THE EFFECT OF SHALE ENERGY ACTIVITY ON HOUSE VALUES

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ABSTRACT

The combination of hydraulic fracturing and horizontal drilling has fundamentally raised the volume of oil and gas that can be extracted domestically in the US. Increased shale oil and gas production benefits U.S. consumers and helps boost local and regional economies. On the other hand, the costs attributed to shale activity appear to be much more localized, prompting the question of whether shale activity benefits the local communities that bear its externalities. Previous conclusions on the net impacts of shale activity on local house values have been mixed. This study analyzes the effect of shale production on typical house prices across counties in the continental U.S. from 2010 to 2019. Our findings suggest that shale activity does not significantly impact typical house prices. We deduce that at a county level, the pros and cons of shale activity related to residential real estate values appear to offset each other.

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1. INTRODUCTION

1.1. Background to Study

The implementation of hydraulic fracturing and horizontal drilling continues to catalyze the U.S. energy industry, boosting domestic oil and gas production. Over the five years that best encapsulated the shale revolution (2008-2013), U.S. onshore oil and gas production increased by 81 and 30 percent, respectively, in the lower 48 states (Fitzgerald 2014, 2). These boosts in production have enabled reductions in energy prices and subsequent advantages for the U.S. in geopolitics by undercutting the influence of OPEC and Russia in the world's market. Additionally, natural gas has a lower carbon footprint than coal when generating electricity. More localized benefits include direct leaseholder payments and possible economic benefits to community-wide employment and income. However, there has been widespread apprehension about the externalities associated with these activities within the communities directly affected. This concern has led states like New York to implement moratoriums on this unconventional extraction (Ifft and Yu 2021, 134). Ultimately, the utilization of these unconventional energy sources is dependent on the decisions of the local jurisdictions nearest the extraction, which this literature can better inform.

The controversy surrounding unconventional shale oil and gas activity emerges from the influence of its positive and negative consequences. Owners of mineral rights targeted by shale energy producers stand to benefit the most locally, with states like Pennsylvania enforcing a minimum one-eighths royalty (Sachs et al. 2020, 1446). Apart from the windfalls to mineral rights holders, local and state governments benefit from the additional revenues of imposed taxes and impact fees. Additionally, although shale oil and gas production only marginally impacts the total U.S. GDP (Kilian 2016, 203), at a more regional scale, its positive contribution to GDP can be much more pronounced among the prevalent shale regions (Ferreira 2018, 253). Similarly, regions with shale activity typically experience job market benefits, including additional jobs, lower unemployment, and higher wages (Hartley et al. 2015; Feyrer et al. 2017; Bartik et al. 2019).

However, shale activity can pollute ground waters through various channels, which poses significant concerns in regions where it is common for houses to rely on well water (Muehlenbachs et al. 2012, 2015). Another source of environmental pollution from shale activity is what gets emitted into the air, both intentionally, such as with methane flaring, and unintentionally with fugitive emissions. Air pollution from shale activity is less localized than water-source pollution, as pollution like ground-level ozone can spread up to 200 miles beyond the drill site (Colborn et al. 2011, 1042). Beyond this, combustion emissions of the drill site equipment and the required trucking further diminish local air quality and contribute to the area's carbon footprint. In terms of the most apparent impacts of shale activity on nearby residents, the disturbances to residents from well-construction and degradation of local infrastructure stand among the top of the list (Theodori 2009, 11). Noise and light pollution are sustained around the clock for several weeks by operators drilling new wells, causing sleep disturbances and various mental and physical ailments. The required trucking to sustain drilling operations brings about more than just combustion emissions; it damages local roads and increases local roadway congestion. In regions with vulnerable geology like Oklahoma, the formerly common practice of injecting wastewater from shale operations into underground wells significantly increases minor to moderate earthquakes. Substantial literature also outlines what is referred to as “the resource curse,” which proponents suggest has a long-run undoing of economic benefits due to factors like the crowding out of labor and capital investment. Finally, shale activity has been linked in past literature to increased aggravated assaults and property crimes, which is theorized to be due to the workforce that shale activity attracts (Lim 2018, 426).

1.2. Problem Statement

As unconventional shale extraction continues to expand production, this industrial activity will continue to encroach on the same area where people live, work, and play. According to Tan et al. (2022), the public is chiefly concerned about the environmental and health risks, followed by the social, economic, and safety risks associated with shale gas activity. Additionally, they find that people nearer to shale energy development are more concerned about the negative externalities. Indeed, residents in shale energy regions have expressed concerns about the potential adverse effects, disruptions to economic activities, regulatory capacity, and risk governance (Israel et al. 2015, 144). If it is proven that living amongst unconventional shale activity poses more harm than good to the local communities, policymakers must consider their response. Out of precaution, policymakers in states such as New York, Vermont, Maryland, and Washington have placed bans and moratoriums in response to such concerns. The impact on the local housing market, whether positive or negative, would have profound implications for existing and prospective homeowners. A rapid increase in population due to shale energy activity would push home values up and reduce housing affordability, making it more difficult for prospective homebuyers to enter the housing market. On the other hand, the adverse effect of shale activity would put a depreciative force on home values in shale-producing communities. Decreased property values reduce home equity, and since most homeowners finance their home purchase with a mortgage, they may end up owing more than the value of their home. House value fluctuations also affect property tax assessments. Since property taxes are assessed based in part on property values, lower house values would reduce property tax revenues for state and local governments. On the other hand, rising home values would increase homeowners' tax burden. Most previous studies have been conducted with a specific geographic scope on various regions of the U.S. that are geologically heterogeneous. This may have contributed to the inconsistent results and conclusions across the studied shale basins in the U.S. Moreover, previous studies tend to focus exclusively on either shale oil or shale gas-producing regions. The nationwide scope of this study allows us to examine the home values in both shale oil and gas-producing regions and identify the common patterns or effects. The objective of this thesis is to contribute to resolving the divergent conclusions made in the existing literature while utilizing unprecedented geographic expanse in analyzing the effect of shale oil and gas activity on local communities across the U.S. We examine the net impact of shale activity and how it is capitalized into house values, following hedonic price theory (Rosen 1974, 34). This is because all “amenities” and “disamenities” of a community become characteristics of the residing house values, which can be implicitly measured through econometric methods. To best capture these impacts at a national level, we collect county-level data from 2010 to 2019 and employ a host of panel estimation techniques, with a primary focus on dynamic panel generalized method of moments (GMM) estimation. Oil and gas activities in the U.S. have long been overseen by states that grant varying degrees of rule-making autonomy to local and county governments (Small et al. 2014, 8293). Hence, a study focusing on a specific shale play will tend to reach conclusions specific only to the communities and period studied. While this paper controls for regional and community-specific characteristics, the national scope of this thesis helps measure and compare the extent of shale energy production on local housing markets relative to the house markets outside of shale plays. This difference means that the results of this study can be more easily applied to shale booms in new plays.

1.3. Organization of Study

This thesis contains six chapters, which follow the following sequence. The next chapter is the literature review, breaking down previous literature by its associated shale basin and or by the impact investigated, separated as amenities and disamenities. In the third chapter, we establish the underlying methodology of the study, addressing both estimation techniques and strategy. In Chapter Four, we detail the data used in the study, where the various sources of the data and corresponding summary statistics are provided. Chapter Five addresses the study's results, informing Chapter Six's conclusions and policy implications.

2. LITERATURE REVIEW

2.1. Overview of Unconventional Shale Oil and Gas Extraction

The process of hydraulic fracturing, also known as “fracking,” involves pumping a fluid mixture of water, sand, and chemicals at high pressure into fractures of target formations, often shale nested deep below the surface. Shale formations are the source rock containing organic matter or the producing formation where natural oil and gas are produced. Since oil and gas in shale formations are trapped in less permeable rocks compared to oil and gas in limestone formations, their extraction was only made economically viable upon the introduction of fracking techniques (U.S. Energy Information Administration 2021, 17). Fracking overcomes this permeability issue by opening new pathways in the rock for oil and gas to flow. However, fracking is just a part of the unconventional nature involved with the wells typically used atop shale formations. Fracking has been most valuable when paired with horizontal wells. As their name implies, horizontal wells are drilled horizontally upon contact with the shale formation/reservoir. This creates more exposure to the source rock, allowing previously unexploitable shale formations to be tapped into, albeit at higher costs than vertical wells (Fitzgerald 2013, 1342). The cost of drilling a single horizontal well mainly depends on the depth and, therefore, the number of stages of drilling required to reach the “kickoff point,” but the costs can exceed upwards of $2.5 million (Ground Water Resources Council 2009, 47).

The process of unconventional drilling can be broken down into five sequences. First is the well pad site development, which is when several acres of land are cleared, access roads are built, and ancillary facilities are constructed. Each well pad allows for numerous wells to be drilled within it. Completing the well pad site allows for vertical drilling, which involves using a rigid pipe to form a “drill string,” the column of the drill pipe that transmits fluid. Once the wellbore reaches a suitable depth below adjacent freshwater aquifers, cement and various casings are put in place to prevent water contamination. Typically, the vertical drilling section will extend 6,000 feet below the surface to reach the kickoff point, which is when the drilling turns horizontal at a 90-degree arc (Clark et al. 2012, 1). The kickoff point begins the third sequence, horizontal drilling, which grants the extractors access to shale over a mile from the vertical wellbore. Subsequently, after the horizontal drilling has reached its full horizontal length, the casing of the horizontal section is perforated to allow for the flow of fluids during the fracking sequence. Fracking then ensues and marks the fourth sequence of the drilling. Fracking must occur in stages since only a limited stretch of the wellbore can be hydraulically fractured at one time. The final sequence before production is the flowback of wastewater, which is either reused or transported from the site for disposal.

Within shale basins, there often are overlapping shale "plays," which are defined as sets of accumulations with similar geographic and geologic properties (Klett et al. 2000, 6). This means extractors can simultaneously exploit multiple layers of shale rock to recover product with varying chemical makeup. It should be noted that shale oil and gas can be marketed the same way conventional oil and gas are in their produced form; the shale prefix only indicates their geologic source. Particularly with shale gas, there are two quality types determined by chemical makeup: wet natural gas and dry natural gas. Wet gas can be defined as natural gas which contains less than 85 percent methane (Field et al. 2014, 955). Wet gas requires additional processing to reach the marketable form because its high proportion of heavy hydrocarbons would prevent its use as a fuel. Shale oil, also known as "tight oil," is characterized by its density, with light oil being preferred for its purity (Kilian 2016, 190). All in all, there is much heterogeneity of the geologic characteristics across shale plays, including the main driver of the play (oil or gas), the depth and thickness of the shale formation, and the quality of the produced oil or gas.

2.2. Introduction of Literature

The majority of the related literature analyzes housing values using individual housing transactions, while a smaller set of literature looks at county-level median or average prices (Weber et al. 2016; Rakitan 2018; Bartik et al. 2019; Jacobsen 2019; Apergis et al. 2021; Ambrose and Shen 2023). Individual transaction-level analyses can observe and control for specific housing characteristics, such as square footage, lot size, distances to amenities or disamenities, and binary variables for whether a property has a garage, basement, or private water. While this data granularity is preferable, it is unavailable across the U.S. To illustrate this point, Norwood (2020) attempts to use transaction data for 11 states from 2000 to 2018 and runs into state-level reporting inconsistencies, which causes him to drop entire states from his primary analysis (Norwood 2020, 9).

The analysis within the relevant literature most often uses some form of the difference-in-difference technique (Muehlenbachs et al. 2012, 2015; Timmins and Vissing 2015; Delgado et al. 2016; Boslett et al. 2016, 2019; Rakitan 2018; Cheung et al. 2018; Jacobsen 2019; Bartik et al. 2019; Norwood 2020; Shappo 2020; Ifft and Yu 2021; Ambrose and Shen 2023). Difference-in-difference estimation can be broken down to using a “treatment” effect dummy variable, where the treatment group is the houses, zip codes, or counties with exposure to shale activity. Also, within studies that use individual transactions, it is typical for various distance boundaries to be used in defining additional treatment groups, with the expectation that the effects (positive or negative) will become less extreme and perhaps statistically insignificant with increased distance. In general, studies have found that a change in the capitalization of shale activity can be observed when the spatial buffer or boundary to shale wells is extended beyond 1 mile or 2 miles (Gopalakrishnan and Klaiber 2014; Muehlenbachs 2015; Norwood 2020; Mothorpe and Wyman 2021) although there is heterogeneity in the boundary ranges used (Keeler and Stephens 2020). These changes in the capitalization of shale activity are typically explained by houses either not receiving mineral rights lease payments or being sufficiently far enough to avoid the well-site disamenities.

When comparing unobserved amenities and disamenities, there are more types of localized disamenities than localized amenities observed in the literature. These community-level disamenities include water source contamination, air pollution, well construction impacts, roadway usage, induced earthquakes, and the resource curse. This is compared to the amenities commonly identified in the literature: mineral rights royalties and job market benefits. On the other hand, there are also more national amenities than national disamenities identified in the literature. These amenities include lower energy prices, increased national energy security, and lower carbon emissions from displacing coal (Apergis et al., 2023, 99). While relevant to the overall discussion, these national amenities are only used anecdotally in the literature and are not considered in our analysis. Therefore, while it is documented that there are more types of unobserved localized amenities to disamenities, the true crux of previous research, as well as this research, is to determine the net effect of the unobserved amenities and disamenities through the sign of shale activity variables in regression analysis.

2.3. Major Shale Basins

2.3.1. Appalachian Basin

Spanning from central New York to northeast Tennessee, the Appalachian Basin is best known for the Marcellus and Utica shale formations. These two shale formations appear largely indistinct on a map due to shared geography but are positioned at different depths beneath the surface. Although these two formations are capable of producing shale oil, these formations are primarily gas plays. Among proved shale gas reserves, the Marcellus formation is the most substantial in the United States. The geographic span of the Marcellus includes sections of Pennsylvania, Ohio, West Virginia, New York, and Maryland. As of 2021, the West Virginia and Pennsylvania segments of the Marcellus formation account for 36.7 percent of the total shale gas reserves in the country (U.S. EIA 2022, 20). It has been estimated that there is enough natural gas in the Marcellus formation to supply the entire U.S. for at least 20 years (Delgado et al. 2016, 4). Conveniently, the Marcellus Shale is shallower in most locations than the major plays of the Fort Worth Basin or the Anadarko and Arkoma Basins, with depths ranging from 4,000 to 8,500 ft (Ground Water Resources Council 2009, 17).

The modern shale gas play in the Appalachian basin began in the mid-2000s when the unconventional horizontal drilling techniques previously used in the Fort Worth Basin struck great success in Washington County, Pennsylvania (Carter et al. 2011, 221). After this point, production expanded rapidly throughout the basin, particularly in the northern regions of Pennsylvania. As of 2014, Washington County remains the county with the most drilled unconventional gas wells in Pennsylvania and the second densest drilling concentration of unconventional gas wells, with 1.4 wells per square mile (Schafft 2018, 507). However, the highest density of unconventional gas production is in Bradford County (Delgado et al. 2016, 12). The Pennsylvania state government collects a relatively small percentage of oil and gas revenues (less than 2 percent). These revenues are collected through impact fees imposed on each unconventional well drilled, which are five times higher than that of conventional vertical wells (Newell and Raimi 2015, 33). Although a small percentage of revenues, Pennsylvania distributes a large portion of the impact fees to local municipalities, which helps these municipalities address any additional damages to local infrastructure from shale activity. Compared to other shale basins, like the Fort Worth or the Denver-Julesburg Basins, the Appalachian Basin has a higher concentration of rural areas. For the previous literature focusing on the region, this means that the lot sizes being analyzed are typically twice as large relative to those analyzed in literature focusing on other shale regions (Balthrop and Hawley 2017, 353).

