant across all treatment areas. The effects attenuate with increasing distance away,

as expected. The impact of each eastward frac sand mine within a mile is on the order of 12-13%. For eastward frac sand mines located within 1 to 2 miles, the impact is on the order of 10%. From 2 to 4 miles, the effect is around 3.5%.

Negative estimates associated with westward sand mining provide supportive evidence of capitalization of air pollution and ambient dust impacts of silica sand mining. At the same time, positive estimates for eastward sand mining is suggestive of the capitalization of either (1) actual or expected property prices premiums from direct sales of land to mining companies, or (2) expected payments from leasing land for silica sand mining.

5.4. Heterogeneity across both viewshed and cardinal direction

In Sections 5.1 through 5.3, I observed that viewshed and air quality impacts influence the sale price of residential properties in close proximity to silica sand mining. I now differentiate the effect of mining by both viewshed and cardinal direction at the same time by estimating Equation 4. Each viewshed/direction combination captures a different combination of impacts: (1) westward, visible frac sand mines influence both air quality and viewshed, (2) westward, non-visible frac sand mines influence only air quality, (3) eastward, visible frac sand mines influence only viewshed, and (4) eastward, non-visible frac sand mines are subject to neither viewshed nor persistent air quality impacts.

Evidence from Table 7 largely supports earlier results. Properties subject to both viewshed and air quality impacts decrease in value across all four buffer sizes, though the effect is only statistically significant from two to four miles (8-10% for each frac sand mine). There is no effect of westward, non-visible mines. Additionally, I find evidence

of appreciation for those properties that are not impacted by either environmental cost (i.e., those properties with non-visible, eastward mines). This effect is statistically significant across all models and attenuates from 20% at 1 mile to 6% at 4 miles. My estimates are not statistically significant for eastward, visible sand mines. However, the difference in estimates for in-view and out-of-view eastward mines is suggestive of there being a strong viewshed impact on property prices.

In Table 8, I test for the robustness of my results for my four mile buffer estimates across alternative subsets of the data. My results from Table 8 generally support my results from Table 7. Parameter estimates across the models are similar to those found in Column 4. Some estimates are larger than from the main sample, but not significantly so. From these results, it appears as those the properties that are most impacted by silica sand mining are those properties that are both in-view and east of the mines. This makes sense, as they are most subject to the viewshed and air pollution impacts of silica sand mining.

6. Conclusions

Although these results are exploratory, they are meaningful as a first step in a longer analysis of the local economic impacts of silica sand mining. Overall, I find evidence of both appreciation and depreciation associated with nearby silica sand mining. My results suggest that silica sand mining's impacts on local views and air quality can be a source of depreciation in home values. Properties with westward mines decrease in value, post-mining, whether or not they have a view of the mine. In-view, westward mines have a larger influence on sale price than those out-of-view, though I am unable to find significant viewshed effects for eastward mines. This may be driven by the small number of observations with viewable, eastward mines. This may be a cause of concern

in Tables 4 and 5, where I do not control for cardinal direction of mines. If only 10% of properties are in view of a mine, I may be misattributing my effect to viewshed when it is more an air quality impact. There also may be an additive effect of air pollution for properties in view of a mine versus those without a view of a mine. Deposition of sand and particulates from mining on trees and topography may lead to greater air quality effects for properties with a clear line of sight to a sand mine. Results from Tables 7 and 8 seem to support this possibility.

Although many frac sand mines were permitted after the beginning of my dataset's timeline, I do not have a large group of pre-mining control observations near future mining sites, nor do I have a rich set of structural property characteristics from which I could use as controls in a propensity score matching analysis. This limits my ability to estimate causal relationships between silica sand mining and residential property prices. It also makes it difficult to fully understand the balance in property characteristics between those properties treated with mining and those that are not treated with mining. The same issue is evident in my comparisons of observations across different directions and views of silica sand mining. However, it is encouraging that my results are similar when I only use those observations with structural information data from the state's Multiple Listing Services.

With that said, these findings reveal an intuitive and consistent story. Silica sand mining seems to influence homebuyers, especially through viewshed and air quality impacts. These results support anecdotal evidence from local residents in Wisconsin, as well as the insights from Parker and Phaneuf (2013), that silica sand mining has environmental impacts that may manifest in housing price decreases. At the same time,

some of my results suggest the possibility of limited price appreciation. Although the mechanism is not clear, this may be due to expectations regarding future leasing activity or direct sales to mining companies for a large premium. Future work in this literature should focus on addressing the above issues to provide stronger policy information for decision-makers and stakeholders in Wisconsin and the surrounding region.

