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I can hear my neighbors' fracking: The effect of natural gas production on housing values in Tarrant County, TX☆

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ABSTRACT

In this study we estimate the effect of hydraulically fractured natural gas wells on residential real estate prices. We exploit variation in distance to nearby gas wells in home sale prices to estimate this effect. In contrast to previous studies, we focus on a relatively densely populated area, a section of the Dallas–Ft. Worth–Arlington urban area. Using a dataset of 127,556 observations from Tarrant County, Texas over the period 2005–2011, we find robust evidence that increased proximity to a well leads to reduced home sale prices. Existence of wells within 3500 ft of a property reduces property values by approximately 1.5–3%. We demonstrate that the reduction seems to be driven by unconventional rather than conventional wells, and that well construction causes an added 1–2% reduction in home value.

1. Introduction

The International Energy Agency projects that by 2020 the United States will overtake Saudi Arabia as the world's largest oil producer, largely because of increasing exploitation of unconventional deposits of hydrocarbons, made possible by hydraulic fracturing, known colloquially as "hydrofracking", or "fracking." By 2007 unconventional production already accounted for 46% of US natural gas production (Smead and Pickering, 2008). Aside from creating thousands of jobs (Weber, 2012, Marchand, 2012, Maniloff and Mastromonaco, 2014),[1] and enhancing US energy security, hydraulic fracturing can make the US economy less carbon intensive because it is used more heavily in natural gas production (US Dept. of Energy, 2009). Although recent price declines in oil and natural gas have negatively affected the industry (gas production peaked in 2015, and more than 70,000 jobs have been shed since the industry's employment peak in 2014 (Dhaliwal and Stuermer, 2015), hydraulic fracturing will remain an important source of energy, producing an additional 230 trillion cubic feet of gas through 2040 (Hughs, 2015).

Hydraulic fracturing has risks and negative impacts, which have been frequently highlighted in popular media.[2] Hydraulic fracturing causes earthquakes (Frohlich, 2012); leaking well casing can contaminate air and groundwater (Darrah et al., 2014), and above ground infrastructure may provide dis-amenities to homeowners. The issue is growing in significance because as of 2013, 15.3 million Americans live within 1 mile of a hydraulically fractured well (Gold and McGinty, 2013).

One way to measure a *portion* of the potential costs and benefits of hydraulic fracturing—those costs and benefits borne by residential property owners—is through real property spillovers. Our paper focuses on Tarrant County, TX and uses variation in homes sales price and spatial variation in well location to quantify the costs (benefits) of hydraulic fracturing from the perspective of homeowners. Tarrant County, which is centered on Fort Worth, is largely urbanized, much of it being spanned by municipalities making it economically important and policy relevant. Tarrant County overlies the prodigious Barnett Shale, which accounts for 6% of natural gas production in the United States (US Dept. of Energy, 2009). The formation spans multiple counties;

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[1] Munasib and Rickman (2015) are less sanguine about nonconventional oil and regional economic impacts. They find significant economic benefits only in North Dakota.

[2] For example, view the website of Dong (2015), which is associated with the movie *Gasland*. Zeller (2010) or Gold and McGinty (2013) provide examples of hydraulic fracturing in national media, Henry (2011) an example in local (Ft. Worth) media.

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however, in Tarrant County alone, the appraised mineral value of natural gas deposits exceeds $2.54 billion.[3] Here the costs and benefits of hydraulic fracturing are important because of the density of population exposed to these costs and benefits—Tarrant County is home to 1.9 million people. Previous studies have focused on comparatively rural areas of Pennsylvania and New York (Boslett et al., 2014; Delgado et al., 2014; Gopalakrishnan and Klaiber, 2014; Muehlenbachs et al., 2012, 2015) demonstrating that hydraulic fracturing can be associated with large reductions in home values when interacted with groundwater usage. However, for homes with piped water, no effects, or even positive effects are found. In our urbanized study area, the overwhelming majority of observations fall into municipalities with access to piped water, and we find a persistent negative effect on home sales in close proximity to hydraulically fractured wells.[4]

Our data set comprises 127,556 observed home sales during the time period 2005–2011 from the Multiple Listing Service in Tarrant County, TX. We match these data to property records provided by the county. Natural gas well information is provided by *DrillingInfo*, including spatial location of wells, and completion date. We use hedonic regression to find that hydraulically fractured wells negatively affect home values. We find that sales within 3500 ft of a completed well have prices reduced significantly by about 3%, or around $5000, evaluated at the mean. As a robustness check, we re-estimate our main regressions based on a synthetic control sample, arriving at nearly identical results. We also use the repeat sales approach, and find that an additional completed well within 3500 ft of a sale significantly reduces price by around 1.5%.

In extensions of our empirical model, we examine the effect of well construction and differential effects between conventional and unconventional drilling. Our estimates indicate that well construction is not the sole driver of the negative effects of hydraulic fracturing on housing—we continue to observe negative effects of well proximity even after construction is completed. The persistence of negative effects after construction may be explained by the visual dis-amenity of the well pad, air contamination (Pétron et al., 2012; McKenzie et al., 2012) risk of spills, earthquakes or the risk of earthquakes, and the expectation of future re-fracturing. We also find that hydraulically fractured wells are significantly more detrimental to home values than conventional drilling.

The paper proceeds as follows. Section 2 provides a background on hydraulic fracturing, and Section 3 places this paper within the context of prior research. Section 4 discusses the implementation and specification of the hedonic regression. Section 5 documents the data. Section 6 presents and analyzes the results. Section 7 concludes.

2. Background

Two advances in drilling technology have allowed for economically viable exploitation of natural gas deposits in the Barnett Shale. These advances are hydraulic fracturing and horizontal drilling. The process of hydraulic fracturing involves pumping water mixed with certain chemicals at high pressure into the reservoir rock to fracture the rock. Gas can then flow along the fractures at economic rates to the well-face and then to the surface. Horizontal drilling allows more of the well-face to be exposed to the production zone, and thus produced. For example, if the target formation is 20 ft thick and oriented horizontally, a vertical well would only be exposed to those 20 ft; on the other hand, a horizontal well could run a much longer length of the formation, draining a much larger area. This means fewer horizontal wells are required to drain a field. Horizontal drilling combined with fracturing has led to the shale gas boom. Hydraulic fracturing was first experimented with in Texas in the 1950s (US Department of Energy, 2009). Hydraulic fracturing was implanted in the Barnett Shale in 1986, the first horizontal well in 1992 (US Department of Energy, 2009).