Many homeowners on the southern edge of New York began signing mineral rights leases by 2008, and the state saw the shale drilling permits trickle in thereafter (Ifft and Yu 2021, 137). However, on July 23rd, 2008, New York implemented a statewide moratorium on fracking due to environmental and health concerns, preventing any horizontal wells from ever being drilled. The primary factor being considered in the state's decision was that part of the watershed supplying New York City with its drinking water lies above the Marcellus Shale, posing "unacceptable threats to the unfiltered fresh water supply of nine million New Yorkers" (New York Department of Environmental Protection 2009). Another consideration in the moratorium decision was that shale gas development would only directly benefit a few of the counties in the region as many of the other counties did not have economically lucrative subsurface formations (shale was too thin or too deep below ground).

In order to exploit these vastly different regulatory spheres in neighboring Pennsylvania and New York, Boslett et al. (2016) utilize a counterfactual approach using two counties from Pennsylvania as the control group (Tioga (PA) and Bradford counties) and three counties in New York as the treatment group (Steuben, Chemung, and Tioga (NY) counties). The concept behind the border discontinuity approach in Boslett et al. (2016) is that the neighboring counties do not significantly differ, including their high fracking potential, except in their attitudes and regulations towards shale activity. The author's findings show that housing prices rose 10 percent more in the counties where fracking was allowed, which indicates positive overall net expectations of shale development in the region and a negative effect from the moratorium (Boslett et al. 2016, 25). However, criticism of this approach used by Boslett et al. (2016) arrives from Stephens and Weinstein (2019) and Ifft and Yu (2021) for the assumption of parallel price trends in both states and no consideration for proximity to shale activity across borders. Ifft and Yu (2021) specifically examine the moratorium's impact on farmland values, concentrating solely on New York counties within an 18-month timeframe before and after the moratorium (Ifft and Yu 2021, 139). Their conclusions support Boslett et al. (2016) in that they find that the moratorium hurt farmland in the treatment region (Allegany, Steuben, Chemung, Tioga, Broome, and Chenango counties of New York). However, like Weber and Hitaj (2015), they also acknowledge that farmland likely does not capitalize the dis-amenities of shale activity to the same degree as residential properties (Ifft and Yu 2021, 134).

As for West Virginia, like other states in the basin, their wealth of resources has historically not left them great wealth in economic terms. The state has experienced numerous waves of resource extraction from timber to coal, yet the significant profits from these resources have historically been found leaving the state. In 2022, West Virginia ranked 2nd among U.S. states in coal production (U.S EIA 2023) while being 49th in per capita personal income (U.S. BEA 2023). Keeler and Stephens (2020) set out to find whether the net effect of unconventional shale gas wells is any different from these previous forms of resource extraction regarding the economic welfare of West Virginia. Using a matching technique on 15,000 West Virginia housing transactions from 2006 to 2015, the authors find adverse capitalization effects caused by proximity to drilling (Keeler and Stephens 2020, 7).

Like Keeler and Stephens (2020), Ambrose and Shen (2023) are interested in how the extraction history of certain areas of Pennsylvania affected resident's perception of the 2007 shale boom, as reflected by changes in house prices from 2004 to 2012. Their study consequently classifies Pennsylvania zip codes into four types based on their extraction history: dual exploration regions (conventional and non-conventional drilling), conventional drilling regions, unconventional drilling regions, and no drilling regions. Ambrose and Shen (2023) find that the number of fracking wells positively influenced housing prices across all regions, and the adverse effects of fracking incidents subsided after two months (Ambrose and Shen 2023, 303). The most intriguing finding of their study is that the unconventional shale boom had a strong positive effect on the housing market in unconventional drilling regions that eventually faded after three years, while dual exploration regions seemed to have more accurate and consistent investor expectations of the shale boom, likely due to more previous experience (Ambrose and Shen 2023, 318). This finding is corroborated by an earlier survey study by Suchyta (2020), who observes that shale gas development in the Marcellus was viewed favorably, evidenced by residents in the region being more satisfied with where they lived. The result defies the notion of place disruption brought about by development. However, Suchyta (2020) acknowledges that the cross-sectional survey study could not discern whether the respondents were generally more likely to view development positively or whether they became more satisfied with the communities because of the benefits resulting from shale energy development.

In contrast to the previous studies in the region, which primarily focus on short-run welfare effects during the unconventional shale boom, Shappo (2020) attempts to shed light on more long-term costs from shale activity. She does this by studying the region during both the boom and bust phases of the production cycle, focusing on unplugged wells in Pennsylvania.

Plugging wells is an expensive process, and when it is difficult to pin down the responsibility for plugging wells, wells are typically left abandoned. Shappo (2020) uses a large sample of 35 counties from 1980 to 2017, which is further refined in her models that account for mineral rights leasing. These models restrict the sample to 25 counties from 1995 to 2017. Since the data in Shappo (2020) spans well before the unconventional shale boom, less than 10 percent of the wells in their complete sample are unconventional (Shappo 2020, 9). In measuring the impact of wells, the author uses count rings identical to those used in Muehlenbachs et al. (2015) (1 km, 1,5 km, and 2 km). They find that the effect of active wells is negative, but these effects are less pronounced compared to the case of abandoned wells. Abandoned wells are observed to have further negative consequences on housing values when left unplugged, with the average treatment effects being $15,188 and $27,465 at 1.5 km and 1 km, respectively (Shappo 2020, 23). Ultimately, Shappo (2020) finds valuable returns to well plugging, leading to almost entirely restored house prices, as the effect of plugged wells in the OLS results is found insignificant on housing values (Shappo 2020, 22).

2.3.2. Fort Worth Basin

Unlike other major shale basins in the US, the Fort Worth Basin is distinctive because it is just west of a combined statistical area (CSA), resulting in a dynamic of shale activity amidst an urban population and smaller land lots. The primary shale formation in this basin is the Barnett Formation, which spans 5,000 square miles and 24 counties north and west of the Dallas-Fort Worth metroplex (Bunch et al. 2014, 833). The Barnett Shale is where unconventional horizontal wells first became widespread after Devon Energy popularized them in the early 2000s (Wang and Krupnick 2015, 27). Devon Energy had already been developing horizontal shale extraction techniques when they acquired fracking pioneers Mitchell Energy &

Development. This allowed them to combine horizontal drilling and fracking technologies, launching a fracking boom after years of trial and error. In the subsequent years, the industry saw natural gas prices increase, which expanded these unconventional operations' profit margins. By 2011, the Barnett Shale accounted for over seven percent of the total natural gas withdrawals in the United States (Allen 2014, 65). The depth of the Barnett Shale is 6,500 to 8,500 feet, meaning that the time required to drill new wells can be significantly more than wells in the Marcellus Shale (Ground Water Resources Council 2009, 17). Like the Marcellus Shale, the Barnett Shale is primarily a natural gas play. In fact, the average shale gas content is among the highest in major shale plays, 3 to 5 times higher relative to the gas content produced in the Marcellus Shale (Ground Water Resources Council 2009, 18).

Timmins and Vissing (2015) are the first to present a hedonic study on shale activity focusing on the basin, utilizing data from housing appraisals from 2000 to 2013 in Tarrant County, Texas. In their simple hedonic models, Timmins and Vissing (2015) reveal that there is a negative statistically significant relationship between nearby drilling and appraisal values, and the marginal effect nearly doubles if the sample is restricted to houses with an active natural gas lease (Timmins and Vissing 2015, 12). Using a dual-gradient model, the authors analyze both the effects of spatial proximity and lease quality on the value of housing appraisals. They determine that specific clauses placed on shale energy producers during the bargaining process add or subtract statistically significant value to the homes sampled, with a $849.72 willingness to pay (WTP) for a clause restricting attorney fees and a -$490.63 WTP for a clause allowing for surface water use (Timmins and Vissing 2015, 22).

Unlike in the Appalachian Basin, shale activity in the Fort Worth Basin is taxed like property. This characteristic of the basin allowed Weber et al. (2016) to use annual changes in oil and gas tax bases and an instrumental variable (IV) approach to determine that the zip codes with increased shale activity (proxied by increased oil and gas tax revenue) lead to statistically significant increases in county median house prices (Weber et al. 2016, 601). However, they found that having more wells drilled in prior years hurt the median house price, perhaps supporting that productive shale leases are capitalized into housing prices, especially since mineral rights were not controlled for. Staying in Tarrant County, although Balthrop and Hawley (2017) are unable to examine clauses in mineral leases like Timmins and Vissing (2015), they improve upon the literature in the basin by using prices from housing transactions instead of appraisals. Focusing on the period between 2005 and 2011, their baseline hedonic model estimates that an additional fracking well within 3500 ft decreases housing values by 2.8 to 3.5 percent (depending on the fixed effects terms included), which would be, on average, a $4720 to $5900 reduction per transaction (Balthrop and Hawley 2017, 355). By focusing on a subsample where houses are more likely to be reliant on groundwater, Balthrop and Hawley (2017) find results consistent with the baseline regression, suggesting no impacts conditional on water source (Balthrop and Hawley 2017, 358). As a robustness check, the authors estimate a repeat sales model (thereby controlling for property-level unobservables) and discover results similar to the previous specifications (Balthrop and Hawley 2017, 360).

2.3.3. Denver-Julesburg Basin

The Denver-Julesburg (DJ) Basin, also sometimes known as the Denver Basin, spans four states (Colorado, Kansas, Nebraska, and Wyoming), but its production is primarily centered around northeast Colorado (He et al. 2018, 223). Within this basin are several shale plays, including the Niobrara, Gothic, and Pierre, with production growth primarily centered around the Niobrara play. The DJ Basin's production is more shaded towards shale oil than other basins like the Appalachian Basin (Stephens and Weinstein 2019, 1379). Since the regions in the DJ Basin do not have the same conventional oil and gas history that the Appalachian and Fort Worth Basins have, the region has faced fiscal challenges in creating the infrastructure to accommodate unconventional shale activity (Newell and Raimi 2015, 40). Survey data suggests that Colorado residents have greater concern for the environment when compared to residents in other shale basins or the U.S. at large (Stephens and Weinstein 2019, 1384). Adding to this, the Environmental Protection Agency (EPA) classified nine counties in Colorado as ozone non-attainment areas in 2015, further motivating concerns about shale activity (Oonk 2020, 10). Like Texas, Colorado applies local property tax rates to the value of produced and assessed oil and gas in their borders (Newell and Raimi 2015, 19). With this being the case, in 2012, 52 percent of Weld County's property tax base was oil and gas property (Raimi and Newell 2014, 49).

The previous hedonic literature focuses on Weld County in Colorado (Bennett and Loomis 2015, James and James 2015, He et al. 2018), where most shale exploration occurs. In 2011, around 40 percent of Colorado's active shale wells were located in Weld County (Swarthout et al., 2013). The first study to focus on Weld County is Bennet and Loomis (2015), who find a slight negative impact from shale oil and gas in urban areas of Weld County, with their focus on the shale activity within a half-mile radius of homes up to 60 days prior to their "closing" (purchase settlement). They estimate that an additional drilled well decreases house prices by an average reduction of $1,856 in 2009 dollars (Bennett and Loomis 2015, 1178). Bennet and Loomis also control for oil and gas employment, finding it positively affects house prices. The authors express that the implicit prices of shale drilling may be more extreme in areas dependent on well water but are unable to obtain the necessary data. In comparison to Bennet and Loomis (2015), James and James (2015) find more substantial losses in house value resulting from proximity to shale wells in Weld County, an average loss of $15,000 as the distance decreases by 1 km (James and James 2015, 20). It should be noted that James and James (2015) use only one year of data and thus have around 15 percent of the sample size that was used in Bennett and Loomis (2015), implying that estimates of Bennett and Loomis (2015) may be more reliable. The subsequent study to focus on Weld County is He et al. (2018), who fail to substantiate the adverse effects of shale activity cited by the previous two papers. While these prior authors use data from 2012 and prior (before shale activity and housing markets boomed in Colorado), He et al. (2018) utilize data on housing transactions, well permits, and oil and gas-related employment from 2014 to 2017. Using an IV approach to control for spatial autocorrelation, the authors conclude that the lack of statistically significant effects from approved drilling suggests there are likely positive effects from private mineral rights leasing offsetting the negative effects (He et al. 2018, 239).

Contrary to the prior research in the basin, Stephens and Weinstein (2019) consider seven other counties in addition to Weld in the Front Range of the Rocky Mountains in Colorado. Stephens and Weinstein (2019) attempt to address factors Bennet and Loomis (2015) do not, such as water source type, split estates, proximity to other disamenities, and natural amenities. As a baseline estimate, they observe that an additional producing horizontal well within 1 mile of homes decreases their value by nearly $3,000 (Stephens and Weinstein 2019, 1391). Stephens and Weinstein (2019) prove that the natural amenity of mountain views has a significant positive impact on housing values across specifications, and additional results from interaction effects show that houses near the mountains suffer more considerable losses from additional nearby shale activity (Stephens and Weinstein 2019, 1391). Surprisingly, the adverse effects of proximity to feedlots are only about half the impact of an additional well within 1 mile. When analyzing these effects over time with cross-sectional regression for each year, Stephens and Weinstein (2019) find that the effects of proximity to shale activity dissipate with time. These seemingly conflicting results are attributed to uncaptured dynamics in housing demand, as unlike in other shale basins, the DJ Basin has recently experienced significant in-migration.

2.3.4. Anadarko & Arkoma Basins

Oklahoma has a long history of fossil fuel mining, especially using conventional extraction methods. In 2019, Oklahoma was the fourth-largest producer of crude oil in the U.S. (Apergis et al. 2021, 5). The Anadarko and Arkoma Basins are home to the Woodford Shale, which is estimated to be twice as large as the Barnett Shale in Texas. The depth of the formation has extreme variability depending on location, ranging from 6,000 feet to 11,000 feet (Ground Water Resources Council 2009, 17). The Woodford Shale is primarily a natural gas play, similar to the neighboring Barnett Shale. Shale gas extracted from the Woodford Play is also relatively high in gas content, just slightly behind the Barnett Shale (Ground Water Resources Council 2009, 22). Although shale extraction can be traced back to the late 1930s in the Woodford Shale (Wickstrom 2008), shale activity began in earnest in the late 1990s with Newfield Exploration utilizing vertical wells (Agrawal et al. 2012, 43). From this point in the 1990s until 2006, only 100 vertical wells were drilled, 60 of them by Newfield (Agrawal et al. 2012, 43). However, after the switch to horizontal wells in the Barnett Shale, the Woodford operators quickly followed suit, adapting to the new extraction technique. With the introduction of horizontal wells, the formation went from an average of 2 wells drilled per year to 35 per year in 2004 (Wickstrom 2008). Regarding taxation in the region, Oklahoma applies a severance tax and property tax on oil and gas within its borders (Wickstrom 2008), like the DJ Basin and the neighboring Fort Worth Basin.

Using data from 2000 to 2015, Apergis (2019) analyses how the number of and distance to oil and gas fracking wells affects house prices across Oklahoma at the county level. In both regards, he finds positive impacts (6.9 percent), particularly upon the beginning of the unconventional shale boom of 2007 (Apergis 2019, 98). To check the robustness of their analysis, two cointegration tests confirm a long-run equilibrium among house prices in their sample. Lee and Whitacre (2021) explore the effects of both unconventional and conventional shale in two contrasting counties of Oklahoma: Canadian County and Payne County. The primary differences noted between these counties are their heterogeneous population density and typical distribution of shale wells. Canadian County is a part of the Oklahoma City area and has most of its shale wells in remote locations. Meanwhile, Payne County is primarily home to a small college town and has shale wells dispersed throughout residential areas (Lee and Whitacre 2021, 4). They run separate analyses for unconventional and conventional shale development, positing that the analysis of conventional wells is still relevant to the study of unconventional wells since a large proportion of the population may not know the difference between the two extraction methods. Boudet et al. (2012) support this notion by citing a national poll that found 37 percent of people are uninformed about fracking (Boudet 2012, 58). Unlike Aperigs (2019), Lee and Whitacre (2021) discover generally insignificant effects when considering count and distance measures (Lee and Whitacre 2021, 10). This insignificance is supported by additional semi-parametric analyses, which allow for a nonlinear relationship between house prices and shale drilling activity. Mothorpe and Wyman (2021) investigate the impact of shale injection and production wells on house prices in Oklahoma County from 2006 to 2018, a neighboring county to Canadian county studied in Lee and Whitacre (2021). For both the count of injection and production shale wells within 2 km, negative impacts are found to be statistically significant in all specifications (Mothorpe and Wyman 2021, 45). In this sense, Morthorpe and Wyman (2021) create a discrepancy among the results for the Anadarko and Arkoma Basins.