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Tables and Figures

Table 1: Summary statistics

	Properties with a sand mine			
	< 20 miles away		< 4 miles away	
Sale Price (in \$000s, CPI-adjusted to 2015)	135.0 (70.0)		129.8 (65.9)	
Distance to interstate highway	14.1 (12.1)		9.6 (10.5)	
Distance to railway	2.3 (2.8)		1.6 (2.0)	
Agricultural %	22.1 (23.2)		25.3 (23.0)	
Lot size (acres)	3.7 (8.4)		4.2 (9.3)	
# of observations	25,953		4,507	
% of properties with a sand mine...	r = 1 miles	r = 2 miles	r = 3 miles	r = 4 miles
within r miles	1.5%	6.4%	14.1%	25.0%
within r miles and in view	0.8%	2.0%	3.5%	4.9%
within r miles and to the west	1.2%	4.9%	10.9%	19.5%
within r miles, in view, and to the west	0.7%	1.7%	3.0%	4.3%

Notes: All distance variables are in miles. Distance to the closest interstate highway and railway is based on U.S. Census Bureau's Tiger Geodatabase data from 2010. Agricultural % values are based on National Land Cover Database (NLCD) 2011 data. As a note, the parcel data that I used were not amenable to calculating statistics within parcel boundaries due to some overlapping parcel boundaries. Thus, I used focal statistics in ArcGIS and calculated local statistics within 500 meters around each parcel's centroid.

Table 2: Impact of silica sand mining on nearby residential property prices

	(1)	(2)	(3)	(4)
# of mines: 0 to 1 miles	0.045 (0.065)	0.012 (0.042)	0.007 (0.042)	0.049 (0.0482)
# of mines: 1 to 2 miles	0.006 (0.031)	-0.012 (0.038)	-0.016 (0.039)	0.012 (0.0248)
# of mines: 2 to 4 miles	-0.038* (0.022)	-0.060** (0.024)	-0.067*** (0.024)	-0.013 (0.014)
# of observations	25,953	25,953	25,953	25,953
R-Squared	0.001	0.080	0.085	0.182
Property variables	N	Y	Y	Y
Year FE	N	N	Y	Y
Census tract FE	N	N	N	Y

Notes: Our variable of interest is a count variable indicating the number of sand mines within the given buffer at the time-of-sale. Observations represent single family residential properties sold from 2011 to early 2016 in our study area in Wisconsin. We truncate the data set to exclude the 5 and 95 percentiles of sale price. We only use those residential properties that are within twenty miles of a sand mine permitted before or after the sale of the home. The dependent variable is the natural log of sale price (CPI-adjusted to 2015 values). Property variables include quadratics of acreage, distance to the closest interstate highway, distance to the closest railway, and the percentage of land in an agricultural use within 500 meters of the parcel's centroid. Census tracts are based on U.S. Census 2010 boundaries. Standard errors are shown in parentheses and are estimated using tract-level cluster-robust inference: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 3: Additional robustness checks

	(1)	(2)	(3)	(4)	(5)
	No price restriction	Only census tracts w/ mines	< 10 miles away	Counties w/ structural variables	Properties w/ structural variables
# of mines: 0 to 1 miles	0.074 (0.053)	0.056 (0.048)	0.052 (0.048)	0.084 (0.071)	-0.038 (0.082)
# of mines: 1 to 2 miles	0.016 (0.021)	0.015 (0.024)	0.017 (0.025)	0.021 (0.034)	0.003 (0.029)
# of mines: 2 to 4 miles	-0.018 (0.015)	-0.014 (0.014)	-0.007 (0.013)	-0.027 (0.018)	-0.021 (0.020)
# of observations	28,703	14,783	11,167	10,552	4,039
R-Squared	0.185	0.148	0.136	0.157	0.543
Property variables	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y
Census tract FE	Y	Y	Y	Y	Y