The Barnett Shale is special because its ultra-low permeability makes it difficult for gas to flow to the well at economical rates. Conventional production normally requires permeabilities in excess of 100 millidarcies,[5] but the Barnett shale permeability is several orders of magnitude lower, ranging between 0.01 and 0.00001 millidarcies, (US Dept. of Energy, 2009). With conventional drilling technology extraction would not be profitable; the gas could not flow rapidly enough to the surface to be economical. Hydraulic fracturing and horizontal drilling overcome these difficulties in two ways: the hydraulic fracturing opens new pathways in the rock along which the natural gas can flow; simultaneously, horizontal drilling exposes more production piping to the resource bearing strata, so the natural gas has less distance to travel through rock in order to reach the production area.[6] Moreover, from an economic perspective fracturing is extremely cost effective. Multiple wells can be drilled from a single production area, making the surface footprint smaller. Horizontal drilling allows wells to be extended in any direction, and, relative to conventional drilling, this means fewer wells are needed for recovery. Finally, because the wells are concentrated, less pipeline and fewer access roads are needed.

The period of well construction and fracturing is the most conspicuous time in the lifecycle of the well. Before the well is drilled, the operator must receive a drilling permit from the Texas Railroad Commission, and negotiate lease payments to mineral owners. Once the rights having been obtained, drilling and fracturing commence. A drilling derrick in excess of 150 ft tall is brought in to bore the well. From the vertical well, 3–4 horizontal wells are drilled in any direction into the pay area far below (Devon Energy). During the drilling process casing is cemented in along the way to isolate the production area and provide structure to the well to prevent collapse. When surface valving is added, the well is said to be completed.

The horizontal wells must then be fractured.[7] Trucks are brought in to pump fracturing liquids into the well. The number of trips is substantial: Gopalakrishnan and Klaiber (2014) report that over 800 one-way heavy truck trips, and well over 1500 one-way light truck trips are necessary per well. The process of fracturing is loud, registering 50 dB at 1000 ft.[8] The process is also water intensive, requiring 2–3 million gallons per well. 15–80% of these fracturing fluids return to the surface where they are stored in above ground pool awaiting permanent disposal.[9] Fracturing fluid is mostly water but has numerous chemical additives. While the specific chemicals are often proprietary trade secrets, the US Department of Energy reports that additives typically include acids to dissolve minerals clogging pore spaces, biocides to prevent bacterial growth, corrosion inhibitors to protect equipment, sand to keep fractures propped open, friction reducers to aid flow, gels to suspend the sand in water, and surfactants to increase fluid viscosity (US Department of Energy, 2009, pg 63, exhibit 36).

Once drilled and fractured, the wells become comparatively unobtrusive, with only a few square meters of surface valving left behind per well if the wells are connected directly to pipeline. Without pipelines, more obtrusive surface storage is necessary and trucks must periodically come to empty these storage units. The well can produce an average of two years before it needs to be serviced, and in some

[3] Tarrant Appraisal District, MNRL file downloaded Aug 1, 2014.

[4] We include, however, a robustness check to further control for possible drinking water source.

[5] "Porosity and Permeability." *Oil on my shoes: Introduction to Petroleum Geology.* Accessed June 25,2015, http://www.geomore.com/porosity-and-permeability-2/.

[6] The increased length of pipe exposed to the pay zone reduces the pressure drop around the well bore, lowers fluid viscosities, and reduces sand production, among other things.

[7] This process takes between 3 and 10 days (Halliburton).

[8] "Oil and gas noise." *Earthworks.* Accessed June 26, 2015, http://www.earthworksaction.org/issues/detail/oil_and_gas_noise#.VNFEw2jF98F.

[9] There are three options for disposal: the water may be re-injected into the well, treated and discharge into surface water, or applied to land surface. All options for disposal require permits.

cases can be re-fractured multiple times. The barren half-acre pads may also contribute to the long-term dis-amenity. Fenced off and treeless, the plots frequently contain “frack ponds” of residual fluids from construction.

3. Literature review

Our paper fits into the broader real estate literature that uncovers the property value effects of local (dis)amenities, for example, school quality (Haurin and Brasington, 1996), foreclosures (Harding et al., 2009), forced sales (Campbell et al., 2011), sex offenders (Linden and Rockoff, 2008), and environmental degradation (Nelson, 1981; Currie et al., 2015). The approach has more recently been used to quantify the costs and benefits of unconventional natural gas production on local housing values (Boxall et al., 2005; Muehlenbachs et al., 2015; Timmins and Vissing, 2015).

Hydraulic fracturing has the potential to provide benefits for nearby homeowners through the rents generated from production. These benefits may be direct. For fee simple estates (where mineral rights are still attached to surface rights), homeowners may receive bonus and royalty payments from productive wells. The benefits to homeowners may also be indirect. Hydrocarbon production can result in job creation (Weber, 2012; Marchand, 2012; Maniloff and Mastromonaco, 2014) and may stimulate housing demand (Ooms and Tracewski, 2011; Weber et al., 2014).

Natural gas production and hydraulic fracturing have many potential costs to homeowners, whether through the degradation of groundwater or air, increased noise and traffic during drilling, the unsightly land footprint of production, the potential for spills and other environmental hazards, and their consequences for health and safety (Lipscomb et al., 2012). Environmental degradation is one of the overarching concerns. Leaking well casing can result in unintended methane emissions above ground, and can pollute aquifers with gas and fracturing chemicals below ground. Leaking petroleum infrastructure has been demonstrated to have a negative effect on home values (Zabel and Guignet, 2012), and such pollution has alarming health and safety consequences. Rahm (2011) cites a study of exposure of households in Dish, Texas,[10] 65% of whom had toluene in their system, 53% had xylene. Additionally, the Environmental Protection Agency issued an endangerment order requiring immediate action by a Fort Worth company to protect residents in neighboring Parker County from methane exposure, after reports of inflammable taps and bubbling drinking water.[11] A stated preference study in New York suggests that individuals find the existence of hydraulically fractured wells objectionable and have a statistically significant willingness to pay to avoid using electricity produced from such wells (Popkin et al., 2013).

Oil industry equipment comes with other safety concerns and dis-amenities which may affect sales price (Lipscomb et al., 2012). For example, pipelines occasionally explode[12]; however, Boxall et al. (2005) find no evidence that pipelines negatively affect sales price. Flower and Ragas (1994) show proximity to oil refineries is correlated with lowered home values. Gopalakrishnan and Klaiber (2014) document increased truck traffic and noise during construction and fracturing which may provide nuisance for homeowners. Land footprints during construction may be large and unsightly. Moreover, for buyers of split estates (where mineral rights and surface rights have been separated) with no surface exclusion, there is a risk they may have to yield surface use without reparation at some future date. The threat of accidents and spills may also depress sales prices.