2.4. National Analyses

As noted in section 1.2, national analyses are essential because they are more easily applied to shale booms in new plays and allow comparisons between the housing markets in shale oil and shale gas plays. To illustrate this point, no existing related literature exists on the housing market in the Bakken Shale in the Williston Basin. Understanding the welfare impacts of shale activity in these areas based on studies of the Marcellus or Barnett Shale becomes very difficult, especially considering that the Bakken is an oil play while the Marcellus and Barnett are gas plays. Additional sources of often unobserved heterogeneity across the plays would be their existing oil and gas infrastructure, the productivity of wells, the use of wastewater injection wells, the proportion of split estates, and reliance on private water. These characteristics all influence the capitalization of shale activity differently across regions, but analysis at the national level can potentially control for these unobserved differences and provide more generalizable results. Additionally, in the context of existing literature, national analyses are more recent in nature (from 2016 to 2023) than those conducted on specific plays or basins. The advantage of these more recent analyses is that they can capture the cyclical nature of shale production. Our data shows that the national-level busts in shale oil and gas production occurred in 2014, which is approximately the center point of our analysis.

While Israel et al. (2015) may be the first to survey residents of 24 U.S. states to elicit public concerns about shale gas development, to the best of our knowledge, Jacobsen (2019) is the first paper to explore the effects of shale activity on communities across the nation (working paper in 2016). Jacobsen (2019) explores both the labor and the housing market impacts of fracking from 2012 to 2017 in 153 of the 160 non-metropolitan areas (NMAs) defined by the BLS. Although the focus of Jacobsen (2019) is mainly on the effects of shale on wages, their analysis of housing markets found that house prices in boom areas experienced a relative increase of 12.5 percent over the study, more than double the effect of rents (5 percent) (Jacobsen 2019, 22). Their reasoning for the more substantial impacts on house values compared to rents is that renters do not benefit from mineral rights leasing. Rakitan (2018) builds off Jacobsen (2019) with a similar analysis, but at the county level instead, with 2,141 counties from 29 states that have or are adjacent to shale regions. Apart from having a national scope, these papers are similar because they also focus on labor market outcomes, with house values being only a component of local welfare. In Rakitan (2018), three classifications of counties are identified: "boom" counties, producing counties, and non-producing counties. Rakitan (2018) finds consistently positive effects on the labor market, which corroborates results from Jacobsen (2019), but regarding the housing market, he finds inconsistent results across specifications. His specifications show that shale boom treatment counties generally have positive effects on house value growth but also show adverse effects on house value measured in logged levels. Additionally, the results of the treatment-on-treated effects display consistent adverse effects on house values, with average percent changes in housing values as large as -9.5 percent (Rakitan 2018, 38).

Like Jacobsen (2019) and Rakitan (2018), Bartik et al. (2019) seek to provide a more comprehensive analysis of fracking across the U.S. by analyzing nine different shale plays as well as looking beyond just housing market indicators of fracking impacts. However, as a component of the desired welfare WTP estimates, Bartik et al. (2019) analyze the impact of fracking on county median home values with counties in the top quartile of Rystad's “prospectivity” index for each shale play as the treatment group. The authors find that treated counties saw housing values increase by 5.7 percent and rental prices by 2.0 percent from 2000 to 2013 (Bartik et al. 2019, 140). Compiled with estimates of changes in population and income, their housing estimates allow them to determine that the net WTP for permitting fracking is approximately $2000 per household annually (Bartik et al. 2019, 149). The analysis of Norwood (2020) does not follow the other national analyses in analyzing alternative welfare outcomes but instead adds to the literature by using, as best as we can tell, the most significant volume of housing transactions among relevant literature. With the Zillow Transaction and Assessment Dataset (ZTRAX) as his source for 11 energy-producing states from 2010 to 2018, his full sample includes over 15 million transactions. This is unique because all other national analyses (including this one) use county average or median house prices instead of individual transactions. Also, in the previous studies with a DiD approach, the treatment groups are not separated by distance measures, like in Norwood (2020). Among the preferred household fixed effects and repeat sales models, Norwood (2020) observes an increase in house prices for homes within 2 miles of a shale well (Norwood 2020, 29). In the zip code fixed effects and spatial DiD models, the author again finds positive effects on houses near a well, with the effects decreasing in magnitude with added distance (Norwood 2020, 16).

2.5. Amenities

2.5.1. Royalties

As of 2012, 76.2 percent of the subsurface minerals in the continental U.S. were privately owned, allowing for enormous local economic gains through royalty payments from shale activity (Fitzgerald 2014, 5). Illustrating this, the income from royalties and other associated streams increased by an average of 460.8 percent among the highest-tier Marcellus Shale counties during the beginning of the shale boom (Hardy and Kelsey 2015, 332). It is standard in mineral rights leasing agreements for a one-time bonus payment, which is a small incentive for the owner if the leased subsurface is unproductive. However, this is almost always surpassed in value by the associated royalties if production occurs. Additionally, by its one-time nature, this bonus payment cannot be capitalized into the value of a home after a lease is already signed. Leases may include a delay compensation for the time between signing the lease and the onset of development (Weber et al. 2013, 7). Ifft and Yu (2021) note that signing bonuses can vary from $50 to $6,000 per acre. In certain states, mineral rights leasing requires that royalty payments be a minimum of 12.5 percent of the gross value (volume times price) of the gas extracted, but they can be much higher (Ifft and Yu 2021, 134). Larger parcels of mineral rights are more valuable to shale energy producers due to the decreased transaction costs and difficulties compared to bundling the same amount of land among multiple leasers. Anecdotally, this should mean that owners of more significant mineral rights parcels typically have more bargaining power and, therefore, are the ones who get elevated royalty rates (Kelsey et al. 2012a, 13). Using average 2008 prices, this minimum 12.5 percent royalty meant that mineral rights owners received $450,000 during the first year of each typical Marcellus Shale well (Paredes et al. 2015, 113). Unfortunately for owners, these windfalls are not sustained long-term, as most wells experience a 50 to 70 percent output reduction within the first three years (Paredes et al. 2015, 113).

However, these royalty windfalls do not always go to those residing at the property with the drilling activity, as mineral rights can be separated from land rights in what is known as split estates—split estates cause residents to bear any costs from shale activity on their property without compensation. It is also worth considering the situation for renters in the rural farmland where shale activities typically occur. In these areas, landlords who do not operate farms make up a large proportion of the landowners, upwards of 40 percent nationally (Weber et al. 2013, 8). This means that even outside of the case of split estates, there are still many residents renting who are not in a position to benefit from adjacent shale activities. Demonstrating this concept, Kelsey et al. (2012b) estimate that during 2010, 40 percent of gas leases in Bradford County, PA, did not go to county residents (Kelsey 2012b, 13). Collins and Nkansah (2015) survey West Virginia landowners and established that landowners with split estates report more than twice as many problems with shale activity as landowners who owned their mineral rights (Collins and Nkansah 2015, 697). Split estates are more common in the Barnett and Bakken formations of the Fort Worth and Williston Basins, respectively, compared to the Appalachian Basin's Marcellus formation (Fitzgerald 2014, 6). These differences are made apparent in Weber and Hitaj (2015), who use panel fixed effects and cross-sectional quantile regressions to determine that from 1992 to 2012, shale activity increased farmland values by 48 percent in three counties apart of the Marcellus formation in Pennsylvania (Tioga, Bradford, and Susquehanna counties) while only increasing farmland values by nine percent in four counties apart of the Barnett formation in Texas (Parker, Hood, Johnson, and Wise counties) (Weber and Hitaj 2015, 15). These observations align with Fitzgerald (2014) and are substantiated by subsequent insights in Weber and Hitaj (2015), which suggest that differences in farmland appreciation occur during leasing periods and are not caused by differences in mineral rights taxation (Weber and Hitaj 2015, 16).

In Stephens and Weinstein (2019), there are multiple instances suggestive of royalties being positively capitalized into house prices. Firstly, they discover that government-owned mineral rights decrease housing values by 4 percent, displaying an underlying value to mineral rights (Stephens and Weinstein 2019, 1392). Additionally, houses with public water benefit from being closer to active shale development with time, suggesting that royalty payments exceed the negative externalities of shale activity for these residents. Royalty payments also appear to play a significant role in Shappo (2020), who observed adverse effects from proximity to producing wells except in the case of the interaction between proximity to producing wells and mineral rights leases, which results in a 3 percent increase in value with each well drilled within 1 km (Shappo 2020, 46). Additionally, the adverse effects of abandoned wells are magnified in royalty treatment groups, which Shappo (2020) reasons to be because well abandonment marks the end of royalty payments.

2.5.2. Job Market Benefits

By nature, there has been relatively little change in conventional oil and gas production over time, meaning that the newer unconventional shale methods have been critical to the employment growth in the oil and gas sectors. From 2007 to 2012 (during the shale boom), U.S. employment in the oil and gas sectors grew at an annual rate of 5.23 percent and 29.02 percent, respectively (Hartley et al. 2015, 611). In 2012, 1.2 million jobs were created in unconventional oil and gas-producing states (Munasib and Rickman 2015, 2). Therefore, the numbers suggest that shale activity has produced job market benefits, even in the wake of the 2007 Great Recession. Still, there are some questions about whether the job market benefits are localized and sustained. A single shale well requires more than 400 employed individuals, but this workforce is only needed during the drilling period, which typically lasts three months (Lee 2015, 63). Therefore, the level of employment is highly dependent on the number of new wells being drilled, which in turn is dependent on the fluctuating prices of oil and gas. Due to the suddenness of employment in the oil and gas industry, much of the workforce employed by shale development are transient workers that do not substantially contribute financially to the local area, instead residing in temporary housing known as “man camps” (Lee 2015, 64). For this reason, studies that analyze wages and employment are not as effective as measures of local welfare because these benefits could end up going to non-local commuters.

To analyze the effect of shale development on local labor markets, some studies use employment or income multipliers instead of econometric analysis. These multipliers use input-output analysis to measure the change in aggregate income or employment resulting from an exogenous change in spending or output, respectively (Lee 2015, 62). However, Kinnaman (2011) notes that the studies using standard methods to compute these multipliers are based on Keynesian assumptions like full employment and often overstate the volume of direct local spending (Kinnaman 2011, 1247). Hartley et al. (2015) apply multiple econometric methods in analyzing the effects of shale development on Texas job markets from 2001 to 2011, and they find that new fracking wells had caused statistically significant boosts to job creation but had insignificant effects on wages (Hartley et al. 2015, 618). Weinstein et al. (2018) support the assertions of Kinnaman (2011) regarding the overstatements made in early input-output studies in the region, finding an earnings multiplier of 1.3 for oil and gas industries in nonmetro counties across the U.S., which is more modest compared to estimates put forth by earlier studies (Weinstein et al. 2018, 204). This multiplier suggests that each $1 of net earnings in oil and gas results in 30 cents of net earnings for other industries.

Hardy and Kelsey (2015) focus on Marcellus Shale counties in Pennsylvania from 2007 to 2010, separating the counties by their number of shale wells. They observe that the eight counties with the most shale wells experienced, on average, a 6 percent increase in total taxable income, a 1.5 percent increase in gross compensation income, and a 14.4 percent increase in net profits income, while the non-shale counties experienced declines in all of these categories (Hardy and Kelsey 105, 332). However, Hardy and Kelsey (2015) note that these top-tier shale counties experienced wages and salary growth that was faster than employment. Bennet and Loomis (2015) include a variable specifying oil and gas employment in their analysis of the urban landscape of Weld County and find that this variable yields positive and statistically significant effects on house prices from 2009 to 2012 (Bennet and Loomis 2015, 1181). In the labor market analysis of Bartik et al. (2019), the authors observe 5 percent increases in employment and 3 to 6 percent increases in wages for top quartile shale counties during the years 2000 and 2009 to 2013. Interestingly, when switching the employment data to a measure that considers place of work instead of place of residence, they find a much greater increase of 10 percent, a possible sign of transient workers. Most importantly, they find no industries with a statistically significant decline in employment in the treated counties from 1990 to 2013 (Bartik et al. 2019, 134). Consistent with Hartley et al. (2015) and Bartik et al. (2019), Feyrer et al. (2017) reveal up to a 0.43 percent increase in employment from shale production across the U.S. from 2005 to 2012, suggesting an increase of 640,000 total jobs (Feyrer et al. 2017, 1332).

2.6. Disamenities

2.6.1. Water Source Pollution

The main ways that shale activity can negatively impact local water supplies are through wastewater disposal, structural leakages in well casings, and erosion. Wastewater, also known as produced water, includes fracturing fluids and geologic compounds naturally present in underground layers. The fracturing fluids contain a range of additives like gelling agents, antiscalants, surfactants, and biocides (Burton et al. 2014, 1680). However, the full array of chemicals in fracturing fluids remains unknown because these are regarded as “trade secrets” within the industry. When wastewater is returned as “flow back,” it has been found to contain unusually high salt concentrations and radioactive materials from the soluble radium rocks below

(Carpenter 2016, 48). In cases where the composition of stray gases in contaminated well water is consistent with that of the target shale formation, it is likely that “fugitive” or stray gas has leaked through malfunctioning well casing (Vengosh et al. 2014, 8337). These fugitive gases can pollute well water within 1 km of the drill site. Additionally, with shale development comes many earth-disturbing processes like land clearing, grading, and excavating, all of which increase the potential for erosion. Without proper controls in place, sediment from this erosion is carried by runoff into nearby streams. Critically, shale gas well pads are often located adjacent to small streams and watersheds, amongst which many individual shale wells may exist.

Regarding wastewater disposal, there are several handling techniques, all of which raise varying emission concerns. In some instances, wastewater is deposited into evaporation ponds/pits (Field et al. 2014, 956). Evaporation ponds are not covered, so this process will often cause downwind emissions or accidental spillages during overflows caused by major rain events. Additionally, truck accidents while transporting wastewater to treatment facilities can result in serious spills. Considine et al. (2011) report that 56 wastewater and fuel spill occurrences were classified as major spills (of 100 gallons or more) by the Pennsylvania Department of Environmental Protection from 2008 to 2010 (Considine et al. 2011, 8). Fracking wastewater is also sometimes treated at facilities and then returned to local water supplies, but this wastewater treatment can be insufficient in many cases. Early in the shale boom of Pennsylvania, publicly owned treatment facilities were quickly blocked from treating fracking wastewater because these facilities were ill-equipped to handle the high concentrations of dissolved salts in fracking wastewater (Burton 2014, 1684). Demonstrating this, Olmstead et al. (2013) conduct the first systematic study using spatial water quality data in Pennsylvania. They observed that “treated” wastewater discharge resulted in higher downstream chloride levels (Olmstead et al. 2013, 4962). Additionally, the authors reveal that the runoff from drilling sites raises the concentration of suspended solids in downstream samples. Therefore, it is critical that these wastewaters are treated by dedicated water treatment systems and that the water is preferably recycled for further use in future operations. The proportion of wastewater recycled in operations varies widely across shale regions, with reportedly 95 percent of flowback being recycled in the Appalachian basin and only 20 percent being recycled in the Fort Worth basin (Clark et al. 2012, 7).

In a sequence of papers, Muehlenbachs et al. (2012, 2015) use data at the beginning of the unconventional shale boom in Pennsylvania to focus on how shale activity is capitalized differently by houses depending on distance to wells and water access. In Muehlenbachs et al. (2012), the researchers employ a triple difference approach, with and without matching, to account for unobservable factors linked to shale extraction in Washington County specifically. Notably, the authors find opposite effects for piped vs. well water within a 2 km radius of a shale well: a 10 percent boost in property values for the former and a -27 percent hit for properties classified as the latter (Muehlenbachs et al. 2012, 29). In the resulting paper, Muehlenbachs et al. (2015) expand the scope of their study, focusing on 1,000 houses across 36 counties of Pennsylvania while using similar matching estimators based on the distance to wells and water access. The findings generally supported their earlier study, with well water houses inside 1 km dropping 17 percent in value and insignificant positive effects for piped water houses (Muehlenbachs et al. 2015, 3649). Upon expanding the buffer of the nearest shale well to 1.5 km, a statistically significant 3 percent increase in house values is observed for piped water homes (Muehlenbachs et al. 2015, 3650).