Notes: This table is used to test for the robustness of my results in Table 2. In Column 1, I include no price restrictions. In Column 2, I only include observations from those census tracts that contain or are within two miles of a frac sand mine. In Column 3, instead of only cutting observations that are beyond twenty miles away from a sand mine, I now additionally cut those beyond ten miles away from a mine. In Column 4, I only include observations from counties from which I received property structural data from the state's Multiple Listing Services (i.e., Chippewa, Eau Claire, Jackson, Monroe, and Trempealeau). In Column 5, I only include those observations from Column 5 for which I have structural data. I control for these variables, including the number of bedrooms, bathrooms, and the finished living area of the property. Census tracts are based on U.S. Census 2010 boundaries. Standard errors are shown in parentheses and are estimated using tract-level cluster-robust inference: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 4: Impact of silica sand mining on nearby residential property prices, by visibility

	(1)	(2)	(3)	(4)
	< 20 miles	< 10 miles	Only census tracts w/ mines	Only properties with structural chars.
Control obs. Buffer				
# of in-view mines: 0-1 miles	0.021 (0.076)	0.025 (0.077)	0.022 (0.076)	-0.038 (0.076)
# of out-of-view mines: 0-1 miles	0.067 (0.058)	0.075 (0.057)	0.072 (0.058)	-0.053 (0.117)
# of in-view mines: 1-2 miles	-0.071* (0.042)	-0.064 (0.041)	-0.070 (0.042)	-0.052 (0.033)
# of out-of-view mines: 1-2 miles	0.032 (0.022)	0.033 (0.022)	0.037* (0.022)	0.021 (0.029)
# of in-view mines: 2-4 miles	-0.107*** (0.030)	-0.103*** (0.029)	-0.099*** (0.031)	-0.110*** (0.039)
# of out-of-view mines: 2-4 miles	-0.0003 (0.013)	-0.002 (0.013)	0.005 (0.012)	-0.005 (0.020)
# of observations	25,953	14,783	11,167	4,039
R-Squared	0.183	0.151	0.140	0.546
Property variables	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Census tract FE	Y	Y	Y	Y

Notes: My variable of interest are a series of count variables indicating the numbers of in-view and out-of-view sand mines within given buffers at the time-of-sale. Observations represent single family residential properties sold from 2011 to early 2016 in our study area in Wisconsin. I include only those observations that overlay a sandstone basin with sand suitable for hydraulic fracturing. I truncate the data set to exclude the 5 and 95 percentiles of sale price. The dependent variable is the natural log of sale price (CPI-adjusted to 2015 values). Property variables include quadratics of acreage, distance to the closest interstate highway, distance to the closest railway, and the percentage of land in an agricultural use within 500 meters of the parcel's centroid. I include year fixed effects and census tract fixed effects. Columns 1 and 2 restrict our control observation subset to be located within 20 and 10 miles, respectively, of a mine at any time. Column 3 only includes observations from those census tracts that contain or are within two miles of a frac sand mine. Column 4 only includes those observations with structural data from the Multiple Listing Services in Wisconsin. I control for these variables, including the number of bedrooms, bathrooms, and the finished living area of the property. Census tracts are based on U.S. Census 2010 boundaries. Standard errors are shown in parentheses and are estimated using tract-level cluster-robust inference: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 5: Alternative visibility approach using r-mile buffers

	(1)	(2)	(3)	(4)	(5)	(6)	(5)	(6)
Buffer = r miles	1 mile		2 mile		3 mile		4 mile	
In-view mines < r miles	-0.047 (0.102)	0.020 (0.081)	-0.025 (0.040)	-0.051 (0.038)	-0.060* (0.030)	-0.065** (0.029)	-0.073*** (0.025)	-0.082*** (0.026)
Out-of-view mines < r miles	-0.033 (0.089)	0.074 (0.058)	0.018 (0.020)	0.041* (0.024)	-0.002 (0.013)	0.018 (0.015)	0.0003 (0.010)	0.011 (0.011)
# of observations	471	25,953	1,777	25,953	3,513	25,953	5,432	25,953
R-Squared	0.316	0.182	0.247	0.182	0.201	0.182	0.181	0.183
r-mile limit for controls	Y	N	Y	N	Y	N	Y	N
Property variables	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
Census tract FE	Y	Y	Y	Y	Y	Y	Y	Y