The initial studies on the effect of hydraulic fracturing proper have been largely concentrated in the Marcellus Shale of Pennsylvania and New York. In a series of papers Muehlenbachs et al. (2012, 2015) use a triple difference-in-difference approach to quantify the effect of hydraulic fracturing on real estate prices. The authors find that the negative effects of hydraulic fracturing are felt largely by homes dependent on groundwater; the effect for homes with piped water is insignificant or even slightly positive. In a study focused within Washington County, PA, Gopalakrishnan and Klaiber (2014) find that negative effects of hydraulic fracturing are felt by homes on groundwater during the well construction phase, but that these effects rapidly attenuate once well construction has finished and when distance from the well increases. In a study covering two counties in northeastern Pennsylvania, Delgado et al. (2014) fail to find strong evidence that hydraulic fracturing substantially reduces home values. Boslett et al. (2014) exploit a drilling moratorium in New York to find that the prospect of shale development increases the value of properties.

The Barnett shale of Texas has become the target of a second wave of papers examining the impact of hydraulic fracturing, among them, this one. Weber et al. (2014), examining the Dallas Ft. Worth area, find that property values have appreciated in shale producing ZIP codes relative to non-shale ZIP codes. This is attributable to the effect shale gas development has had on public finances, which has allowed for more public spending with lower property taxes. An issue that has been plaguing the hydraulic fracturing literature has been an inability to observe whether the sale of a property retains rights to the subsurface minerals. Vissing (2015) and Timmins and Vissing (2015) have begun analyzing mineral contracts in Tarrant County, which is a significant development both for the hydraulic fracturing literature and mineral rights literature that must be underscored. Vissing (2015) examines the census-tract level quality of mineral leases with other census tract variables. Timmins and Vissing (2015) examine the effect of proximity to hydraulically fractured wells and lease quality on home appraisal values. While this paper does not try to connect mineral leases to home sales, we are able to estimate a hedonic model with observed home sale prices rather than appraisal values.

Our paper contributes to the literature on a variety of fronts, by focusing on an urbanized area where groundwater is less important, by examining the difference between conventional and non-conventional wells, and by presenting net cost estimates relevant for urban drilling using a variety of empirical methods.

Our high-density urban area with many observations contrasts with the studies of Muehlenbachs et al. (2012), Gopalakrishnan and Klaiber (2014), Delgado et al. (2014), Boslett et al. (2014) and Muehlenbachs et al. (2015), which look mainly at rural and suburban areas in Pennsylvania. Muehlenbachs et al. (2012, 2015) and Gopalakrishnan and Klaiber (2014) find heterogeneous effects between homes on groundwater and those on piped water. These studies demonstrate that the properties relying on groundwater seem to more heavily bear the dis-amenity costs from hydraulic fracturing. Groundwater considerations are of less concern in Tarrant County, where the overwhelming majority of properties in the sample have access to municipal water.

Our higher density urban areas mean smaller plot sizes and more people exposed to hydraulically fractured wells. Average lot size in the Pennsylvania studies runs from 0.56 acres in Muehlenbachs et al. (2012) to over 8 acres in Delgado et al. (2014). In comparison, the average lot size in the Tarrant County sample is 0.25 acres. The difference is important because the net effect of higher density settlement is unclear. On one side, higher density means that more homeowners are exposed to the full cost of being in close proximity to hydraulic fracturing, while receiving less of the benefits because lease payments must be split more ways. The other side is that higher density might make homeowners less sensitive to nearby drilling: there are likely alternative roads that can be used during construction, and hydraulically fractured wells might be more effectively hidden, or relegated to areas with preexisting

[10] Located in Denton County, Tarrant's neighbor to the north.

[11] The EPA's press release can be found here: http://yosemite.epa.gov/opa/admpress.nsf/ab2d81eb088f4a7e85257359003f5339/713f73b4bdceb126852577f3002cb6fb!OpenDocument.

[12] A 2009 pipeline explosion in Amarillo, TX registered a 4.0 magnitude earthquake (Rahm, 2011).

dis-amenities (in our sample, drilling is noticeably correlated with railroads.) Moreover, the differences in plot size are indicative of different land use (viz. agricultural, residential) and can mean different impacts of hydraulic fracturing in urban and rural areas (Lipscomb et al., 2012). Finally, our high-density area implies "thicker" housing markets, a necessary condition for effective hedonic estimation.

Looking more into areas outside of Pennsylvania is also important because state regulation may affect measured dis-amenities from hydraulic fracturing. Estimated dis-amenities may not be the same from one state to another. Policy with respect to hydraulic fracturing operations differs between Pennsylvania and Texas, although it is not clear which state has more stringent regulations. Pennsylvania has longer setback restrictions on wells from buildings and water sources, while Texas has more restrictive venting and flaring regulations (Richardson et al., 2013). There are also local zoning and noise regulation that may have an effect on the dis-amenities homeowners are exposed to. Finally geological variables are at play as well—the Marcellus shale formation runs from 2000 to 8000 ft below the surface in Pennsylvania, while the Barnett shale in Tarrant County lies between 5000 and 7000 ft.[13] To the extent that formation depth can insulate the surface from the environmental problems associated with hydraulic fracturing, measured impacts in Tarrant County will be lessened.

Our study also examines the difference between conventional and unconventional production to examine the degree to which unconventional production presents different net costs and benefits to homeowners relative to conventional drilling. Unconventional production and drilling differs from conventional production along at least five dimensions that have bearing to our study: drilling/production footprint, well stimulation, active operation, well productivity and potential for environmental damages. Relative to conventional production, the costs to homeowners of unconventional production are larger: the pads have a greater land footprint, require stimulation, and have greater perceived potential for environmental harm. On the benefits side, unconventional production in the Barnett Shale is currently more productive (generating greater royalties, and lease payments), although these wells are likely to have more rapid decline rates, requiring more attention and maintenance.[14] Thus unconventional wells are likely to have greater perceived costs, but for mineral rights owners, also greater potential benefits.

Lastly, our paper uses a variety of estimators relying on both temporal and spatial variation to measure the treatment effect of nearby hydraulically fractured wells on property values. These estimators include hedonic estimators, synthetic control matching, and a repeat sales estimator. Use of the repeat sales estimator allows us to better control for property level fixed effects. Muehlenbachs et al. (2015) control for property fixed effects, but many of the study's observations come from rural areas (the paper includes 36 counties in Pennsylvania overlying the Marcellus Shale). Muehlenbachs et al. (2012) employ fixed effects estimation, but only covers Washington County, PA. Estimates in Gopalakrishnan and Klaiber (2014), Timmins and Vissing (2015) as well as Delgado et al. (2014) rely on spatial variation: identification comes from comparing observations within the same time period and geographic boundary that are near and far from a well. Besides relying on spatial identification, we are able to take an additional step by identifying our estimates by comparing sales price of a home before and after drilling.