Like Muehlenbachs et al. (2012), Gopalakrishnan and Klaiber (2014) utilize spatial variation techniques for the same era of shale development in Washington County, Pennsylvania.

With a greater focus on the period of construction for nearby well sites, Gopalakrishnan and Klaiber (2014) show minor average negative effects of 3 percent in property values, with this being driven by a -15 percent effect for groundwater-dependent homes during the first six months following the issuance of a shale drilling permit (Gopalakrishnan and Klaiber 2014, 54). Wrenn et al. (2016) take a different approach from Muehlenbachs et al. (2012) and Gopalakrishnan and Klaiber (2014) by instead analyzing the yearly bottled water purchases of households in the region from 2005 to 2010. Their results defend the notion that shale activity harms private water supplies as they isolated a $12.9 million averting expenditure in 2009, followed by a $19 million averting expenditure for 2010 (Wrenn et al. 2016, 799).

Delgado et al. (2016) attempt to elucidate concerns left by Muehlenbachs et al. (2012, 2015) and Gopalakrishnan and Klaiber (2014). Specifically, there are concerns about the potential bias from residual effects in Washington County and other counties in Pennsylvania, stemming from a lengthy history of resource extraction predating the widespread adoption of unconventional shale drilling (Delgado et al. 2016, 2). The authors' strategy to address these concerns is to stick to two counties that have only recently experienced large amounts of extraction through shale production. Interacting shale binary treatment variables with a water source indicator variable, they are unable to show any meaningful adverse effects on groundwater-dependent houses in either Bradford or Lycoming counties (Delgado et al. 2016, 14). Keeler and Stephens (2020) find similar insignificance of water source interaction effects in the full sample of their study, covering housing transactions in West Virginia from 2006 to 2015. However, this study also uses a subsample from 2006 to 2011, which garners results consistent with those of Muehlenbachs et al. (2015) (Keeler and Stephens 2020, 8).

Other shale basins do not always present the same risk to drinking water as in the Marcellus Basin due to differences in the reliance on private water. For example, public water coverage area comprised 99.6 percent of the Weld County sample in He et al. (2018). Surprisingly, Stephens and Weinstein (2019) nonetheless observe that as shale activity increased over time in their sample, the value of public water consequently also increased in their study of the Front Range of the Rocky Mountains (Stephens and Weinstein 2019, 1932). This is corroborated by a positive sign on the interaction between the distance to the nearest producing well and the private water dummy variable, which suggests that residents on private water prefer being farther away from shale development. In the Cheung et al. (2018) study of Oklahoma, a well-water-dependent subsample reveals a negative but insignificant impact from shale-induced earthquakes, with the lack of significance possibly owing to a small subsample (Cheung et al. 2018, 163). This inconsequential aspect of water-source in Oklahoma is also demonstrated by the insignificance of a groundwater dependence interaction term in Mothorpe and Wyman (2021), who focus on Oklahoma County. Like Cheung et al. (2018), Mothorpe and Wyman also reason that the statistical efficiency of the finding was impacted by the small portion of ground-water dependent homes (Mothorpe and Wyman 2021, 48).

2.6.2. Air Pollution

Shale activity is a source of a variety of air pollutants, including shale gas itself. Besides the methane in shale gas, the production and transportation processes also factor into the pollution, which can result in poor health outcomes for individuals in nearby communities. Litovitz et al. (2013) identify four shale production activities in particular that can harm local air quality over time: equipment and water transportation, well drilling and fracking, on-site diesel combustion, and the use of gas-powered compressor stations (Litovitz et al. 2013, 2). A primary cause of localized emissions is the transportation of water required to drill each shale well, typically more than 2 million gallons of water (Shonkoff et al. 2014, 787). Most of the time, this water cannot be piped to the drill site, which instead entails 300 to 1300 trips made by heavy-duty trucks for each well (Roy et al. 2014, 27). Besides water, the proppant sand used to keep fractures open must also be delivered by truck in the drilling stages. All of this trucking leads to high emissions of fine diesel particulate matter (PM), which is a cause of cardiovascular illnesses and respiratory diseases like lung cancer. Additionally, the trucks typically make use of unpaved roads, which will produce dust pollution.

Well-drilling and fracking can emit subsurface gases when the structural integrity of a well is compromised. In particular, wellbore cement failures can cause methane and hydrocarbons to migrate along improperly plugged wells (Shonkoff et al. 2014, 792). During the drilling process, workers at the drill site are exposed to silica dust from the proppants used, exposure to which is associated with silicosis (a lung disease), pulmonary disease, and tuberculosis, among other conditions (Shonkoff et al. 2014, 790). Equipment leaks from connectors, valves, and other hardware at the wellhead are known as “fugitive” emissions, and they are caused by the high pressure of the gas moving through a wellhead, making them typically difficult to measure because of their unexpected nature. Since fugitive emissions from wellheads involve produced gas, they are a definite source of volatile organic compounds (VOCs). The term fugitive emissions can also be used to refer to emissions from pipelines and methane tanks, which release methane, hazardous air pollutants, and VOCs (Field et al. 2014, 956). VOCs, which are released at a higher intensity with wet gas wells, can also be emitted during the venting processes, which occur multiple times during a well’s existence. Venting occurs once before the initial production begins, which is called “completion venting.”

Subsequent venting may occur in what is referred to as "blowdown venting," which is used to resolve obstructions like fluid buildup and is typically needed if operators are trying to put a well back into production after some time.

Combustion emissions primarily come from the shale gas compression stage, which takes place to prepare natural gas for delivery in high-pressure pipelines (Field et al. 2014, 957). Compression stations typically run 24 hours a day, and operators typically utilize 3 to 15 large natural gas-fired compressors with 1000 to 2000 horsepower (hp) each (Roy et al. 2014, 28). Combustion emissions are also derived from the drill rigs, fracturing pumps, and wellhead compressors. The drill rigs involve 5 to 7 independently powered diesel engines, typically rated between 500 and 1500 brake horsepower (bhp) (Roy et al. 2014, 24). Diesel engines in excess of 1000 hp run fracturing pumps, which pump the fracturing fluids and proppants, and each well drilling typically involves 8 to 10 of these pumps (Roy et al. 2014, 26). Wellhead compressors use much smaller combustion engines that raise the pressure of the produced gas for its end use. By nature, all these combustion engine types emit nitrogen oxides (NOx), VOCs, and PM.

The types of pollutants that can occur from shale development are NOx, PM, VOCs, polycyclic aromatic hydrocarbons (PAHs), methane, and odor-causing compounds like hydrogen sulfide (Rich et al. 2013, 62). These emissions cause pollution concentrations that often exceed EPA guidelines for noncarcinogenic and carcinogenic health risks (Shonkoff et al. 2014, 789). NOx and VOCs, in particular, are the two main precursors of ground-level ozone, which creates the risk of respiratory effects (Pride et al. 2015, 2). These respiratory effects, in turn, lead to increased asthma attacks, hospital admissions, and daily mortality. Ground-level ozone can spread up to 200 miles from the drilling site, threatening certain trees and crops in the area (Colborn et al. 2011, 1042). It is worth noting that methane emissions are perhaps not a localized cost as they are not known to be particularly health-damaging; instead, they have greater implications for climate change. However, methane is often coproduced with heavier gases that are health-damaging and have some minimal risk attributable to its explosive properties. An example of these explosive properties occurred at a house near Cleveland, Ohio, that exploded in 2007 due to methane contamination in a private water well (Shonkoff et al. 2014, 792).

In a pilot study of the DJ basin, Pétron et al. (2012) observe ambient emission data from daily air samples from 2007 to 2010 to discover strong atmospheric signatures of two VOCs, alkane and benzene, the latter of which being a carcinogenic pollutant (Pétron et al. 2012, 17). The analysis of Pétron et al. (2012) also shows tight correlations between alkane mixing ratios that are suggestive of a single source in a section of the DJ basin with no major cities, pinning shale operations as the only likely candidate (Pétron et al. 2012, 8). In the same region, McKenzie et al. (2012) measure residents according to subchronic non-cancer hazard indices. They observe that residents living beyond half a mile away from shale wells scored 0.2, while those living within half a mile of a shale well registered a 5.0 (McKenzie et al. 2012, 83). These differences are attributed to neurological, hematologic, respiratory, and developmental effects. Rich et al. (2013) conduct ambient air sampling in the Fort Wort shale basin from 2008 to 2010 to discover that in 98 percent of methane samplings, the concentration measures were above laboratory detection limits (Rich et al. 2013, 65). Perhaps most surprisingly, Rich et al. (2013) find that rural areas within the shale basin typically had methane concentrations above urban background concentrations. Similarly to the Pétron et al. (2012) study of the Front Range in Colorado, Rich et al. (2013) find benzene in 38 of 50 sites sampled in the region (Rich et al. 2013, 65). Helmig et al. (2014) recap winter ozone studies done in 2012 and 2013 for the Uintah Basin in northeast Utah, which is associated with conventional and unconventional oil and gas.

They find some of the highest alkane non-methane hydrocarbon concentrations ever reported, exceeding those reported in the most heavily polluted inner cities, even though the basin lacks major urban areas (Helmig et al. 2014, 4714). Contradicting Rich et al. (2013), Bunch et al. (2014) discover no evidence that communities in the Fort Worth Basin were exposed to levels of VOCs that would pose a health concern from 2010 to 2011 (Bunch et al. 2014, 838). Zhang et al. (2023) estimate the causal effect of shale well preparation and production on local PM pollution in the Marcellus region. They observe a 2.19 percent increase in PM measures associated with well preparation and a 1.35 percent increase associated with well production, both significant at the 1 percent level (Zhang et al. 2023, 467).

2.6.3. Well Construction Disturbances

The drilling of an unconventional shale well is a process that creates many disturbances or "stressors" to nearby residents and wildlife. These disturbances most commonly include noise and lights. These consequences are familiar to conventional drilling methods, but unconventional drilling tends to occur closer to resident populations and has a drilling process that takes several times as long. Drilling a horizontal well typically takes 4 to 5 weeks of constant around-the-clock development, depending on the depth of the shale formation (Hays et al. 2017, 449). During nighttime development, artificial lighting is needed for the well area, the compressor stations, and access roads. Besides the initial drilling process, another source of light pollution is the flaring process, which is burning natural gas for testing reasons or because the gas is unwanted, as is the case at some oil wells (Boslett et al. 2021, 5). The consequences of these unnatural disturbances to nearby residents include sleep disturbance, stress, mood changes, diminished cognition, hypertension, and heart disease (Witter et al. 2013, 1006). These issues arise because although residents may be consciously undisturbed by the shale activity, the human body automatically reacts to the lights and noise by releasing adrenaline, tensing muscles, and constricting blood vessels (McCawley et al. 2013, 9). To address these issues and stay within city ordinances, shale energy producers have utilized directional lighting and sound-deadening technology. Directional lighting can be used to keep the necessary lighting facing downward on the well pad and away from neighboring residences and roads. Sound-deadening technology tends to take the form of blanket-like enclosures that can be wrapped around drill rigs to act as an acoustic barrier. Unfortunately, these technologies have only been used on a case-to-case basis thus far.

Using satellite data and self-reported data on health outcomes, Boslett et al. (2021) show that shale activity is directly responsible for light pollution in the rural areas of shale plays, and this light pollution disrupts the sleep of local residents. In particular, they observe that residents of a county with at least 100 unconventional wells are six percentage points more likely to sleep less than 7 hours per night and three percentage points more likely to report insufficient sleep in general (Boslett et al. 2021, 15). Upon examining the spatial and temporal persistence of capitalized dis-amenities risk, Gopalakrishnan and Klaiber (2014) find that the risk of dis-amenities is most impactful when the intensity of shale activity is at its peak, during the well-construction phase (first six months following an issued well permit) (Gopalakrishnan and Klaiber 2014, 58). They describe how the construction dis-amenity is highly visible and often occurs before potential buyers have a well-informed risk perception regarding the shale activity (Gopalakrishnan and Klaiber 2014, 55). In their analysis of Weld County, Colorado, Bennett and Loomis (2015) show that the number of wells drilled before a sale has statistically significantly negative impacts on the sale price. Meanwhile, during this same 60-day window, the number of producing wells does not have any statistically significant impact on the sale price across the entire sample and increases house prices in the urban subset of the sample (Bennet and Loomis 2015, 1177). Bennet and Loomis (2015) suggest this difference could be attributable to construction dis-amenities like noise. Although acknowledging a slight additional short-term negative effect from the construction of shale wells, Balthrop and Hawley's (2017) results show fairly consistent adverse effects from 6 months after construction and thereafter (Balthrop and Hawley 2017, 350). Balthrop and Hawley (2017), therefore contradicting Gopalakrishnan and Klaiber (2014) and Bennet and Loomis (2015), discern that perceived environmental damages have more critical effects compared to the effects of new well construction.

2.6.4. Roadway Usage

As addressed in section 2.4.1, roadway traffic can become a severe issue due to shale energy producers' extensive water and wastewater disposal needs. When disposing of wastewater via truck, producers try to minimize their costs by utilizing the most nearby disposal facilities. However, local ordinances and restrictions can further increase the minimum distance required to be traveled by these trucks. In 2009, a study surveying residents of the Fort Worth shale basin found that eight of the ten top problems regarding shale activity were directly or indirectly related to traffic and road damage (Theodori 2009, 107). While shale energy producers may be held financially responsible for having roads repaired through road maintenance agreements (RMAs), this repair process creates road closures that would not have otherwise occurred. Shale energy producers often need to build roads to access their drill sites, although these roads are commonly made of sand and gravel. Apart from the large trucks required to carry water, proppants, and equipment, each well being drilled adds 120 to 150 additional commuters to each site. To address increased traffic volumes in high-density shale areas, some counties have widened county roads from two to four lanes, costing an estimated $160 million in one case

(Raimi and Newell 2014, 50). An increased volume of vehicle traffic necessarily leads to increased accidents and traffic fatalities. The increased traffic also may discourage the use of associated walking and biking paths, which could, in theory, affect residents' health and fitness levels.

Road damage can be costly for local townships, mainly if revenue collected from production is not allocated accordingly. Roadways are designed according to expected use, and correspondingly, their useful life is directly related to the frequency and weight of traffic experienced. This outlines why previously existing roads in unconventional shale areas degrade so fast; they were not built to be regularly used by heavy trucks. The common forms of pavement damage include base failure, cracks, bleeding, and worn center and edge lines (Quiroga 2012, 38). The heaviest load associated with shale operations is hauling the drill rig to the well pad (Banerjee 2012, 50). The drill bit is typically hauled around 30 miles to the well pad, though this distance can vary depending on the location (Banerjee 2012, 50). As alluded to, some shale energy producers are held financially responsible for road damage through RMAs, though in some cases, RMAs are not properly upheld by operators (Raimi and Newell 2014, 65). Interestingly, RMAs can take the form of informal agreements stipulating that local operators pay for the necessary materials for the roads they damage while the local township or county provides the labor crews to conduct the repairs (Raimi and Newell 2014, 65). These RMAs can contribute millions of dollars in relief per year to local municipalities. However, since RMAs are sometimes structured as donation agreements, it is ambiguous how these situations would be resolved if the energy developers were to “walk away” from their commitments (Quiroga 2012, 156).