Notes: In this table, I continue to explore the impact of views of silica sand mining on residential property sales. In odd columns, I only include those properties within r miles of a frac sand mine, pre and post-mining. In even columns, I do not make the above restrictions for control observations. In these columns, I use all observations with twenty miles of a sand mine, conditional on sale price and property type restrictions. My controls are the same as those used in Table 2. Standard errors are shown in parentheses and are estimated using tract-level cluster-robust inference: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 6: Impact of silica sand mining on nearby residential property prices, by cardinal direction

	(1)	(2)	(3)	(4)
	< 20 miles	< 10 miles	Only Census Tracts w/ mines	Only properties with structural chars.
# of westward mines: 0 to 1 miles	0.018 (0.053)	0.023 (0.052)	0.021 (0.052)	-0.061 (0.090)
# of eastward mines: 0 to 1 miles	0.125* (0.072)	0.131* (0.074)	0.124* (0.074)	0.034 (0.064)
# of westward mines: 1 to 2 miles	-0.025 (0.032)	-0.022 (0.031)	-0.020 (0.032)	-0.014 (0.031)
# of eastward mines: 1 to 2 miles	0.097*** (0.026)	0.097*** (0.026)	0.103*** (0.025)	0.050 (0.044)
# of westward mines: 2 to 4 miles	-0.033** (0.015)	-0.032** (0.015)	-0.025 (0.015)	-0.029 (0.021)
# of eastward mines: 2 to 4 miles	0.0346* (0.0189)	0.030 (0.019)	0.036** (0.017)	0.014 (0.028)
# of observations	25,953	14,783	11,167	4,039
R-Squared	0.183	0.150	0.139	0.544
Property variables	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Census tract FE	Y	Y	Y	Y

Notes: In this table, I explore the effect of silica sand mining based on whether it is westward or eastward of a property. I do this in an effort to understand how air pollution and ambient dust levels influence sale price. My indicator of cardinal direction is based on the direction field for each frac sand mine in our data set. I hypothesize that residential properties with frac sand mines that are situated to the west are more likely to be negatively influenced by air pollution and ambient dust. Columns 1 and 2 restrict our control observation subset to be located within 20 and 10 miles, respectively, of a mine at any time. Column 3 only includes observations from those census tracts that contain or are within two miles of a frac sand mine. Column 4 only includes those observations with structural data from the Multiple Listing Services in Wisconsin. I control for these variables, including the number of bedrooms, bathrooms, and the finished living area of the property. Standard errors are shown in parentheses and are estimated using tract-level cluster-robust inference: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 7: Impact of silica sand mining on nearby residential property prices, by view and cardinal direction

	(1)	(2)	(3)	(4)
Buffer	1 mile	2 mile	3 mile	4 mile
Visible, westerly sand mine	0.011 (0.090)	-0.078* (0.041)	-0.092*** (0.029)	-0.104*** (0.028)
Visible, easterly sand mine	0.068 (0.121)	0.074 (0.061)	0.056 (0.046)	0.032 (0.039)
Non-visible, westerly sand mine	0.022 (0.061)	0.003 (0.031)	-0.016 (0.018)	-0.010 (0.012)
Non-visible, easterly sand mine	0.202*** (0.071)	0.121*** (0.029)	0.092*** (0.025)	0.056*** (0.018)
# of observations	25,953	25,953	25,953	25,953
R-Squared	0.182	0.183	0.183	0.184
Property variables	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Census tract FE	Y	Y	Y	Y

Notes: In this table, I differentiate the effect of mining on residential property sale price by both views and air quality level. Each variable represents a count of one combination of viewshed level (i.e., in-view or out-of-view of a frac sand mine) and cardinal direction (i.e., eastward or westward of a frac sand mine). I again only include those properties within r miles of a frac sand mine, pre and post-mining. Thus, I am comparing those observations with westward, visible mines; westward, non-visible mines; eastward, visible mines; and eastward, non-visible mine, post-mining, to observations close to the future, but not current, mines, and observations that are relatively far way (> 2 - 4 miles, depending on model) from mining activity. My controls are the same as those used in Table 2. Standard errors are shown in parentheses and are estimated using tract-level cluster-robust inference: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 8: Robustness checks for four mile buffer models