[13] Information on the Marcellus Shale from Pennsylvania State Center for Marcellus Research and Outreach: http://www.marcellus.psu.edu/resources/maps.php. Information on Barnette Shale from the Energy Information Agency: https://www.eia.gov/oil_gas/rpd/shaleusa1.pdf.

[14] For conventional fields, the IEA in their 2008 World Energy Outlook estimates a production weighted average world decline rate of conventional fields between 3 and 11 per annum%. Unconventional fields have higher decline rates of 60% to even in excess of 80% in the first year (Jacoby et al. 2011, Lund 2014). However, with both vertical and horizontal wells being drilled into the Barnett Shale, we observe the horizontal wells to be more productive.

4. Methodology

We employ hedonic regression to estimate the impact of having a well nearby on transaction price. The methodology was developed by Rosen (1974) with the recent literature reviewed in Kuminoff et al. (2010, 2013). In thick housing markets, a residential property can be decomposed into a bundle of attributes for which consumers have some willingness to pay. By regressing home price on the attributes, the average marginal willingness to pay can be recovered—they are the estimated coefficients. Our question is whether, conditional on other housing attributes, people demand compensation (or are willing to pay) in order to live within a certain distance of a well. The equation we estimate is

$$\ln P_{ijt} = \alpha + \Gamma W_{it} + \Omega X_i + \phi_t + \mu_j + \varepsilon_{ijt}. \tag{1}$$

The dependent variable, P_{ijt}, is the natural log of the transaction price for a home i in ZIP code j at time t. The vector W_{it} comprises a series of identifiers on whether the home is within 3500, 5000, or 6500 ft of a well.[15] We use multiple ring boundaries in order to examine the sensitivity of the threshold definition for the treatment group to the measured treatment effect. Our boundaries closely align with the thresholds used by Muehlenbachs et al. (2015) of 1 km, 1.5 km, and 2 km. (in feet, 3280′, 4920′, and 6560′). Other papers have used boundaries between 0.75 mile and 2 miles (Gopalakrishnan and Klaiber, 2014), and between 1 and 4 miles (Delgado et al., 2014). Gopalakrishnan and Klaiber find significant attenuation of the treatment effect by 2 miles; Delgado et al. estimate that the treatment effect attenuates to zero around 4 miles. Because our study area is significantly denser, we expect remote drilling to have less of an effect: there will be more intervening properties and a greater selection of alternative routes. Tables 2 and A1 indicate that treatment effects become statistically indistinguishable from 0 beyond 5000 ft; thus we consider the 6500′ threshold sufficient. Below 3500, we have few observations in the treatment group.

The estimands, Γ, test the hypothesis that landowners require lower prices due to proximity to hydraulic fracturing. The vector X_i includes a standard set of observed property characteristics, such as number of bedrooms, number of bathrooms, and square footage; it also includes location (dis)amenities such as distance to the central business district and indicators of being nearby lakes, railroads, highways, or rivers. The hedonic model includes time dummies, ϕ_t, and ZIP code fixed effects, μ_j.

Lastly, we estimate a repeat sales model as a robustness check to our primary specification. A major concern with hedonic models is the presence of unobservable characteristics of the properties that are correlated with observed variables, including W_{it}. By looking at repeat sales, we difference out the effect unobservables (when they are constant).[16] The estimating equation is

$$\ln\left(P_{ijt+\tau}/P_{ijt}\right) = \Gamma(W_{it+\tau} - W_{it}) + \sum_{j=1}^{J} \eta_j D_{ij} + \varepsilon_{ijt} \tag{2}$$

Each property included in the repeat sales method experiences at least two transactions: the original transaction price at time t is given by P_{ijt}, and the second price at time $t + \tau$ is denoted $P_{ijt+\tau}$. The percentage change in price is explained by the change in proximity to

[15] These identifiers vary by specification and may also include if the home is nearby a construction well or close to a specified count of wells.

[16] Of course, the repeat sales method has drawbacks as well. Particularly, the significant loss in transaction data as it requires a particular home to be sold more than once during a short time span (which by itself may signal that the home is different in some way) and the assumption that the home is not significantly altered during the study period. Whether the repeat sales model is superior to the hedonic estimates depends on assumptions about the existence and constancy over time of neighborhood and property-level unobservables.

hydraulically fractured wells. We also include the standard D matrix identifying the sales dates.[17]

5. Data

Our sales data in current dollars comes from the Multiple Listing Service over the period 2005–2011, containing over 129,000 transactions, 64% of which are single transactions (in the sense that we observe the property sold only once). The MLS data is merged by address with appraisal data from the Tarrant Appraisal District[18] in order to gain information on property attributes, including number of bedrooms, number of bathrooms, year built, number of structures, acreage, area, central heating and air, and garage characteristics. The file is only available for 2014, so the merge makes the assumption that properties have not changed significantly over the period of study. We eliminate all non-residential properties, properties with missing information, and non-armslength transactions, those with sales prices below $10,000. This leaves 127, 556 observations, 96.67% of which are single family.[19]

Well information for Tarrant County comes from *DrillingInfo*, and includes well activity and completion date. There are a total of 4124 wells in our sample. 99% of the wells are classified as natural gas production wells, 97% are drilled in the Newark East field; 95% of the sample is drilled into the Barnett Shale formation. 84% (3, 484) of wells are classified as horizontal wells, having a mean completion date of Oct 9, 2008. The earliest completion date for horizontal wells in the sample is September 12, 2002; the latest is June 7, 2011. Conventional wells (vertical and diagonal) tend to be older: there are 640 conventional wells with mean completion time of March 22, 2003. The earliest completion date is June 1, 1966; the latest completion date is July 24, 2010.

We've included both active (95%) and inactive wells, and conventional and unconventional wells in the baseline regression sample because the existence of oil and natural gas infrastructure has the potential to cause dis-amenities to homeowners. We examine heterogeneous effects of conventional and unconventional wells later in the paper, in Table 4.

The location of wells and the number of observed sales according to ZIP code is detailed in Fig. 1. The location of oil or natural gas wells is indicated by the points. Red areas represent ZIP codes with relatively many observed residential transactions, blue areas represent ZIP codes with comparatively few transactions. The distribution of wells is particularly dense in the north-central/north-west area of Tarrant County, but particularly sparse in the northeastern part of the county (the exception being those wells that lie within DFW Airport).