In the Barnett Shale region, Banerjee et al. (2012) estimate the typical damage caused by shale gas development roadway use and the associated service life reduction of four different road types (interstate highways, U.S. highways, state highways, and farm-to-market roads). Aggregating these road types to a total, they find that constructing a new well causes excess wear and tear 13 percent above its traffic design and can reduce the service life by 29 percent (Banerjee et al. 2012, 56). Using similar metrics as used in Banerjee et al. (2012), Abramzon et al. (2014) calculate the consumptive roadway use costs associated with shale activity in the Marcellus areas of Pennsylvania. Abramzon et al. (2014) estimate that each well drilled costs the state between $13,000 to $23,000 in damages (Abramzon et al. 2014, 3). Abramzon et al. (2014) recommend three approaches to address this issue: additional fees based on usage, truck size and weight requirements, or infrastructure quality adjustment. Staying within the Pennsylvania region of the Marcellus Shale, Graham et al. (2015) analyze traffic accident data on 12 northern and six southwestern shale counties from 2005 to 2012. Using a DiD approach, they find that the northern shale counties experienced significantly increased vehicle and heavy truck crash rates, although the southwestern counties displayed insignificant results (Graham et al. 2015, 205). Graham et al. (2015) reason that the insignificance in the southwestern region could be due to a lower overall number of wells drilled, drivers having more previous experience with heavy traffic, and sounder existing infrastructure. In Gopalakrishnan and Klaiber (2014), interacting shale well count and distance to the nearest roadway leads the authors to conclude that the damage of roadways is negatively capitalized into house values consistently over time, unlike other dis-amenities they cite in their paper (Gopalakrishnan and Klaiber 2014, 55).

2.6.5. Induced Earthquakes

After 2009, Oklahoma began to experience unprecedented seismic activity, such that the average magnitude 3.0 (M3) quakes (low risk of damage) between 2000 and 2008 increased by over 2400-fold by 2015 (Morthrope and Wyman 2021, 34). Undoubtedly, at least some of this increase cannot be natural, leading the Oklahoma Geological Survey (OGS) to recognize the majority of them as induced (Cheung et al. 2018, 165). The relationship of this seismic activity to shale development is not through the fracking process itself but the subsequent disposal of wastewater using Class II underground injection control (UIC) wells. In fact, 98 percent of induced earthquakes are determined to be caused by the secondary injection of wastewater like that of UIC wells (Morthrope and Wyman 2021, 34). Class II UIC wells are inactive crude oil production wells repurposed to inject wastewater into deep sedimentary formations (Mothorpe and Wyman 2021, 36). This process is a typical byproduct of shale activity, as the UIC process is the most economical way to dispose of wastewater. However, the process can lead to seismic consequences in regions with susceptible geology, like Oklahoma (Cheung et al. 2018, 154). This is because wastewater injection increases pressure on pre-existing faults that can trigger earthquakes (Langenbruch and Zoback 2016, 1). Since these earthquakes lack historical precedent in the region, they are typically not covered by resident's property insurance, posing prohibitively expensive costs to landowners in the case of damaging earthquakes. With the 2016 earthquake in Pawnee, Oklahoma, less than 2 percent of insurance claims were paid out (Ng'ombe and Boyer 2019, 423). As a result, residents have attempted to hold oil and gas companies responsible for damages in court, but these cases are almost always dismissed because courts in Oklahoma do not view wastewater injection as an atypically perilous activity (Ng'ombe and Boyer 2019, 423).

However, in early 2016, regulations began to be implemented to limit the amount of wastewater injection in Oklahoma by 40 percent (Langenbruch and Zoback 2016, 1). Since then, earthquakes above magnitude 3.0 have steadily decreased (Petersen et al. 2018, 1049). Since the cause of many earthquakes in Oklahoma can be isolated to shale wastewater injection, the effect of earthquakes on the housing market becomes a relevant measure in the literature. Cheung et al. (2018) investigate the impact of underground injection control (UIC) wells and linked seismic activity on house prices across Oklahoma from 2006 to 2014. They hypothesize shale gas development to be negatively capitalized into house prices, which is generally observed in the DiD and hedonic specifications, with larger impacts on house prices associated with more intense earthquakes (Cheung et al. 2018, 162). Oil and gas well counts in these models also had a small but significantly negative impact within a 2 km boundary. Mothorpe and Wyman (2021) build off Cheung et al. (2018) and discover that the price impacts of earthquakes in Oklahoma County are dependent on income quartiles, suggestive that the older homes of lower income quartiles are perceived to be at greater risk of damage to induced earthquakes. They also notice that these housing market impacts begin to diminish before earthquake activity does, suggesting inconsistencies between the risk of earthquakes and how it is perceived (Mothorpe and Wyman 2021, 50).

2.6.6. The Resource Curse

Resource dependence is associated with booms in short-run employment and economic activity. However, studies have shown that in the long run, resource-dependent communities suffer from high unemployment, poverty, instability, and low educational attainment (Jacquet 2014, 8322). “Crowding out” is the primary phenomenon theorized to cause this natural resource curse; the idea is that while resource extraction is the primary focus of economic activity, local supply constraints for capital and other factors of production can leave other local industries “out to dry.” This is mainly driven by the labor market, where although an in-migration of labor can be expected, the extraction sector will also compete with local businesses for existing labor. In the short term, the higher wages caused by shale activity can be prohibitive for local businesses and result in their failure or migration. Then, once the boom ends, residents, who may have captured the higher wages from the shale firms in the short run, may struggle to find new employment opportunities. Another reason for the resource curse is that rapid in-migration can lead to poorly planned housing development, resulting in substandard housing conditions. In-migration typically also increases living costs and rents, which can motivate the out-migration of previously existing residents, particularly if they are not homeowners (Jacquet 2014, 8322).

Brown (2014) analyzes whether there were signs of a resource curse for 647 nonmetropolitan counties across nine states and discovered no such evidence. Instead, Brown observed a 13 percent increase in employment, with other sectors experiencing insignificant declines in employment or additional growth (Brown 2014, 133). Feyrer et al. (2017) analyze shale-producing counties across the U.S. from 2005 to 2012, finding some results opposing Brown's (2014) regarding the resource curse. They discovered that the mining and transportation industries capitalized most on shale production; meanwhile, the manufacturing industry experienced a wage drop (Feyrer 2017, 1324). Similarly, Weinstein et al. (2018) find evidence suggesting crowding out effects in the Marcellus region, perhaps due to commuting workers transferring benefits to adjacent metro areas (Weinstein et al. 2018, 200). Keeler and Stephens (2020) note that shale gas production growth peaked in West Virginia in 2011. Subsequent analysis reveals evidence of a bust period in 2012, as indicated by the reversed sign on the drilling intensity variable after the sample was split into boom-and-bust subsamples (Keeler and

Stephens 2020, 8). Keeler and Stephens (2020) note regions with a history of resource extraction have likely already experienced previous resource booms and busts (Keeler and Stephens 2020, 3), and it is therefore reasonable that areas like West Virginia would have homebuyers rapidly altering their preferences once shale production growth slowed.

3. METHODOLOGY

3.1. Estimation Techniques

3.1.1. Pooled OLS

A panel data set entails repeated observations across time for the same set of observational units. The primary benefit of panel data is the ability to control for individual heterogeneity with most estimation techniques (Baltagi 2013, 6). However, pooled OLS treats all observations as independent and identically distributed despite the time and cross-sectional dimensions of the data. Hence, pooled OLS is generally a less desirable estimation technique for panel data.

3.1.2. Fixed Effects

An alternative transformation that addresses the correlation between regressors and unobserved fixed effects is the deviation from within-group means (MDEV) transformation. This transformation is thought of as taking deviations from cross-section means and then following that with an OLS regression (Hsiao et al. 1999, 145). Thus, within-in-groups estimation can be represented as:

$$y_{it} - \bar{y}_i = \beta(x_{it} - \bar{x}_i) + \varepsilon_{it} - \bar{\varepsilon}_i, \qquad i = 1, \dots, N, \qquad t = 1, \dots, T.$$

where $\bar{y}_i$, $\bar{x}_i$, and $\bar{\varepsilon}_i$ are group means for each variable in a manner where $\bar{y}_i = T^{-1} \sum_{t=1}^{T} y_{it}$, and so on (Wooldridge 2013, 435). When interpreting the within-groups fixed effects (FE) estimator, the parameters are only identified through the within dimension of the data (Verbeek 2004, 347). The critical aspect of the equation above is that the MDEV transformation eliminates the unobserved heterogeneity term a_i by concentrating on how y_{it} differs relative to $\bar{y}_i$. A natural consequence of this time-demeaning transformation is that any regressors that are constant over time for each individual are eliminated, including the intercept. Following this logic, in an unbalanced panel dataset, like the one used in this paper, if any panels contain only one observation, they do not influence the analysis.

As long as these unobserved individual or group-specific effects are time-invariant and the regressors are strictly exogenous with the error term, the FE approach will be unbiased and consistent as T approaches infinity. Strict exogeneity requires that

$$E[x_{it}\varepsilon_{is}] = 0 \qquad \text{for all } s, t,$$

where x_{it} is x_i in period t and ε_{is} is ε_i in a different period s (Verbeek 2004, 346). This condition invariably impedes the use of lagged dependent variables in FE estimation. However, it is also possible for other explanatory variables that depend on y_{it} to violate the above condition. Unlike pooled OLS, the disturbances for FE models use a one-way error component model for the disturbances, such that

$$\varepsilon_{it} = \varepsilon_i + v_{it}$$

where ε_i is the unobserved individual specific effects and v_{it} are all of the other remaining disturbances (Baltagi 2013, 13).

3.1.3. System GMM

When modeling average house prices at the county level, two concerns remain unaddressed by the preceding techniques. Firstly, previous studies have found that house values have an influence of previous values on current realizations (Zabel 2016, 384). These dynamics call for the introduction of lagged dependent variable(s). This becomes advantageous because it provides the history of the independent variables, allowing for the new measured influence from the independent variables to be isolated from the complete set of information producing any particular observation (Greene 2003, 307). Unfortunately, in the previously described methods, including lagged dependent variables will cause endogeneity because this new lagged term will be correlated with the disturbance. The other concern unaddressed by the previously detailed estimation techniques is possible endogeneity in the regressors. Particularly common with socioeconomic variables, there are multiple different possible causes of endogeneity ranging from reverse causality to omitted variable bias. Endogeneity in the explanatory regressors typically calls for instrumental variable (IV) methods to avoid biased and inconsistent estimates. One common technique to address endogeneity is two-stage least-squared (2SLS). However, this approach requires finding at least one external variable that is both exogenous and partially correlated with the endogenous variable being addressed. In practice, finding a variable that satisfies these two conditions can be very challenging (Wooldridge 2013, 488).

A remedy to both of these two concerns is the Arellano-Bond difference GMM estimator (Holtz-Eakin et al. 1988; Arellano and Bond 1991) or the Blundell-Bond system GMM estimator (Blundell and Bond 1998), a later expansion of the difference GMM. The Arellano-Bond estimator was designed to account for additional orthogonality conditions between lagged values of y_{it} and the disturbances, which previous estimators did not capture. The difference GMM involves transforming regressors to create a first-differenced (FD) equation, which removes the individual fixed effects and then instrumenting lagged levels of the endogenous variables into this FD equation to address possible endogeneity. The procedure to obtain the difference GMM one-step estimates involves using generalized least squares (GLS) on the differenced equation. Subsequently, Arellano and Bond show that the residuals from the one-step estimator can be used to update the covariance matrix in the second step, leading to a two-step estimator that is more efficient when disturbances are heteroskedastic (Arellano and Bond 1991, 279).

Two other critical details in Arellano and Bond (1991) are the tests for serial correlation and over-identifying restrictions. When testing specifications, the authors acknowledge that although it was acceptable for first-order serial correlation in the errors of the FD equation, the consistency of the GMM estimator relies upon no second-order serial correlation in the errors (Arellano and Bond 1991, 281). This means that when testing the “Arellano-Bond AR(1) test”, the null of no first-order serial correlation is expected to be rejected. However, notably, the null of no second-order serial correlation should not be rejected with the “Arellano-Bond AR(2) test”. Additionally, Arellano and Bond (1991) suggest that when there are more moment conditions than estimators, the extra moment conditions should be used to employ Sargan’s test of over-identifying restrictions (Arellano and Bond 1991, 282). In this Sargan test, the null of exogenous instruments should not be rejected. However, Roodman (2009) notes that p-values on the test of 0.25 or higher are a potential sign of too many instruments (Roodman 2009, 129).

Many subsequent papers were able to improve upon the Arellano and Bond estimator, the first being Ahn and Schmidt (1995). Ahn and Schmidt (1995) discover that additional nonlinear moment conditions are unused by the Arellano Bond estimator (Ahn and Schmidt 1995, 10)[1]. They also discover an inherent small-sample bias in the two-step Arellano and Bond estimator, which Windmeijer (2005) consequently addresses. Windmeijer (2005) offers corrected standard errors based on Taylor series expansion, which he shows to be more accurate when dealing with finite samples and only linear moments (Windmeijer 2005, 30)[2]. Additionally, Tauchen (1986) is the first to point out that a bias-efficiency trade-off is caused by too many moment conditions in certain specifications as T increases past 50 (Tauchen 1986, 406)[3].

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[1] Sebastian Kripfganz implemented these nonlinear moments in his GMM Stata program, xtdpdgmm.

[2] For this reason, the finite-sample correction of Windmeijer is applied by default in xtdpdgmm when robust standard errors are indicated.

[3] Roodman would later label this issue as “instrument proliferation” and included instrument collapsing and curtailing options in his popular xtabond2 command to limit this instrument proliferation. These options are similarly available in the xtdpdgmm Stata command.

Blundell and Bond (1998) offered perhaps the most significant improvement from the Arellano and Bond estimator when they developed the system GMM. Blundell and Bond accredit the poor precision and bias of the Arellano and Bond estimator to its issue with weak instruments in cases of a random walk for the dependent variable (Blundell and Bond 1998, 121). To address this weak instruments problem, the authors put forth a new GMM estimator that, in addition to using lagged levels as instruments for the FD equation, also implements lagged differences for the levels equation. The system GMM requires an initial conditions restriction on y_{i1}:

$$E[\Delta y_{i1} a_i] = 0$$

such that in all subsequent periods, y_{it} converges towards its mean (Blundell and Bond 1998, 124). This initial condition restriction is what allows for $\Delta y_{i,t-1}$ to become available as an instrument for $y_{i,t-1}$. Similarly, the following constant correlation restriction:

$$E[x_{it} a_i] = E[x_{is} a_i] \qquad \text{for all } s, t,$$

previously put forth by Arellano and Bover (1995) establishes Δx_t as a valid instrument for x_t, when x is a predetermined variable since its difference is strictly exogenous with the contemporaneous error term. In addition to showing stark efficiency gains in comparison to the system GMM, Blundell and Bond (1998) use Monte Carlo simulation analysis to exhibit that when faced with an example application to a short T and persistent data set, the system GMM also shows improved precision (Blundell and Bond 1998, 138). Since our data follows this profile of a short T with high autoregressive dependence, we use the Blundell and Bond (1998) estimator as our dynamic panel GMM estimator. We further detail our choice of GMM specification in section 3.2.

However, as Roodman points out, subtracting the previous observation (in period $t-1$) from the current observation (in period t) “magnifies gaps in unbalanced panels” (Roodman 2009, 104). Therefore, if data is unavailable for some years, then first-differencing eliminates some observations in the unbalanced panel data set. Thus, Arellano and Bover (1995) suggest an alternative to first-differencing: the forward orthogonal deviations (FOD) transformation method (Arellano and Bover 1995, 41). The FOD method subtracts the mean of all available future observations from the current observation regardless of the number of gaps in the data, and only the last observation is dropped. For example, the FOD transformed dependent variable is

$$y_{it}^{*} = c_t \left(y_{it} - \frac{1}{T-t} (y_{it+1} + y_{it+2} + \cdots + y_{iT}) \right), \qquad t = 1, \dots, T-1,$$

where $c_t = ((T-t)/(T-t+1))^{\frac{1}{2}}$, T is the total time periods, and c_t serves as a weight that equalizes the variances (Arellano and Bover 1995, 46) and assures y_{it} to be identically distributed (Roodman 2009, 105). The same transformation is implemented on the other variables to create FOD-transformed variables. The FOD method helps preserve data size by minimizing data eliminations in transforming unbalanced panel data.