	(1)	(2)	(3)	(4)	(5)
	No price restriction	> 10 miles	Only census tracts w/ mines	Counties w/ structural variables	Properties w/ structural variables
Visible, westerly mine	-0.105*** (0.028)	-0.099*** (0.028)	-0.099*** (0.029)	-0.111*** (0.035)	-0.091*** (0.030)
Visible, easterly mine	0.066 (0.066)	0.026 (0.037)	0.039 (0.039)	0.072* (0.042)	-0.010 (0.099)
Non-visible, westerly mine	-0.007 (0.014)	-0.011 (0.012)	-0.004 (0.011)	-0.013 (0.018)	-0.010 (0.023)
Non-visible, easterly mine	0.043** (0.020)	0.053*** (0.018)	0.058*** (0.016)	0.062** (0.029)	0.027 (0.030)
# of observations	28,703	14,783	11,167	11,009	4,039
R-Squared	0.187	0.152	0.141	0.152	0.546
Property variables	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y
Census tract FE	Y	Y	Y	Y	Y

Notes: In this table, I test for the general robustness of our results from Column 3 in Table 7, using a four mile buffer. In Column 1, I do not use a sale price restriction. In Column 2, I only use those observations that are within ten miles of a mine. In Column 3, I only use those observations from census tracts that contain or are within two miles of a frac sand mine. In Column 4, I include observations from only those counties from which we received limited structural information. In Column 5, I only include those observations from which we received limited structural information. I control for quadratics of the number of beds, the number of bathrooms, living area, and acreage. I also include year fixed effects and census tract fixed effects. I relax our control variables and do not include any locational variables (e.g., distance to interstate highway) due to our small sample size. Standard errors are shown in parentheses and are estimated using tract-level cluster-robust inference: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Figure 1: Silica sand regions in Wisconsin

Notes: Silica sand mine locations are from the Wisconsin Department of Natural Resources. I followed Locke (2015) in her work on silica sand mining and zoning to determine the boundaries of silica sand basins. These boundaries are based on Wisconsin Department of Natural Resources and United States Geological Survey data. Wisconsin DNR data was used to understand the location of different types of bedrock, including sandstone, while the USGS data was used to classify the sandstone's age. Only those sandstone basins from the Cambrian and Ordovician ages are shown.

Figure 2: Study area in western Wisconsin

Notes: Silica sand mine locations are from the Wisconsin Department of Natural Resources. My study area includes Barron, Buffalo, Chippewa, Clark, Dunn, Eau Claire, Jackson, Monroe, Pepin, Pierce, St Croix, Trempealeau, and Wood counties.

Figure 3: Silica sand mining buffers

Notes: This figure shows examples of distance buffers around silica sand mines in our sample. Silica sand mine locations are from the Wisconsin Department of Natural Resources.

Technical Appendix

Each manuscript of my dissertation relies heavily on hedonic valuation. This technique was first outlined by Rosen (1974) and has a long history of use in the economics literature. In this technical appendix, we describe the methodology's theoretical underpinnings and its key assumptions. We discuss the first and second stages of hedonic valuation in turn.

First Stage of Hedonic Valuation

Hedonic valuation is based on the idea that a good's price is related to levels of its characteristics. This approach is only relevant to those classes of projects that are differentiated in characteristics. This makes sense, as goods with homogeneous characteristics would all sell at the same price. Two examples of goods that are differentiated in terms of their characteristics include residential houses and automobiles. All residential houses have beds and bathrooms, but the level of these assets varies across houses. Some residential properties have two bedrooms; others have three bedrooms. On the other hand, automobiles vary in size, miles per gallon, and interior options. Some automobiles have leather interiors, while others have basic fabric interiors.

These and other characteristics of these types of goods influence sale price. Residential property prices are generally higher for properties with more bedrooms; automobile prices are higher for cars with a sunroof. These types of characteristic-price relationships form the logic behind hedonic valuation. By exploring how sale prices change in response to changes in characteristics, one can decompose how each characteristic influences the good's ultimate price at the margin.

How is a hedonic price function formed in a competitive market setting?

Following Rosen (1974) and Freeman (2003), consider a hypothetical housing market where each house is decomposed into vectors of its characteristics:

$$(1) \ h = (S, N, E) .$$

Characteristics of houses are included in three vectors: S includes structural characteristics, such as the number of bedrooms, number of bathrooms, and acreage of the property; N includes neighborhood characteristics, such as local school quality, proximity to local grocery stores, and local crime levels; and E includes environmental characteristics, such as the level of surrounding tree cover, air quality levels, and proximity to local parks and greenspaces.