Data are plotted in ArcGIS to create spatial variables. ESRI map files are used to overlay municipal areas, counties, ZIP codes, school districts, roads, lakes, and railways. We then create buffers around sales of 3500, 5000, and 6500 ft and count the number of wells within each concentric ring. We refer to these buffers as ring 1, ring 2, and ring 3, respectively. From these counts, we generate identifiers, w_{3500}, w_{5000}, and w_{6500}, which are equal to one when the well count in the ring is greater than 0. We also explore pad effects and generate identifiers which are equal to one when the count in the ring is between 1 and 6, 7 and 12, and over 13.

Summary statistics are presented in Table 1, with different samples separated into different columns. For our full sample, the average sale has just over 3 bedrooms, and 2 bathrooms; 72% of households have a two-car garage, 97% have central heating and air, and 16% have a swimming pool. Sales price is lower for houses with at least one well within 3500 ft than for the full sample average. Conversely, properties with no wells within 6500 ft have more living area and are more likely to have a swimming pool, but are older and farther from the city center. In order to control for these observable differences in housing sales between properties, we estimate a series of standard hedonic regressions (in Tables 2, A1) detailed in the next section.

We also break down the full sample into a series of subsamples to examine potential sources of bias in our hedonic models. The group of sales that never have a well within 6500 ft acts as a control group. Those sales that have no wells in the vicinity during the transaction, but acquire one within 6500 ft and within two years are the treatment group prior to treatment. Ideally, the means of these two samples should be similar, yet *all* of the variables are statistically different (significant at the 95% level or greater). Other columns demonstrate that these results are robust to different buffer distances to the nearest well. If the treatment and control samples are different in observed variables, then the samples may also differ in correlated unobserved variables, which would bias our estimates from baseline hedonic and Box–Cox regressions. We therefore implement a matching strategy to build a synthetic control group that is observationally similar to the treatment group in Section 6.2.

6. Results

6.1. Baseline hedonic models

Table 2 shows the estimation results for Eq. (1).[20] We use five specifications which vary due to the inclusion of dummy variables for whether there is a well within a ring of 3500 ft of the sale, within 3500–5000 ft of the sale, and within 5000–6500 ft of the property. Alternatively, we measure pad effects. Because the average pad contains 4–6 wells, we create dummy variables for homes with 1–6, 7–12, and 13 or more wells within each ring. We also vary the fixed effects included in each model.

The first column of Table 2 reports coefficient estimates for a standard hedonic regression. Standard errors are clustered at the ZIP code level, and quarter-year fixed effects and ZIP code fixed effects are also included. Signs and significance are as expected with the exception of bedrooms. Another bedroom reduces sale price by 3.7%. It should be remembered that this specification controls for the size of the house and property, thus adding another bedroom into the same sized house may well reduce the value. Importantly, control coefficients remain stable across specifications.

Specifications 2 and 3 include well indicator dummy variables for each of the three rings; specification 3 also includes ZIP code-quarter fixed effects.[21] Properties with hydraulically fractured wells within 3500 ft have reduced transaction prices, controlling for observable home and location amenity effects. The magnitude of the reduction in price ranges from 2.8% to 3.5%, or evaluated at the mean transaction price, between $4720 and $5900. As expected, Table 2 shows that wells farther away have less effect on home price: the effects are not statistically significant and are of reduced magnitude (between 0.3% and 1.3%).

[17] This matrix identifies the quarter of each transaction and is determined at a specific geographic area, *j*. We utilize a few different geographic areas, county, city, and school district level, so we keep Eq. (2) general in terms the number of areas. As the number of repeat sales properties is significantly lower than the total transaction dataset, we are unable to evaluate at the ZIP code level.

[18] This data is available for download at the TAD website. *AAAA* file, downloaded April 4th, 2014.

[19] The Tarrant County Appraisal District classifies residential properties into single-family (A) and multi-family (B) with sub-classifications as follows (number of observations in parentheses): A1 single-family (123,307), A2 mobile homes (236), A3 condominiums (2019), A4 townhomes (586), B1 multi-family (2), B2 duplex (1336), B3 triplex (39), B4 quadriplex (31). Estimation of Table 2 using A1 single-family observations produces nearly identical results and is available upon request.

[20] Box–Cox transformed estimates can be found in Appendix A.

[21] Specification 2 incorporates quarter-year and ZIP code fixed effects whereas specification 3 contains additional fixed effects for the interaction between quarter-year and ZIP code.