However, FOD is not the only alternative transformation to FD in dynamic panel GMM estimation. The deviations from within-group means (MDEV) transformation used in FE models is also a valid transformation for strictly exogenous regressors (Kripfganz 2019, 88). Kripfganz (2021) notes that a mix of model transformations can be utilized for the transformed equation (FOD, MDEV, and FD) and that using an MDEV transformation is the optimal way to treat strictly exogenous variables because the transformation maximizes the possible correlation between the instrument and the regressor. Given the benefits of the FOD and MDEV transformations, our system GMM specification takes on the form:

$$\begin{bmatrix} \tilde{\Delta} y_{it} \\ y_{it} \end{bmatrix} = \alpha + \lambda \begin{bmatrix} \tilde{\Delta} y_{it-p} \\ y_{it-p} \end{bmatrix} + \beta_1 \begin{bmatrix} \tilde{\Delta} x_{it1} \\ x_{it1} \end{bmatrix} + \beta_2 \begin{bmatrix} x_{it2} - \bar{x}_{i2} \\ x_{it2} \end{bmatrix} + \begin{bmatrix} \tilde{\Delta} \varepsilon_{it} \\ \varepsilon_{it} \end{bmatrix}$$

where $\tilde{\Delta}$ indicates a FOD transformation, y_{it-p} is the p^{th} lag of y_{it}, x_{it1} is an endogenous explanatory variable, and x_{it2} is a strictly exogenous variable. In the top of the stack is the transformed equation, which is instrumented by lagged levels, and in the bottom of the stack is the levels equation, which is instrumented by lagged differences. Kiviet (2020) notes the requirement of what he refers to as effect-stationarity for the lagged differences of a variable to a valid instrument in the levels model. However, Kiviet (2020) emphasizes that if a set of specified regressors include some that appear not to be effect-stationary, this does not suggest that system GMM cannot be pursued. Instead, he suggests that only the variables that appear effect-stationary should be instrumented in the level model (Kiviet 2020, 38).

3.2. Empirical Strategy

The hedonic pricing method (HPM) is often applied to the housing market, which is a method to describe how buyers select goods based on their relevant characteristics. In the HPM, housing market outcomes are decomposed to revealed preferences in equilibrium such that the price of a house is the function of the house's nonmarket attributes, including any positive or negative externalities of shale activity (Rosen 1974, 34). Thus, econometric analysis is used to derive the implicit impact on local welfare from shale activity at the county level. In other words, if prospective homebuyers value the amenities of shale energy over its dis-amenities, then house prices in counties with more shale production should increase, ceteris paribus. Including year fixed-effects dummies helps control for systematic trends in the housing market and makes the assumption of equilibrium conditions more feasible.

Our analysis includes the same set of thirteen control variables in the pooled OLS, fixed-effects, and system-GMM models. The variables of interest in this study are two logged-transformed shale production variables: the natural log of shale oil production and the natural log of shale gas production. Next, we include four socioeconomic control variables: the natural log of GDP per capita, the percentage of high school graduates, the percentage of at least some college experience, and the state mortgage rate. To account for demographic characteristics, we include the following four demographic control variables: the natural log of population density, the median age of the population, the percentage of the black population, and the percentage of married couples with children. Finally, we designate three structural variables: the percentage of apartment units, the median structural age, and the average bedrooms per unit. In addition to this set of explanatory variables, each specification includes the complete set of year dummies, with the 2010-year dummy being the omitted group. However, the 2011- and 2012-year dummies are dropped in the system-GMM estimation due to the inclusion of two lags of the dependent variable.

In choosing between the Arellano-Bond one-step GMM estimator and the Blundell-Bond two-step system GMM estimator, the latter is specified for increased efficiency. Preliminary candidate results suggest that two lags of the dependent variable are appropriate. Since this study deals with unbalanced data with gaps, we follow the advice of Roodman (2009) and incorporate the FOD transformation in place of the first differences for the exogenous and predetermined variables in our transformed model. To maximize the possible correlation between the instruments and regressors, we utilize the MDEV transformation for our strictly exogenous regressors. Specification choices regarding instruments are adapted from the sequential selection process of Kiviet (2020), and candidate models are tested by the Andrews-Lu model and moment selection criteria, for which we rely on the Akaike Information Criterion (AIC). This informs our use of only the first lags for all variables in the transformed equations. In the levels equation, only contemporaneous lags are included as additional lags are redundant (Kripfganz 2019, 31). Kiviet (2020) remarks that regressors should be inspected for this effect-stationarity assumption using incremental overidentification tests. However, when these tests are applied in our study, they suggest including variables that drive the overall Sargan overidentification test to thresholds of a high concern for the problem of too many instruments (to p-values of 0.8 and above). For this reason, in determining which variables to treat as effect-stationary, we instead analyze the stability of regressors over time. This analysis yields four variables to be effect-stationary that are instrumented for the levels model: the average bedrooms per unit, the percentage of apartment units, the natural log of population density, and the percentage black. The collapse option is also used for all lags to mitigate the “too many instruments” problem. Finally, to address heteroskedasticity, panel-robust standard errors are included.

4. DATA

The data used in this study is a panel dataset for all counties within the contiguous United States that could be matched with the shale and control variables. Table 1 gives a description and the source of all variables. In total, the dataset covers 2,932 counties. However, since the dataset is unbalanced with gaps in some panels, the total number of observations from 2010 to 2019 is 24,863.

Table 1. Data Description and Sources

Variables	Description	Source
House Value	Represents the "typical" county home value in dollars. Zillow calculates it as a weighted average of the middle third of homes in a given county.	Zillow Home Value Index (Zillow 2023)
Shale Oil	Annual production of shale oil in barrels.	Mineral Answers (Mineral Answers 2023) & States' Websites
Shale Gas	Annual production of shale gas in cubic feet.	
% with Children	The percentage of married-couple families with children of the householder under the age of 18.	ACS DP02 Data Profile (U.S. Census 2023a)
% Apartment Units	The percentage of housing units in a structure consisting of 20 or more units.	ACS DP04 Data Profile (U.S. Census 2023c)
Avg. Bedrooms Per Unit	Represents the average number of bedrooms per housing unit. It was calculated using the proportions of the total housing units that fall under the specified bedroom categories.	
Age of Population	The median age of the population in years.	ACS DP05 Data Profile (U.S. Census 2023d)
% Black	The percent of the total population whose race is Black or African American.	

Table 1. Data Description and Sources (continued)

Variables	Description	Source
Population Density	The population per square mile of land area. It is calculated by first converting the land area from square meters to square miles. Finally, the total population is divided by this land area in square miles.	ACS DP05 Data Profile (U.S. Census 2023d) and TIGERweb State-Based Data Files (U.S. Census 2020)
% High School Grad	The percentage of the 18- to 24-year-old population whose highest educational attainment was high school graduation or an equivalency.	ACS S1501 Subject Table (U.S. Census 2023f)
% at Least Some College	The percentage of the 18- to 24-year-old population whose highest educational attainment was at least some college (also includes those who earned any college-earned degrees).	
Structure Age	Measures the median age of housing unit structures. It is calculated by subtracting the median year built from the current year for the estimate.	ACS B25035 Detailed Table (U.S. Census 2023e)
GDP Per Capita	The gross domestic product per capita in thousands of dollars. It was calculated by dividing the BEA all industry total GDP by the Census ACS total population estimate.	BEA CAGDP2 (U.S. Bureau of Economic Analysis. 2023a) and ACS DP05 Data Profile (U.S. Census 2023d)
Mortgage Rate	Represents the state-wide average 30-year fixed home mortgage rate.	ILM3 State Indices (Bloomberg L.P. 2023)

The Zillow Home Value Index (ZHVI) represents typical county house values, including single-family residences, condominiums, and cooperative housing. Importantly, the ZHVI values are average values, not median values. This is because it estimates a sale price for every home, not just those sold, avoiding the bias associated with median sale prices (Weber et al. 2016, 615). The county-level ZHVI used in this study is calculated as the weighted average of the middle third of homes in each county for each month (Allison, 2022). To match it with our explanatory variables, we took an annual average of these monthly ZHVI values. In order to obtain the data on shale oil and gas production, various state websites were used in addition to Mineral Answers.

Table 2. Summary Statistics

	Mean	SD	Min	Max
House Value ($'000)	134.20	85.50	15.06	1583.27
Shale Oil (millions)	0.53	4.77	0.00	189.00
Shale Gas (millions)	8.67	58.56	0.00	1970.00
Population Density	293.93	1944.48	0.22	72993.50
GDP Per Capita ($'000)	42.69	29.87	8.71	910.35
% High School Grad	35.58	8.91	0.00	100.00
% at Least Some College	46.35	12.62	0.00	92.30
% Apartment Units	2.87	4.06	0.00	78.80
Age of Population	40.52	5.01	22.70	67.40
Structure Age	39.39	11.01	10.00	80.00
Mortgage Rate	4.09	0.42	3.32	5.15
Avg. Bedrooms Per Unit	2.70	0.19	1.20	3.83
% Black	9.26	13.91	0.00	86.40
% with Children	27.18	5.10	4.90	54.30

Number of observations = 24,863

The primary data source for the control variables is the Census American Community Survey (ACS) 5-year estimates. Specifically, data profiles, subject tables, and a detailed table were used to obtain the data for seven of the control variables. These different data tables provide annual cross-sectional county-level estimations of social, economic, demographic, and housing characteristics for all counties in the U.S., which can then be pooled into a panel. The 5-year estimates were selected instead of 1-year estimates because of sampling issues with the 1-year estimates that caused many more observations to be missing. The 5-year estimates are an average, including the current and four previous years. It is important to note that, unlike the Decennial Census, the ACS surveys are aimed at a sample of the population and yield estimates rather than exact measures. In addition to the Census, we used BEA’s interactive tables and a Bloomberg terminal to pool data on county gross domestic product (GDP) and state mortgage rates. Table 2 presents the summary statistics for all of these variables. Table 3 presents the correlation matrix for the house value and shale production variables.

Table 3. Correlation Matrix for Variables of Interest

	House Value	Shale Oil	Shale Gas
House Value	1		
Shale Oil	0.020	1	
Shale Gas	0.001	0.232	1

The summary statistics show that our sample's typical county house price was $134,200. The lowest typical county house price was $15,060, observed in Lawrence County, Illinois, in 2012. The highest typical county house price of $1,583,270 was for Nantucket County, Massachusetts, in 2019. This wide range of typical housing values is more extreme than in similar analyses (Rakitan 2018; Jacobsen 2019), partly due to this paper's wider scope of geography. Supporting this reasoning, the mean value is very close to that of Rakitan (2018) and Jacobsen (2019). For the shale oil and shale gas variables, on average, more cubic feet (CF) of shale gas were produced in each county than barrels of oil. These oil and gas production averages were 530,000 barrels and 8.67 million CF, respectively. Due to the limited literature using shale production data, it is not possible to effectively compare the summary statistics of the shale variables. Midland County, Texas, in 2019, provided the largest shale oil production in our sample, with 189,000,000 barrels of oil produced. De Soto Parrish, Louisiana, produced 1,970 million CF of shale gas in 2019, the largest yearly total for gas production in our sample.

Our sample's average population density for counties is 293.93 people per square mile of land area. This population density measure is at its lowest in Garfield County, Montana, during 2019 and at its highest in New York County, New York, during 2017, with population densities of 0.22 and 72,993.50 people per square foot, respectively. GDP Per Capita ranges from $8,710 to $910,350, with an average of $42,690. The variation in this variable across different counties can be challenging to pin down since it can be influenced by population as well as GDP. To illustrate this, Eureka County, Nevada, is responsible for the largest GDP Per Capita, which is also among the sample's top five least populated counties per square mile. Interestingly, the counties with the smallest GDP Per Capita have little to no shale production, such as Long County, Georgia, which had the smallest GDP Per Capita in 2010. For the % High School Grad variable, the widest variation exists between Hooker County, Nebraska, where none of their residents aged 18 to 24 had the highest educational attainment of high school in 2019, and San Juan County, Colorado, in which all of their residents aged 18 to 24 had the highest educational attainment of high school in 2018. These opposite extremes both occurred in counties with low populations. The average percentage is 35.58 percent, so typically, over one-third of a county’s population aged 18 to 24 has a high school degree or equivalence as their highest attainment. The % at Least Some College has a higher mean percentage, suggesting 46.35 percent of a county’s population aged 18 to 24 has at least some college educational experience to show. Mineral County in Colorado had the highest percentage in 2017, with 92.3 percent of their residents aged 18 to 24 having some experience in college, while San Juan County in Colorado had none of such residents with college experience in 2018. Like with the % High School Grad variable, these extremes occurred in lowly populated counties.

According to the summary statistics of the % Apartment Units variable, the average percentage of housing units in the form of a 20-unit structure or larger is 2.87 percent, rising to 78.8 percent for New York County, New York, in 2019. For the Median Age variable, the average across the sample is 40.52 years. Sumter County in Florida had the highest median age observation in 2019 at 67.4 years, while Madison County in Idaho had the lowest at 22.7 years in

2012. The summary statistics reveal that the typical median age of housing unit structures in the sample is 39.39 years, with the newest housing units being built in Pinal County, Arizona, and the oldest housing units residing in counties such as Brooklyn, New York. As referenced, the Mortgage Rate variable is collected at the state level instead of the county level, which is partly why there is relatively less variation in this variable compared to others in our sample. The average mortgage rate across our sample is 4.09 percent, with the lower bound occurring at 3.32 percent in 2012 and the upper bound occurring at 5.15 percent in 2010. The typical county average number of bedrooms per unit across our sample is 2.7 bedrooms. The smallest county average for this variable occurs in New York County, New York, during 2010, at 1.2 bedrooms. Meanwhile, 3.83 is the highest average number of bedrooms in the sample, occurring in Morgan County, Utah, during 2018. The summary statistics of the % Black variable show that typically, 9.26 percent of a county's residents are black in our sample. The highest abundance of black residents occurred in Jefferson County, Mississippi, which observed an 86.4 percent makeup of black people in 2017. Finally, the % with Children variable has a mean of 27.18 percent in our sample, meaning that 27.18 percent of the married couples have children of the householder whose age is under 18 in the typical county. In 2010, this percentage increased to 54.30 percent for Chattahoochee County, Georgia, and reached as low as 4.9 percent for Sumter County in Florida during 2019.

Figure 1 below is a geographic demonstration of the average annual percentage change in our housing value variable across the years of our full sample. The average percentage changes are graphed in red for negative changes and green for positive changes, with darker shades signifying more extreme average changes. This graph demonstrates how county-level housing values have experienced heterogeneous change over time, particularly in the dark red and green counties. Figures 2 and 3 display the cumulative shale oil and gas production by county from 2010 to 2019. To tie this production to some of the basins discussed in the literature review, many of the major shale basins are displayed with an associated color. For these figures, increased production is presented on darker shades of black. These figures reinforce how shale basins are often more inclined towards either shale oil or gas production and showcase the heterogeneity in production across shale basins. In Figure 4, we include a chart graphing the path of nationwide shale oil and gas production within our dataset. In this graph, the annual sum of shale gas production in CF is on the left axis, and the annual sum of shale oil production in barrels is on the right axis. This figure helps demonstrate the boom and bust-nature of shale production at a national scale.