These characteristics are important in determining sale prices because they provide utility to the consumer.

$$(2) \ U(S, N, E, x) .$$

x is an index to represent all other utility-bearing goods consumed. Thus, consumers essentially face a trade-off between characteristics associated with the house and what they could buy in terms of all other goods. It is generally assumed that homebuyers have perfect information regarding the level of these characteristics.

In this housing market, consumers are presented with a sufficiently large number of options such that he or she can choose which house has the desired levels of characteristics in terms of maximizing utility. Subject to their income, it is assumed that consumers can locate anywhere in the market and that there are no transaction costs associated with re-location.

It is also assumed that consumers cannot repack goods through arbitrage. This condition is important in that it ultimately leads to marginal prices that are non-linear. This forbids consumers from buying two houses with different characteristic combinations at a lower price than if they had only bought one house with the combined characteristics from the two houses. As a result, the budget constraint for the consumers is nonlinear: the marginal price of a characteristic is positive but decreases with increasing levels of the characteristic.

Consumers are price-takers and observe price, $p(h_i)$, which is a function of property characteristics:

$$(3) \quad p(h_i) = p(S_i, N_i, E_i)$$

In determining which house to buy, they consider each good's bundle of characteristics and their relationships to house price, conditional on their household budget, y :

$$(4) \quad y = p(Z_i) + x$$

For simplification purposes, we combine S_i , N_i , and E_i into a single vector of house characteristic, Z_i . Equation (4) states that what a consumer does not spend on a home is spent on all other goods, x .

One can solve the utility-maximization using consumer optimization, which yields:

$$(5) \quad \frac{\partial p}{\partial Z_i} = \frac{\partial U / \partial Z_i}{\partial U / \partial x}$$

Equation (5) states that the implicit price of a particular house characteristic is equal to the ratio of the marginal utility of the house characteristic and the marginal utility of the numeraire good.

Given Equations (2) and (4) above, consumers spend their budget to receive utility from consumption of a house, represented by Z_i , and the numeraire good, x . Each consumer chooses their consumption of house characteristics and the numeraire good to maximize their utility, subject to their non-linear budget constraint. Various combinations of Z_i and x provide the same level of utility. These combinations represent indifference curves:

$$(6) \quad U(Z_i, x) = u.$$

Consumers select a package that provides the highest level of utility and is tangent to the nonlinear budget constraint. The consumer's utility function U is strictly concave and is a function of the numeraire good and the characteristics associated with the given house:

$$(7) \quad U(y - \theta; z_1, z_2, \dots, z_n) = u$$

Rosen (1974) connects this utility function to bid functions, $\theta(h_i)$. Bid functions highlight one's maximum willingness to pay for a particular house, Z_i , with utility-bearing characteristics, z_1 through z_n :

$$(8) \quad \theta(z_1, z_2, \dots, z_n; u, y).$$

Utility, u , is held constant in any given bid function. Thus, this function represents a substitution between the level of characteristics within the chosen bundle and the amount of y used to pay for the bundle while receiving the same utility. This essentially reflects the budget tradeoff between money spent on a house characteristic versus money spent on all other goods.

The slope of the bid function is the marginal rate of substitution between the house characteristic and the numeraire good (i.e., Equation 5). Thus, the bid function θ increases in value with increases in characteristic z_j but at diminishing rates. Holding utility and income constant, the derivative of the bid function represents a consumer's marginal willingness to pay for z_j .

Each consumer faces a market-clearing price of $p(Z_i)$ for any given house Z_i . For each individual characteristic z_j and holding all other characteristics constant, the optimal bundle Z^* occurs where the partial derivative of the hedonic price function with respect to characteristic z_j is equal to the consumer's marginal willingness to pay for that attribute (Equation 9):

$$(9) \quad \frac{U_{z_j}}{U_x} = \theta_{z_j} = p_{z_j}(Z_i^*)$$

At this optimal bundle, the bid function lies tangent with the hedonic price function.

$$(10) \quad p(Z_i^*) = \theta(Z_i^*; u^*, y)$$

In Figure 1 below, we show two buyers with different bid functions for characteristic z_1 . The solution for each buyer to maximize utility lies at a tangency point

along the hedonic price function. Each buyer has different tastes for characteristics, which can be represented in their utility functions. From Figure 1, Buyer #2 has stronger tastes for Z_1 than Buyer #1, and thus purchases more Z_1 .