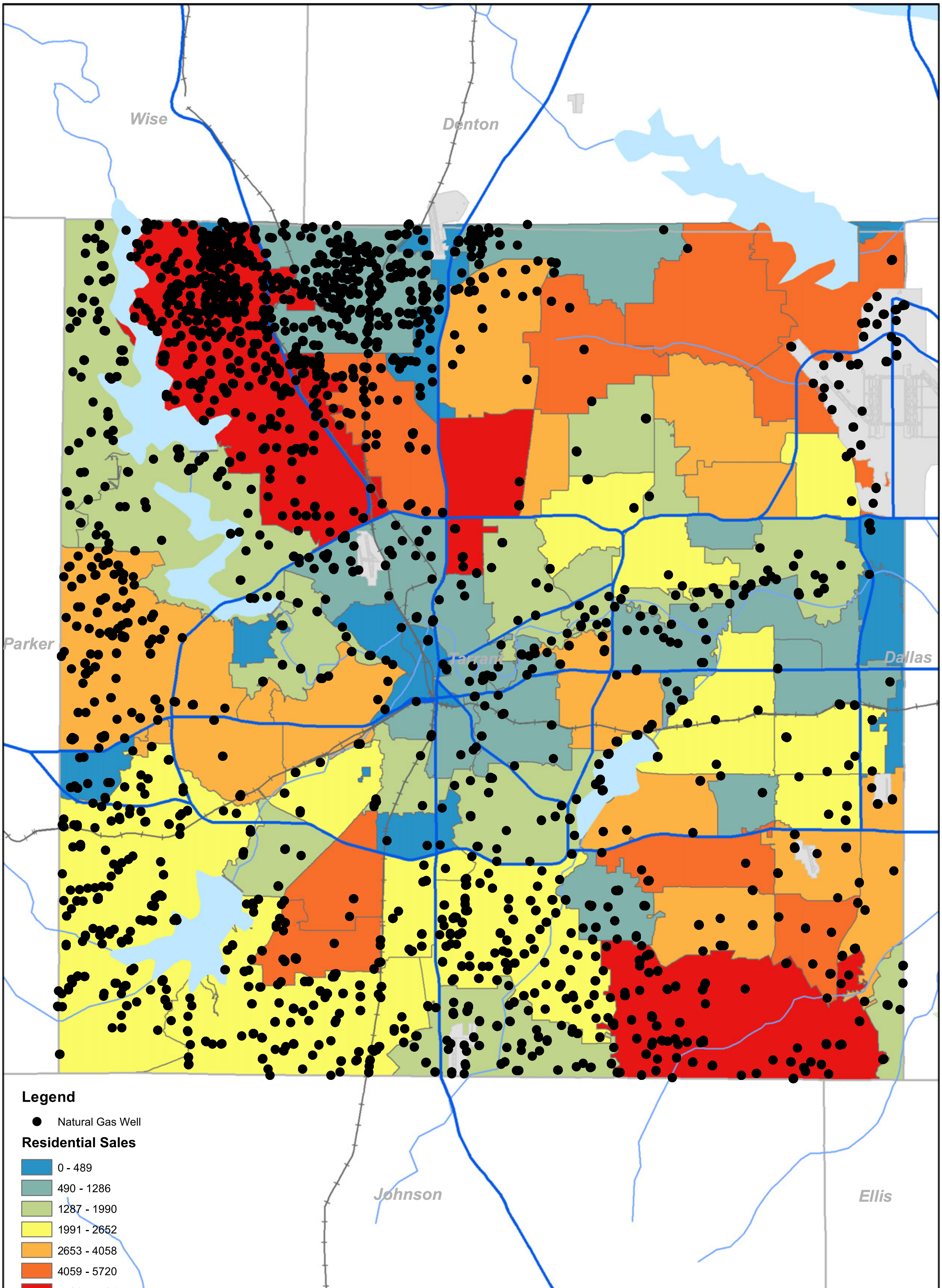

Fig. 1. Tarrant County ZIP codes by residential housing sales.

Table 2 also shows our proxy for pad effects. We use the number of wells within the rings to determine if the property is likely nearby one, two, or more than two pads. In specification 5, which includes space–time interaction fixed effects, having 1–6 wells within 3500 ft (likely 1 pad) reduces home value by 3.2%. The inclusion of the space–time interaction fixed effects reduces the coefficient estimates indicating that

Table 1
Descriptive statistics.

	Full Sample		At least one well within 3500 feet		At least one well within 5000 feet		At least one well within 6500 feet		No well at transaction but at least 1 within a year within 6500 feet		No well at transaction but at least 1 within 2 years within 6500 feet	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Sales Price (dollars)	168,594	157,672	148,800	114,677	147,529	115,815	148,220	120,119	146,502	116,249	149,188	126,970
Log of Sales Price	11.80	0.66	11.73	0.60	11.71	0.62	11.71	0.62	11.70	0.63	11.71	0.63
Number of bedrooms	3.35	0.74	3.39	0.71	3.37	0.71	3.35	0.71	3.29	0.71	3.29	0.72
Number of bathrooms	2.13	0.71	2.10	0.58	2.09	0.60	2.08	0.61	2.03	0.62	2.03	0.64
Living area (sqft)	2096.80	937.59	2097.38	827.24	2062.67	827.92	2048.64	835.87	1967.56	804.54	1971.96	835.33
Swimming pool	0.16	0.36	0.09	0.29	0.10	0.30	0.11	0.31	0.11	0.31	0.12	0.32
Land area (acres)	0.25	0.34	0.28	0.50	0.26	0.44	0.26	0.41	0.23	0.29	0.22	0.28
Central Heating	0.97	0.17	0.98	0.15	0.97	0.16	0.97	0.17	0.96	0.20	0.96	0.20
Central Air-conditioning	0.97	0.17	0.97	0.16	0.97	0.17	0.97	0.17	0.96	0.20	0.95	0.21
Garage, 1 car	0.07	0.26	0.05	0.23	0.06	0.25	0.07	0.25	0.09	0.28	0.09	0.29
Garage, 2 car	0.72	0.45	0.77	0.42	0.76	0.43	0.75	0.43	0.72	0.45	0.72	0.45
Garage, 3 or more cars	0.11	0.31	0.10	0.30	0.09	0.28	0.09	0.28	0.07	0.25	0.07	0.25
Distance from city center (miles)	11.28	4.41	10.67	3.85	10.59	4.00	10.55	4.07	10.83	4.57	11.02	4.70
Within 1/2 mile of a major lake	0.03	0.17	0.03	0.17	0.03	0.17	0.03	0.17	0.03	0.16	0.03	0.16
Within 1/2 mile of a railroad	0.18	0.38	0.23	0.42	0.22	0.42	0.22	0.41	0.19	0.40	0.19	0.39
Within 1/2 mile of a major highway	0.15	0.36	0.13	0.34	0.14	0.35	0.15	0.36	0.14	0.35	0.14	0.34
Within 1/2 mile of a major river	0.07	0.26	0.07	0.26	0.07	0.26	0.07	0.26	0.08	0.27	0.08	0.27
Age of house at time of sale	23.28	19.88	16.14	18.66	18.98	19.96	20.94	20.60	25.91	21.47	25.96	21.41
Structure count	1.00	0.08	1.00	0.08	1.00	0.08	1.00	0.08	1.00	0.08	1.00	0.09
Count of wells within 3500 feet	1.03	2.92	4.77	4.68	3.10	4.41	2.44	4.11	.	.	.	.
Count of wells within 3500-5000 feet	1.40	3.50	4.54	5.51	5.22	4.91	3.31	4.69	.	.	.	.
Count of wells within 5000-6500 feet	2.00	4.42	6.18	6.73	5.10	6.16	4.74	5.77	.	.	.	.
Number of observations	127,556		27,505		42,301		53,877		12,060		21,560	

Notes: Residential sales transaction data for Tarrant County, Texas between January 1st 2005 and September 30th 2011.