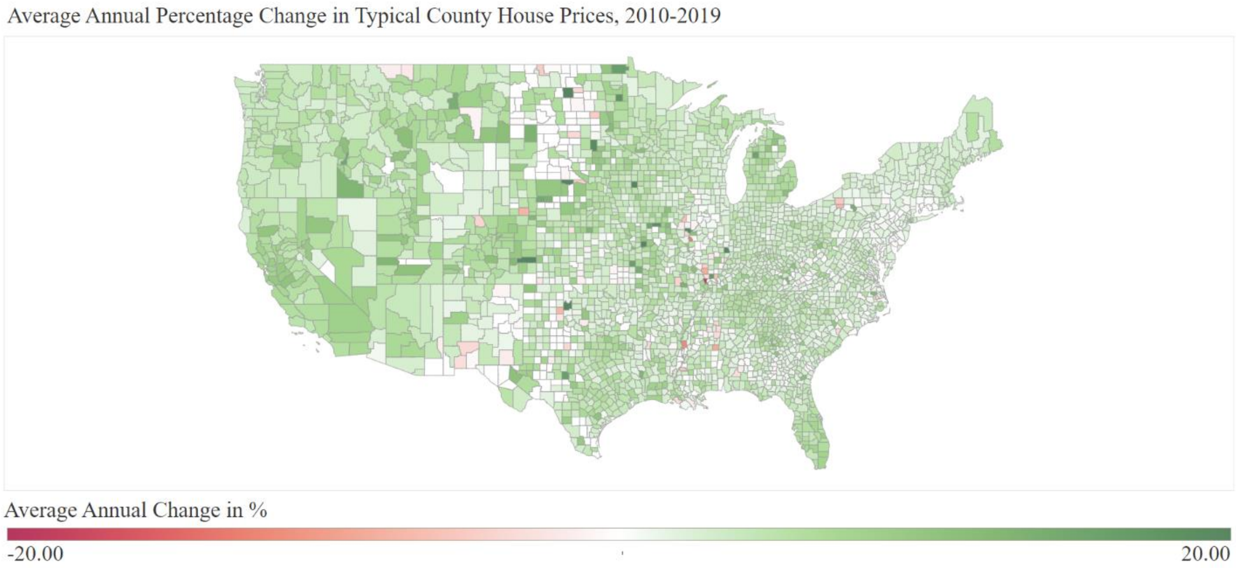

Figure 1. Average Annual Percentage Change in Typical County House Price from 2010-2019.

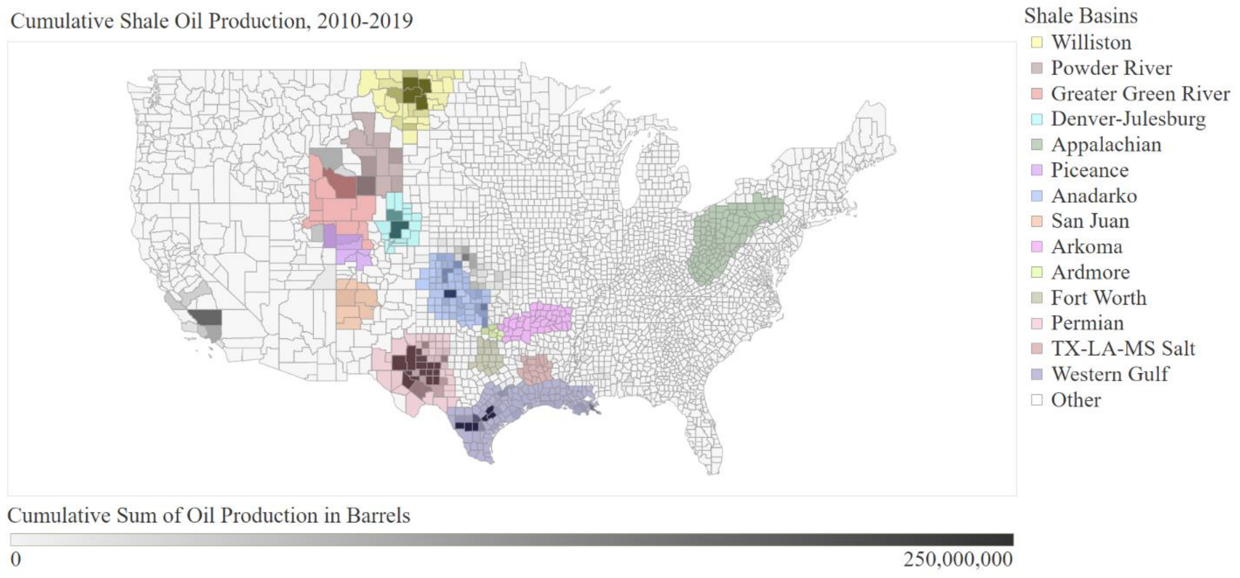

Figure 2. Cumulative Shale Oil Production from 2010-2019.

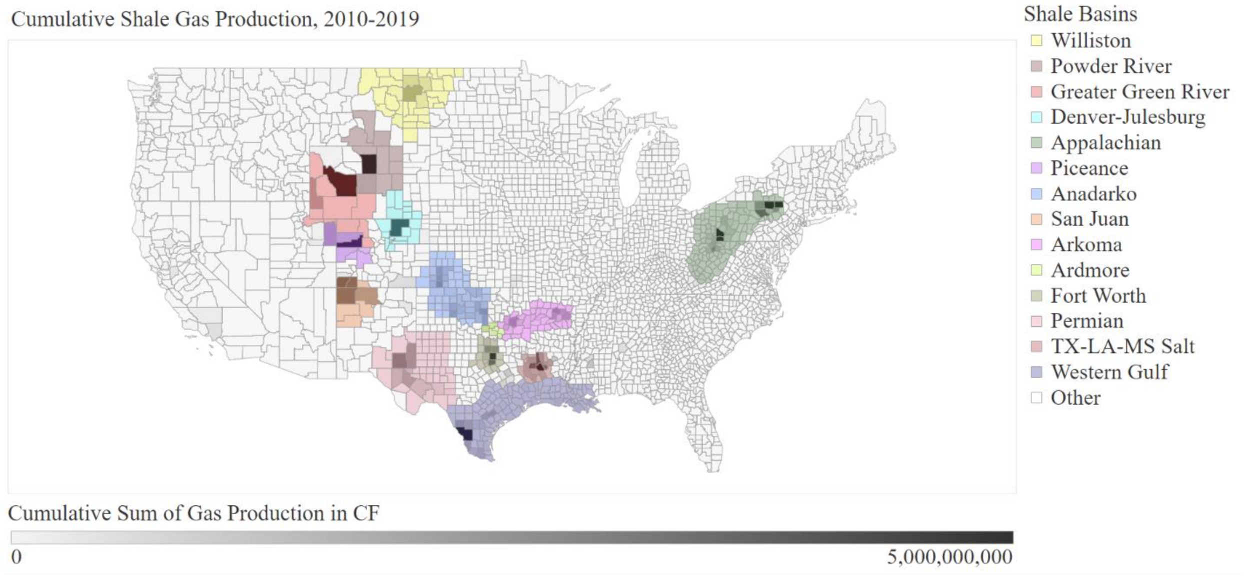

Figure 3. Cumulative Shale Gas Production from 2010-2019.

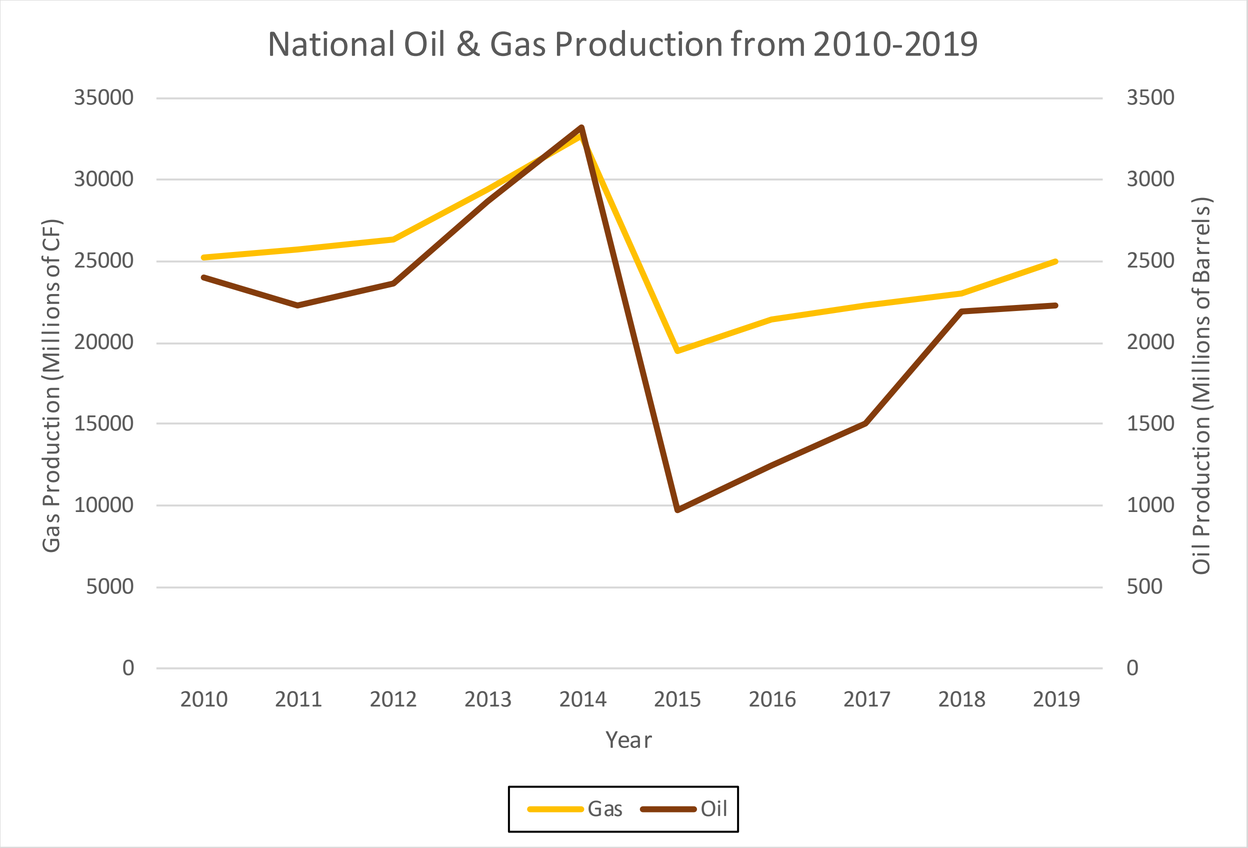

Figure 4. National Oil & Gas Production from 2010-2019.

5. RESULTS

Table 3 provides the results from the specifications from Chapter 3. The pooled OLS specification yielded a reasonably high r-squared at 0.561, with mostly expected results for the control variables. Taken at face value, the Pooled OLS appears to have more significant variables, but this is likely caused by the endogeneity and serial correlation that is not addressed by the pooled-OLS specification. The R-squared improves to 0.729 for the fixed-effects model, but still with one confounding sign on the structure age variable. The system GMM has a similar number of significant control variables to the FE specification, which are all of the expected signs. Additionally, the first lag of the dependent variable is significant and in a range that does not suggest an unstable dynamic accelerating away from equilibrium values (Roodman 2009, 103). The results in the FE and system GMM models suggest that county shale oil and shale gas production does not have statistically significant effects on housing values. We will return to this result later.

The population density variable is positive in all specifications, which follows the expected sign from the literature (Shon and Chung 2018; Giertz et al. 2021). However, the magnitude varies widely from the pooled OLS to the FE, and the statistical significance is lost in the system GMM specification. The significant results are interpreted as a 10 percent increase in the population per square mile corresponding to a 0.52 percent increase in typical house prices in the pooled OLS specification and an 8.12 percent increase in the FE estimation, ceteris paribus. Compared to Shon and Chung (2018), which finds a 3.1 percent impact on median house values after the same change in population density, the pooled OLS point estimate is quite short of this value and conversely, the point estimate for the FE estimate is well beyond what we would expect. It should be noted, however, that the insignificant result of the system GMM estimation is not uncommon in previous studies as well (Wang 2016; Ma and Gopal 2018).

The next control variable, GDP per capita, exhibits a positive and statistically significant effect across all three specifications, although only at the 10 percent level in the system GMM. The coefficients for this variable suggest that a 10 percent increase in the GDP per capita will increase the typical house price by 2.9 percent in the pooled OLS specification, 0.7 percent in the FE specification, and 0.5 percent in the system GMM specification, ceteris paribus. The point estimates for the pooled OLS are nearly twice as large as in Norwood (2020), and the FE and system GMM point estimates are about half the size of those in Norwood (2020). Bourassa et al. (2011) and Lin et al. (2014) also find positive and significant relationships between GDP per capita and house prices. However, the point estimates of these papers are difficult to compare due to differences in functional form.

Since the omitted group in the educational control variables is the percentage of people whose attainment is less than high school, the expected sign for both the % High School Grad and % at Least Some College variables should be positive. However, we expect the point estimate on % at Least Some College to be larger, indicating returns to higher education (Muehlenbachs et al. 2012; Bennet and Loomis 2015; Rakitan 2018). Following this, we find that the % high school grad variable is only significant in the pooled OLS specification, and its point estimate is small, suggesting that a 10 percent point increase in the percentage of people whose highest attainment is high school graduation will increase typical house prices by 1 percent, ceteris paribus. As expected, the % at Least Some College is larger for the pooled OLS specification and displays statistical significance for the system GMM estimation. Ceteris paribus, the pooled OLS and system GMM estimates suggest that a 10 percent point increase in the percentage of people with at least some college experience increases typical house prices by 6 percent and 1 percent, respectively.

Continuing with the control variables, we find that the % Apartment Units is significant in the pooled OLS and system GMM specifications, but their point estimates vary. Nonetheless, both variables follow the expected positive sign (Bogin et al. 2019; Carbone 2021), which may be driven by the fact that apartment units typically exist in areas of high housing demand and can often offer upscale amenities compared to single units. The coefficients indicate that a 10 percent point increase in the percentage of apartment units increases typical house prices by 4.1 percent in the pooled OLS specification and 0.6 percent in the system GMM, ceteris paribus. Unfortunately, these point estimates cannot be easily compared to past studies due to differences in the functional form.

Like the % Apartment Units variable, we find a positive and significant effect with the Age of Population variable only in the pooled OLS and system GMM specifications. These estimates are both consistent with similar variables used in previous studies (Muehlenbachs et al. 2012; Lin et al. 2014; Ma and Gopal 2018; Zapatka and Beck 2021), implying that a 1-year increase in the median age of the population will increase the typical house value by 2.1 for the pooled OLS estimation and 1.3 percent in the system GMM estimation, ceteris paribus. In past studies, this positive effect has been tied to older age segments having a higher proportion of homeowners, lower job-related mobility, and typically less mortgage debt. Unfortunately, the point estimates are not comparable to past studies because age is typically controlled for in specific segments instead of the median measure.

Table 4. Primary Regression Results

	Pooled OLS	Within FE	SYS GMM
L.ln(House Value)			0.672**
			(0.310)
L2.ln(House Value)			0.273
			(0.339)
ln(Shale Oil)	-0.010***	0.000	-0.002
	(0.001)	(0.001)	(0.001)
ln(Shale Gas)	-0.000	-0.001	0.001
	(0.001)	(0.001)	(0.001)
ln(Population Density)	0.052***	0.812***	0.006
	(0.002)	(0.054)	(0.004)
ln(GDP Per Capita)	0.293***	0.072***	0.045*
	(0.007)	(0.013)	(0.026)
% High School Grad	0.001**	0.000	-0.000
	(0.000)	(0.000)	(0.001)
% at Least Some College	0.006***	0.000	0.001***
	(0.000)	(0.000)	(0.001)
% Apartment Units	0.041***	0.000	0.006*
	(0.002)	(0.002)	(0.003)
Age of Population	0.021***	0.001	0.013***
	(0.001)	(0.002)	(0.005)
Structure Age	-0.020***	0.002***	-0.003**
	(0.000)	(0.001)	(0.001)
Mortgage Rate	-0.403***	-0.030***	-0.548
	(0.044)	(0.008)	(0.396)
Avg. Bedrooms Per Unit	0.370***	0.008	0.107**
	(0.018)	(0.027)	(0.048)
% Black	-0.008***	-0.001	-0.000
	(0.000)	(0.002)	(-0.001)
% with Children	0.006***	-0.000	-0.002
	(0.001)	(0.001)	(0.002)
Constant	10.807***	7.991***	1.580*
	(0.228)	(0.253)	(0.933)
N	24863	24863	18957
R-Squared	0.561	0.729	
Year Fixed Effects	Yes	Yes	Yes
Sargan/Hansen p-value			0.2097
AR(1) p-value			0.000
AR(2) p-value			0.223

Standard errors in parentheses
* p<0.10, ** p<0.05, *** p<0.01

One of the most common control variables in the previous studies is structure age, which is significant across the three specifications, but the estimates are quite heterogeneous. The results indicate that if the median age of housing units increases by one year, the typical house price will decrease by 2 percent in pooled OLS, increase by 0.2 percent in the FE, and decrease by 0.3 percent in the system GMM, ceteris paribus. This negative return to age in the pooled OLS and system GMM is the expected sign for this variable based on previous studies (Boxall et al. 2005; Muehlenbachs et al. 2012; Gopalakrishnan and Klaiber 2014; Bennet and Loomis 2015; Balthrop and Hawley 2017; He et al. 2018; Stephens and Weinstein 2019; Keeler and Stephens 2020; Lee and Whitacre 2021; Mothorpe and Wyman 2021). As for comparing the point estimates to studies of a similar functional form, the system GMM is very close to many previous estimates, which range from 0.3 percent to 0.7 percent (Bennet and Loomis 2015; Balthrope and Hawley 2017; Lee and Whitacre 2021). Meanwhile, the pooled OLS is too large even when compared to the largest previous estimates, which are in the 1.2 to 1.4 percent range (Muehlenbachs et al. 2012; Mothorpe and Wyman 2021). Quite frequently in the relevant studies, a squared term is included to control for nonlinear effects (Gopalakrishnan and Klaiber 2014; Boslett et al. 2016; Delgado et al. 2016), but this additional regressor was not significant when included across our specifications.