We have discussed the hedonic valuation framework from the perspective of consumers. This represents only one side of the market. We now outline the hedonic valuation framework from the perspective of producers or suppliers of houses. It is only through a combination between buyers and sellers that a hedonic price function is formed through pairs of bid functions and offer functions meeting at tangents with one another.

Instead of focusing on utility-maximization, producers maximize profit. Each firm produces M houses of specification, Z_i . Each house specification Z_i includes a series of characteristics, which correspond to the consumer problem (i.e., $z_1, z_2, \dots, z_n$).

Total costs associated with producing these houses are $C(M, Z_i; \beta)$, where β is a series of parameters that are in the cost minimization function for the producer (e.g., factor prices). There are no fixed costs associated with being in business without production. The cost to produce a particular specification increases with increasing characteristics (i.e., $C_{Z_i} > 0$) at a non-decreasing rate.

Each firm maximizes profit by choosing specification and the number of houses to produce:

$$(11) \quad \pi = M \cdot p(Z_i) - C(M, z_1, z_2, \dots, z_n),$$

where $p(Z_i)$ is the hedonic price function. Each firm faces the same price schedule since firms are competitors and are unable to change prices by adjusting M .

Each firm chooses specification Z_i and M based on (1) equalizing marginal revenue and marginal cost of additional characteristics and (2) producing M number of specifications such that unit revenue $p(Z_i)$ equals marginal production cost per house:

$$(12) \quad \frac{\partial p(Z_i)}{\partial z_j} = \frac{C_{z_j}(M; z_1, z_2, \dots, z_n)}{M}$$

$$p(Z_i) = C_M(M; z_1, z_2, \dots, z_n)$$

We now define an offer function which indicates the price a firm is willing to accept for the housing bundle, Z_i , given a profit level of π .

$$(13) \quad \phi(z_1, z_2, \dots, z_n; \pi, \beta)$$

This offer function is analogous to the bid function from the consumer problem. It represents the amount of money needed to be received from providing house bundles with varying attributes while holding profit constant. It can be substituted into Equation 10.

$$(14) \quad \pi = M\phi - C(M; z_1, z_2, \dots, z_n).$$

Similar to the consumer problem, profit-maximizing firms will adjust the specification of Z_i in order to receive the highest profit possible. Producers maximize their offer price subject to the market-clearing hedonic price function, which is again given by $p(Z_i)$.

$$(15) \quad p_{z_j}(Z_i^*) = \phi_{z_j}(Z_i^*; \pi^*, \beta)$$

So far, we have described the consumer and producer problems separately and have assumed that $p(Z_i)$ is observed in the market by both parties. However, their decisions are not made in isolation from each other. They are made simultaneously. Consumers purchase houses, Z_i , with characteristics $z_1, z_2, \dots, z_n$ such that their utility is maximized and any deviations in characteristics lead to relative decreases in utility. At the same time, producers create properties with characteristics and levels that maximize profit at a certain sale price. Any deviations in characteristics or asking price lead to a loss in π .

In the market, each buyer is matched to a seller that is willing to sell the desired housing bundle at the buyer's willingness to pay. The agreed-on price maximizes utility for the consumer and profit for the firm. Others buyers with different tastes and preferences are also matched with sellers with different production costs. This variation leads to multiple matches between buyers and sellers all at different points along the characteristics-price frontier. These paired bid and offer functions, tangent to each other at a single point, meet and form a joint envelope that represents $p(Z_i)$, hedonic price function (Figure 1). Thus, a hedonic price function is the set of tangencies between consumers and producers of goods in the market, as represented by individual bid and offer functions.

Second Stage of Hedonic Valuation

The first two sections of Rosen (1974) describe the joint envelope of bid and offer functions from consumers and producers, respectively, which ultimately combine to

create a hedonic price function. The hedonic price function is a reduced-form equation, relating the sale price of a good to its underlying characteristics. In the applied economics literature, most researchers have focused explicitly on estimating the hedonic price function by regressing residential property price against a set of property characteristics. Partial derivatives of this function with respect to each characteristic provide marginal prices for each characteristic, which are equivalent to the marginal rate of substitution between the characteristic and the numeraire good

Yet, the hedonic price function is not a structural equation defining the supply and demand of each characteristic. The first-stage estimated hedonic price function is only relevant for welfare changes due to *marginal* changes in characteristics.