	NEVER one well within 3500 feet		NEVER one well within 5000 feet		NEVER one well within 6500 feet		NEVER one well within 6500 feet, Reduced sample		No wells within 6500 feet	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Sales Price (dollars)	192,866	189,275	222,906	215,557	260,128	238,041	191,194	186,955	183,492	178,784
Log of Sales Price	11.90	0.70	12.04	0.71	12.20	0.70	11.96	0.59	11.87	0.67
Number of bedrooms	3.37	0.76	3.43	0.79	3.54	0.82	3.36	0.77	3.36	0.76
Number of bathrooms	2.20	0.80	2.31	0.86	2.46	0.93	2.18	0.72	2.17	0.77
Living area (sqft)	2177.65	1036.90	2321.76	1124.91	2520.00	1218.65	2147.85	924.83	2132.01	1004.02
Swimming pool	0.21	0.41	0.27	0.44	0.34	0.48	0.22	0.42	0.19	0.40
Land area (acres)	0.24	0.26	0.26	0.30	0.29	0.33	0.23	0.26	0.24	0.29
Central Heating	0.97	0.16	0.99	0.12	0.99	0.07	0.99	0.09	0.97	0.17
Central Air-conditioning	0.97	0.16	0.98	0.12	0.99	0.07	0.99	0.09	0.97	0.17
Garage, 1 car	0.07	0.26	0.06	0.24	0.04	0.20	0.06	0.24	0.07	0.26
Garage, 2 car	0.68	0.46	0.67	0.47	0.65	0.48	0.74	0.44	0.70	0.46
Garage, 3 or more cars	0.13	0.34	0.18	0.38	0.24	0.43	0.10	0.30	0.12	0.33
Distance from city center (miles)	11.56	4.59	12.21	4.52	13.22	4.40	12.14	5.21	11.82	4.57
Within 1/2 mile of a major lake	0.03	0.17	0.04	0.19	0.05	0.21	0.08	0.27	0.03	0.17
Within 1/2 mile of a railroad	0.15	0.35	0.12	0.32	0.09	0.28	0.07	0.26	0.14	0.35
Within 1/2 mile of a major highway	0.16	0.37	0.18	0.38	0.17	0.38	0.19	0.39	0.15	0.36
Within 1/2 mile of a major river	0.08	0.26	0.08	0.27	0.09	0.28	0.06	0.24	0.07	0.25
Age of house at time of sale	26.37	19.55	25.11	18.04	21.95	15.67	24.22	17.61	24.99	19.16
Structure count	1.00	0.07	1.00	0.07	1.00	0.07	1.00	0.08	1.00	0.08
Count of wells within 3500 feet	.	.	.	.	.	.	.	.	.	.
Count of wells within 3500-5000 feet	.	.	.	.	.	.	.	.	.	.
Count of wells within 5000-6500 feet	.	.	.	.	.	.	.	.	.	.
Number of observations	65,728		38,113		22,442		13,200		73,679	

Notes: Residential sales transaction data for Tarrant County, Texas between January 1st 2005 and September 30th 2011. Reduced sample eliminates observations from ten zip codes with one or fewer wells.

Table 2
Standard hedonic method: Contagion effects of nearby hydraulic fracturing wells on transaction price.

Dependent variable = ln(sales price)										
Specification:	(1)		(2)		(3)		(4)		(5)	
	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.
Hydraulic fracturing effects										
Ring 1 − within 3500 ft										
One or more wells			−0.035***	[0.011]	−0.028**	[0.012]				
One to six wells							−0.037***	[0.011]	−0.032**	[0.012]
Seven to twelve wells							−0.036**	[0.015]	−0.027	[0.018]
Thirteen or more wells							−0.009	[0.035]	−0.005	[0.039]
Ring 2 − between 3501 and 5000 ft										
One or more wells			−0.013	[0.008]	−0.007	[0.008]				
One to six wells							−0.014*	[0.008]	−0.010	[0.008]
Seven to twelve wells							−0.013	[0.014]	−0.000	[0.016]
Thirteen or more wells							−0.002	[0.022]	0.014	[0.025]
Ring 3 − between 5001 and 6500 ft										
One or more wells			−0.010	[0.009]	−0.003	[0.009]				
One to six wells							−0.012	[0.008]	−0.006	[0.009]
Seven to twelve wells							−0.001	[0.012]	0.015	[0.014]
Thirteen or more wells							−0.007	[0.018]	0.019	[0.017]
Property characteristic and amenity effects										
Number of bedrooms	−0.037***	[0.009]	−0.037***	[0.009]	−0.036***	[0.009]	−0.037***	[0.009]	−0.036***	[0.009]
Number of bathrooms	0.049***	[0.008]	0.048***	[0.008]	0.049***	[0.008]	0.048***	[0.008]	0.049***	[0.008]
Living area (ft^2)	0.036***	[0.002]	0.036***	[0.002]	0.035***	[0.002]	0.036***	[0.002]	0.035***	[0.002]
Swimming pool	0.109***	[0.009]	0.109***	[0.009]	0.109***	[0.009]	0.109***	[0.009]	0.109***	[0.009]
Land area (acres)	0.143***	[0.012]	0.144***	[0.012]	0.144***	[0.012]	0.144***	[0.012]	0.143***	[0.012]
Central heating	0.110**	[0.045]	0.108**	[0.045]	0.117***	[0.042]	0.108**	[0.045]	0.118***	[0.042]
Central air-conditioning	0.170***	[0.032]	0.171***	[0.033]	0.165***	[0.033]	0.171***	[0.032]	0.164***	[0.032]
Garage, 1 car	0.134***	[0.017]	0.134***	[0.017]	0.134***	[0.017]	0.134***	[0.017]	0.134***	[0.017]
Garage, 2 car	0.292***	[0.022]	0.292***	[0.022]	0.291***	[0.023]	0.292***	[0.022]	0.291***	[0.023]
Garage, 3 or more cars	0.375***	[0.021]	0.375***	[0.022]	0.375***	[0.022]	0.375***	[0.021]	0.374***	[0.022]
Distance from city center (miles)	−0.002	[0.009]	−0.000	[0.009]	−0.001	[0.009]	−0.001	[0.009]	−0.002	[0.009]
Within 1/2 mile of a major lake	0.107**	[0.043]	0.104**	[0.043]	0.106**	[0.043]	0.104**	[0.043]	0.105**	[0.044]
Within 1/2 mile of a railroad	−0.036**	[0.016]	−0.034**	[0.016]	−0.034**	[0.016]	−0.034**	[0.016]	−0.034**	[0.016]
Within 1/2 mile of a major highway	−0.015	[0.014]	−0.016	[0.014]	−0.017	[0.014]	−0.016	[0.014]	−0.017	[0.014]
Within 1/2 mile of a major river	0.063***	[0.021]	0.066***	[0.021]	0.065***	[0.021]	0.065***	[0.021]	0.064***	[0.021]
Age of house at time of sale	−0.005***	[0.001]	−0.005***	[0.001]	−0.005***	[0.001]	−0.005***	[0.001]	−0.005***	[0.001]
Structure count	0.073	[0.083]	0.076	[0.083]	0.097	[0.072]	0.076	[0.083]	0.097	[0.072]
Constant	10.768***	[0.165]	10.774***	[0.166]	10.524***	[0.166]	10.780***	[0.162]	10.531***	[0.160]
Quarter-year fixed effects	Yes		Yes		Yes		Yes		Yes	
ZIP code fixed effects	Yes		Yes		Yes		Yes		Yes	
ZIP code * quarter-year fixed effects	No		No		Yes		No		Yes	
N	127,556		127,556		127,556		127,556		127,556	
R^2	0.836		0.836		0.845		0.836		0.845	

Notes: Standard errors are clustered at the ZIP code level. *, **, and *** denote significance at the 0.10, 0.05, and 0.01 level, respectively.

there is some unobserved difference over time within ZIP code that may be influencing the results.