The Mortgage Rate variable is a less commonly used variable, but intuitively, it should be negative, which is reflected in previous studies (Lin et al. 2014; Vonlanthen 2021; Özgüler et al. 2023). The coefficients of the pooled OLS and system GMM estimations are significant at the 1 percent level, and both follow this expected sign, although with very different magnitudes. The underlying logic for the negative impact is that increases in mortgage rates make houses less affordable, discouraging new buyers from entering the market and thereby reducing demand. The pooled OLS coefficient suggests that a one percentage point increase in the mortgage rate will decrease typical house prices by 40.3 percent. In contrast, the FE coefficient indicates a three percent decrease from the same change in the mortgage rate, ceteris paribus. Both coefficients are large relative to past studies, but the three percent decrease in the FE estimation is much closer to the typical one percent impact (Vonlanthen 2021; Özgüler et al. 2023).

Similar to control variables for the age of units, the number of bedrooms is a prevalent factor to control for. Our results showed the Average Bedrooms Per Unit variable to be positive and significant in the pooled OLS and System GMM specifications. This positive sign is intuitive since homes with more bedrooms are more accommodating, and additional bedrooms lead to additional square footage. In the previous studies with specific housing transactions that are also able to control for square footage, the number of rooms variable is typically negative, if at all significant, because increasing the number of rooms while holding square footage constant translates to smaller rooms (Timmins and Vissing 2015; Bathrop and Hawley 2017). However, in our study, we cannot control for any measures of square footage due to aggregating at the county level. Ceteris paribus, the pooled OLS and system GMM results suggest that an additional average bed per unit increases the typical house price by 37 percent and 10.7 percent, respectively. Both of these point estimates appear larger than the three to four percent range in the previous studies (Keeler and Stephens 2020; Lee and Whitacre 2021; Turner and Seo 2021), with the exception of the system GMM estimate being relatively close to that of Norwood (2020).

Race plays a role in discussions about home values, particularly because of phenomena like "white flight" and "gentrification." We decided to control for % black, for which previous studies found negative and significant effects (Muehlenbachs et al. 2012; Shon and Chung 2018;

Kim et al. 2020; Giertz et al. 2021). In our results, this expected relationship is only significant for the pooled OLS specification. The point estimate for this result means that a 10-percentage point increase in the population whose race is Black or African American will decrease the typical house value by 0.6 percent, ceteris paribus. This point estimate is directly in line with the point estimates in most of the previous studies we examined (Muehlenbachs et al. 2012; Shon and Chung 2018; Kim et al. 2020). As for the final control variable remaining, the results reveal that the % with Children variable is only significant in the pooled OLS specification. This variable is important in explaining house prices because it is associated with a greater demand for space and, therefore, a greater demand for suburban housing. The pooled OLS point estimate says that a 10-percentage point increase in the percentage of married-couple families with children of the householder under the age of 18 decreases house value by 0.6 percent, ceteris paribus. This sign of this variable aligns with the estimation in Boggin et al. (2019), although their study is incomparable in point estimates due to differences between functional forms.

With the control variables now addressed, we outline the findings from the shale production estimates. All of the coefficients are small in magnitude and only in the pooled OLS is a shale variable statistically significant, with a negative effect significant at the one percent level. This significant result should be taken lightly as it is not corroborated in the FE or the system GMM. Additionally, we have shown in comparing the point estimates for the other control variables like population density, median structure age, state mortgage rate, and average beds per unit why pooled OLS is not the preferred specification. Instead, the system GMM is preferred, so the insignificant estimates on these shale variables are what we will discuss. As far as we are aware, the only previous studies that measure shale activity in the form of production are Borchers et al. (2014) and Rakitan (2018), with Borchers et al. (2014) focusing on rural land values instead of house prices. Therefore, the best study to compare our results to is Rakitan (2018), for which they find that a 1 percent increase in production, measured in British Thermal Units (BTUs), corresponds to a 0.005 percent decrease in house values across the full sample of over 2,000 counties. Although the results are significant at the 1 percent level in Rakitan (2018), the point estimate is not very large, which tells a similar story to the small and insignificant estimates in our results.

Additionally, although we cannot directly compare the magnitude point estimates with the other national analyses, we can compare the sign and significance of these shale variables. Jacobsen (2019) and Bartik et al. (2019) use shale boom and shale county indicator variables, with both studies finding corresponding positive impacts at the 1 percent level. We theorize that these results contradict our findings due to the timing of the studies relative to the 2014 “bust” when oil and gas production collapsed. This is because for these house value estimates, Jacobsen (2019) uses data from 2007 to 2012, and Bartik et al. (2019) use data from 2000 to 2013. Unlike this study, these two studies cannot account for the longer-run adverse effects on nationwide house values, which may have become more apparent as lease payments fell in association with the busts in production. Therefore, it may be that the insignificant results of this paper are a consequence of long-run negative impacts offsetting short-run positive impacts within counties. However, this same reasoning cannot be applied to explain the differences in results when compared to Norwood (2020), who uses national data from 2010 to 2018. Norwood (2020) finds that houses within two miles of a fracked gas well sell at higher prices in their DiD results and household FE models. We reason that our results contrast with Norwood's (2020) results in part because we do not limit the sample to states with high shale production. In Norwood’s DiD specifications, which show significant positive impacts, the author drops the states with insufficient shale activity to have a reasonable treatment-control ratio. Since this study does not use a DiD technique, no states were dropped in this analysis. Lastly, as a robustness check, we estimate System GMM specifications that control for basin-level differences and isolate the effect of shale oil and gas. The results are reported in Tables A1 and A2 of the appendix; the results do not change significantly.

6. CONCLUSIONS

The shale revolution, which began with the popularization of hydraulic fracturing and horizontally drilled wells, has led the way to many nationwide benefits, perhaps most importantly, lower domestic energy costs. However, previous research has attempted to determine the impacts on local communities with mixed results. This thesis expands upon previous literature by analyzing the impact of shale oil and gas production on typical house prices nationwide for 2,932 counties from 2010 to 2019. Besides being among only a few nationwide analyses, this study is the first to use production data for years during and after the shale boom. This study utilizes three panel estimation techniques, including an adaptation of the Blundell-Bond system GMM estimator to find that homebuyers perceive the local amenities and disamenities caused by shale activity to offset each other, with no significant impact on typical local house prices in our preferred specification.

The implications of this study for policymakers are multifaceted. Although the impact of shale activity has not been found to be significantly harmful to local housing markets, this does not mean that steps cannot be taken to address some of the disamenities. Local welfare could be more effectively restored if shale energy producers are forced to internalize the costs of the disamenities created by their shale activity. The most common way for states or municipalities to force shale energy companies to internalize their costs is through the appropriate property tax for the value of produced and assessed oil and gas. Additionally, per-well impact fees have been applied statewide in Pennsylvania and by certain counties in Colorado to manage shale-related impacts where traditional property taxes cannot (Raimi and Newell 2014, 75). In the case of damages caused to roadways, we have already witnessed that some municipalities have implemented road maintenance agreements (RMAs) with shale energy producers. More widespread enactment of RMAs would not solve congestion and added construction concerns, but it would at least address the budgetary concerns for municipalities with impacted roadways. If shale energy producers complain that internalizing the costs of shale activity prevents them from turning a profit, policymakers should question whether the shale activity can be justified.

Regulatory policy also has a role in addressing the disamenities that cannot be easily fixed with additional revenue, such as environmental and health impacts. In order to address water source pollution, policymakers should consider increased water testing to ensure that water treatment facilities are not discharging polluted water. As addressed by Shappo (2020), unplugged wells are a significant cause of air pollution. Policymakers should consider developing new compliance procedures for shale energy companies or new public programs to ensure shale wells are plugged after retirement. To control the health effects on nearby residents during drilling periods, policymakers should consider enforcing the use of direction lighting and sound-deadening technology where beneficial. Likewise, further restrictions on the use of Class II underground injection control (UIC) wells in areas with susceptible geology, like Oklahoma, should continue to mitigate the frequency of these induced earthquakes, as already observed.

This study faces some limitations. Due to the national scope of this paper and using county-level observations, this thesis could not specifically control for variables directly linked to the amenities or disamentities covered in the literature review, such as the type of water source. We acknowledge that a potential point of bias in the analysis is not being able to control for county crime rates, which was due to reporting inconsistencies. Crime rates are an important neighborhood characteristic (Rizzo 1979; Tita et al. 2006) and regularly appear as significant when included as control variables in hedonic studies (Sedgley et al. 2008; Lin et al. 2014.;

Evans and Malin 2017). Subsequent hedonic studies on shale activity should consider controlling for the effect of crime rates if researchers can address clearly misreported observations in the FBI Uniform Crime Reporting (UCR) data or perhaps find a different reliable source. Additionally, the results may suffer from bias since shale activity typically occurs in rural areas, and these areas may disproportionately contribute to gaps in the ZHVI due to rural areas having a lower volume of housing transactions. For example, the ZHVI was not calculated for McKenzie County, North Dakota, one of the nation's largest shale oil-producing counties. Other prominent shale-producing counties with missing ZHVI observations include Loving County, Texas; Eddy County, New Mexico; and Stevens County, Kansas.

The data used in this thesis was unable to capture the years at the beginning of the shale boom due to limitations in the data available for certain control variables. Also, the oil and gas production data in our study ended in 2019, precluding us from examining the impact of shale energy production on house values during and after the COVID-19 pandemic. Future research could examine how nationwide results would differ when including these years before and after our study period. Housing prices are only effective indicators of community welfare if housing markets correctly perceive the reality of factors influencing community welfare. Lee and Whitacre (2021) point out that a community’s sensitivity to the amenities and disamenities of shale activity depends on the community's past involvement in other forms of resource extraction. Similar to Ambrose and Shen (2023), nationwide data on each county’s historic production of oil, gas, and coal may allow future research to categorize counties accordingly and measure any differential impacts across these groups.

Overall, localized disamenities are unpreventable where shale activity occurs directly in and amongst the community. At the same time, these disamenities do not necessarily mean that action like a state-wide moratorium must be placed on all shale activity. The correct plan of action for policymakers will always depend on the shale basin-specific factors and likely involve mitigating the disamenities of shale activity using revenue from the shale energy companies. Further research should investigate how shale activity is capitalized into house values in shale basins like the Williston and Antrim to better inform policymakers about the local impacts in those regions. Additionally, future research could separate conventional and unconventional shale production to determine any differences in how they are capitalized into house values. As for the broader literature on unconventional shale extraction, it is clear that further research analyzing the mineral rights leasing process and the associated windfalls is needed to help stakeholders make future decisions.

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APPENDIX. ROBUSTNESS CHECKS

Table A1. Results Controlling for Basin-level Differences

	SYS GMM
L.ln(House Value)	0.701**
	(0.301)
L2.ln(House Value)	0.240
	(0.330)
ln(Shale Oil)	-0.002
	(0.001)
ln(Shale Gas)	0.001
	(0.001)
ln(Population Density)	0.007
	(0.005)
ln(GDP Per Capita)	0.045*
	(0.026)
% High School Grad	-0.001
	(0.001)
% at Least Some College	0.001***
	(0.000)
% Apartment Units	0.006*
	(0.003)
Age of Population	0.013***
	(0.005)
Structure Age	-0.003**
	(0.001)
Mortgage Rate	-0.510
	(0.383)
Avg. Bedrooms Per Unit	0.107**
	(0.046)
% Black	-0.001
	(-0.001)
% with Children	-0.003
	(0.002)
Williston	-0.006
	(0.031)
Powder River	-0.006
	(0.035)
Greater Green River	0.027
	(0.040)

Table A1. Results Controlling for Basin-level Differences (continued)

	SYS GMM
Piceance	0.027
	(0.038)
Denver-Julesburg	0.034
	(0.022)
Fort Worth	0.010
	(0.020)
Permian	0.114**
	(0.053)
Western Gulf	0.048**
	(0.024)
Appalachian	-0.040***
	(0.014)
San Juan	0.016
	(0.033)
Anadarko-Arkoma	0.006
	(0.032)
San Joaquin	0.164***
	(0.049)
Constant	1.506*
	(0.893)
N	18957
Year Fixed Effects	Yes
Sargan/Hansen p-value	0.1866
AR(1) p-value	0.000
AR(2) p-value	0.246

Standard errors in parentheses
* p<0.10, ** p<0.05, *** p<0.01

Note: The TX-LA-MS Salt Basin is the omitted group among the major shale basins.

Table A2. Results Isolating Oil and Gas Production

	Within FE - Oil Only	SYS GMM -Oil Only	Within FE - Gas Only	SYS GMM - Gas Only
L.ln(House Value)		0.668**		0.687**
		(0.311)		(0.307)
L2.ln(House Value)		0.278		0.258
		(0.340)		(0.335)
ln(Shale Oil)	-0.000	-0.001		
	(0.001)	(0.001)		
ln(Shale Gas)			-0.001	0.000
			(0.001)	(0.000)
ln(Population Density)	0.812***	0.006	0.812***	0.006
	(0.054)	(0.004)	(0.054)	(0.004)
ln(GDP Per Capita)	0.072***	0.045*	0.072***	0.046*
	(0.013)	(0.026)	(0.013)	(0.026)
% High School Grad	0.000	-0.000	0.000	-0.000
	(0.000)	(0.001)	(0.000)	(0.001)
% at Least Some College	0.000	0.001***	0.000	0.001***
	(0.000)	(0.001)	(0.000)	(0.001)
% Apartment Units	0.000	0.006*	0.000	0.006*
	(0.002)	(0.003)	(0.002)	(0.003)
Age of Population	0.001	0.013***	0.001	0.013***
	(0.002)	(0.005)	(0.002)	(0.005)
Structure Age	0.002***	-0.003**	0.002***	-0.004***
	(0.001)	(0.001)	(0.001)	(0.001)
Mortgage Rate	-0.030***	-0.547	-0.030***	-0.541
	(0.008)	(0.395)	(0.008)	(0.396)
Avg. Bedrooms Per Unit	0.008	0.106**	0.008	0.099**
	(0.027)	(0.048)	(0.027)	(0.047)

Table A2. Results Isolating Oil and Gas Production (continued)

	Within FE - Oil Only	SYS GMM -Oil Only	Within FE - Gas Only	SYS GMM - Gas Only
% Black	-0.001	-0.000	-0.001	-0.000
	(0.002)	(-0.001)	(0.002)	(-0.001)
% with Children	-0.000	-0.002	-0.000	-0.002
	(0.001)	(0.002)	(0.001)	(0.002)
Constant	7.989***	1.574*	7.992***	1.605*
	(0.253)	(0.933)	(0.253)	(0.947)
N	24863	18957	24863	18957
R-Squared	0.729		0.729	
Year Fixed Effects	Yes	Yes	Yes	Yes
Sargan/Hansen p-value		0.2281		0.1943
AR(1) p-value		0.000		0.000
AR(2) p-value		0.218		0.224

Standard errors in parentheses

* p<0.10, ** p<0.05, *** p<0.01