A second stage of hedonic valuation uses the estimated hedonic price relationship to infer the parameters of marginal bid and offer functions. This stage is especially important since estimates of the marginal bid function allow one to infer the welfare change associated with an exogenous, *non-marginal* change in one of the characteristics of the good. An estimated marginal bid function would allow for the assessment of welfare changes associated with large, widespread changes in characteristics that cause shifts in the hedonic price function.

Rosen (1974) recommends a two-stage least squares process to solve the following system of supply and demand functions, derived from derivatives of the bid and offer functions:

$$(16) \quad \begin{aligned} p_{z_i}(Z) &= \theta_{z_i} = F^{z_i}(z_1, z_2, \dots, z_n, \alpha) \\ p_{z_i}(Z) &= \phi_{z_i} = G^{z_i}(z_1, z_2, \dots, z_n, \beta) \end{aligned}$$

$F()$ represents a marginal demand price for characteristic z_j , which is a derivative of the bid function with respect to the characteristic. On the other hand, $G()$ is the marginal supply price for characteristic z_j , which is the derivative of the offer function with respect to the characteristic. α are exogenous variables that represent consumer-specific demographic variables, tastes, and preferences that may influence one's value function. β is a corresponding set of exogenous variables for the producer (e.g., differences in factor prices and technologies). These exogenous supplier variables are used as instruments for the marginal demand price function.

Yet, the identification of this structural model is complicated. Following Bartik (1987), the nonlinear nature of hedonic prices leads to consumers choosing both quantity consumed and marginal price. This leads to an endogeneity problem. Each consumer's marginal prices are correlated with unobserved tastes and preferences. These tastes and preferences lead to a choice of housing bundle that is indirectly correlated with producer characteristics. Thus, the instruments used for identification are correlated with the residuals in the marginal demand function.

There have been multiple strategies proposed to circumvent this issue. Bartik (1987) proposes an instrumental variable approach that uses exogenous shifts in the consumer budget constraint as instruments. These instruments must be uncorrelated with unobserved consumer tastes and preferences, the main issue inherent in Rosen (1974). Kahn and Lang (1988) advise the use of data from multiple markets and then use market binary indicators as instruments. Consumers across different markets may have similar tastes and preferences but face varying marginal price schedules. The differences in these marginal price schedules are exogenous to consumer tastes and preferences. However,

the underlying assumption of this approach – that consumers in different markets have similar distributions of tastes and preferences – is questionable. More recent approaches include Ekeland, Heckman, and Nesheim (2004), Bishop and Timmins (2015), and Bishop and Timmins (2016). Ekeland et al. (2004) support the general intuitions behind the second stage approach used in Rosen (1974) and suggest two approaches to identification: (1) a non-parametric transformation approach, and (2) a non-linear instrumental variables approach. Bishop and Timmins (2015) employ a maximum likelihood approach to estimate the marginal bid function that is most likely given consumer choices and their demographic information. Bishop and Timmins (2016) apply a panel data approach where they observe multiple sales per household. Since each sale is subject to a different hedonic price function, they are able to estimate two amenity choices under different supply conditions. They use this information to infer individual-specific demand functions. Due to the computational difficulties and theoretical issues associated with estimation of the supply and demand functions in the second stage, most papers restrict their focus to estimating the hedonic price function. However, there have been limited attempts to estimate both the first stage hedonic price function, as well as the underlying demand function (e.g., Bishop and Timmons 2015; Bishop and Timmons 2016).

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Tables & Figures

Figure 1: Joint envelope of bid and offer functions

Notes: Based on a combination of Figures 1 and 2 in Rosen (1974). X-axis represents level of characteristic Z_1 . Θ_1 and Θ_2 represent marginal willingness to pay for an additional unit of Z_1 for two separate consumers with different bid functions. Φ_1 and Φ_2 represent marginal cost to prove an additional unit of Z_1 for two separate producers with different offer functions. Consumers maximize utility subject to their budget constraint and choose a level of Z_1 such that the marginal willingness to pay for additional Z_1 is equal to its marginal cost. Producers maximize profit by choosing a level of Z_1 such that the marginal revenue of an additional unit is equal to its marginal cost. These bid and offer functions form an envelope.