While specification 5 seems to indicate that a property with more than one pad in close proximity does not affect the transaction price, F-tests cannot reject the null hypothesis that the coefficients for 1–6, 7–12, and 13+ wells are all equal. The same holds true for specification 4. These results hold, in general, in analogous specifications in other tables. It should be kept in mind that the coefficients represent the net effect of hydraulic fracturing (benefits minus costs), so we cannot conclude that pad effects are not influencing home values. Nevertheless, because we cannot statistically distinguish separate pad effects, the binary control in specification 3 is our preferred specification.

We examine the robustness of Table 2 estimates in appendices C1–C4, achieving similar results. There is value in getting estimates conditional on having piped water so that results are more comparable to Pennsylvania studies (Muehlenbachs et al., 2015; and Gopalakrishnan and Klaiber, 2014). While we cannot control explicitly for water source, it is reasonable to assume that sales within municipalities at least have access to piped water. Eliminating the 1540 sales outside of municipalities (and more likely to rely on groundwater) leaves estimates virtually unchanged. Controlling for census tract fixed effects in Table C2, reduces coefficient sizes for existence of one or more wells within 3500 ft to 1.5–2.9% (the preferred 1.5% estimate is very close to later repeat sales estimates). Because Table 1 indicates that sales with no wells within 6500 ft seem to be observationally different, we eliminate these observations from the sample in Table C3. In Table C4, we eliminate ZIP codes that have one or fewer wells. Estimates in Tables C3 and C4 lie in between those of Tables 2, and C2.

Our baseline results are significant because they measure the net effect of a nearby well on neighboring property, and are negative without interaction with groundwater. When evaluated at the mean sale price, our estimates of exposure to a well range from 3.5% to 2.8% reduction in sales price (unconditional on water source, 1.5% Table C2), which after allowing for the closer proximity, are similar in magnitude and sign to Timmins and Vissing (2015). In comparison, Muehlenbachs et al. (2012, 2015) find largely positive results. Muehlenbachs et al. (2012) find that conditional on piped water, sales prices increase 10.7%, and that negative impacts from hydraulic fracturing are felt mainly by homes dependent on groundwater, with a 23.6% in sales price when there is a well within 2 km. Muehlenbachs et al. (2015) again find net benefits from being near a well (1.8–3.4%), and that net losses are felt only by properties on groundwater (9.9–16.5%). Gopalakrishnan and Klaiber (2014) find that proximity of a well within 0.75 miles reduces home values by around 0.8–2.1%, but that the negative effects are driven by agricultural lands dependent on groundwater, with reduced property values comparable to findings of Muehlenbachs et al. (2012, 2015).

6.2. Extensions

Previous studies of hydraulic fracturing find that the effect of home values differs during the lifecycle of the well (Gopalakrishnan and Klaiber, 2014). We therefore examine the impact of drilling on sales that occur within six months of well completion, and also sales made after well completion. Table 3 shows that the effects of completed wells are very similar to the results from earlier specifications; however, construction well effects are found to have an additional effect on transaction price. Importantly, short-term dis-amenities from construction appear to have an effect while not altering the long-term effects of proximity to hydraulically fractured wells. Our findings thus diverge from Gopalakrishnan and Klaiber (2014) in that well construction does not seem to be the primary driver of the dis-amenity. Rather, as with Muehlenbachs et al. (2012, 2015) and Popkin et al. (2013), it is perceived environmental damages that provide the likely explanation.

Focusing on the specifications with the space–time interaction fixed effects (specifications 7 and 9), we find properties with at least one construction well within 3500 ft sell for 1.8% less. The second ring effects are also statistically significant and indicate a reduction of 1%, while the third ring effect is an insignificant 0.4%. This pattern is continued when examining pad effects. A property with a pad within 3500 ft sells for 1.8% lower price; the second and third pad effects are not statistically significant but are larger in magnitude than the first ring effect (2.4% and 6.4%, respectively). A single pad between 3500 and 5000 ft away from a property reduces transaction price by 1.1%. The third ring effects are not statistically significant.

In Table 4 we examine whether there are differences in the effects of a well depending on whether it is drilled conventionally (vertically or diagonally) or unconventionally (horizontally). Of the 4124 wells we observe in Tarrant County, 3484 (84%) are horizontal, 435 (11%) vertical, and 205 (5%) diagonal. Table 4 shows that it is the horizontal wells that are responsible for the reduction in home sales price. Conventional wells have no significant effect in specifications 6 and 7; whereas, unconventional wells are associated with a 3–3.8% reduction in home values. These results are consistent with the findings of Boxall et al. (2005) that it is wells that are perceived to have substantial dis-amenities (in their case sour wells, in ours, hydraulically fractured) that are associated with reduced home sale values.

6.3. Repeat sales

Lastly, we estimate a repeat sales model to control for all unobservable characteristics at the property level. The strength of the repeat sales model is that it is better able to control for unobserved (and constant) neighborhood quality than our previous estimates. Repeat sales estimates are identified from homes that go from being exposed to no wells to being exposed to one or more, rather than relying on spatial differences in well exposure, which requires comparing houses that are likely in different neighborhoods. There are nonetheless several

Table 3
Standard hedonic method: Contagion effect for nearby completed and construction hydraulic fracturing wells on transaction price.

Dependent variable = ln(sales price)								
Specification:	(6)		(7)		(8)		(9)	
	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.
Completed well effects								
Ring 1 — within 3500 ft								
One or more completed wells	−0.032***	[0.010]	−0.026**	[0.012]				
One to six completed wells					−0.034***	[0.010]	−0.029**	[0.011]
Seven to twelve completed wells					−0.033**	[0.016]	−0.024	[0.019]
Thirteen or more completed wells					−0.007	[0.035]	−0.003	[0.039]
Ring 2 — between 3501 and 5000 ft								
One or more completed wells	−0.011	[0.008]	−0.005	[0.008]				
One to six completed wells					−0.011	[0.007]	−0.007	[0.008]
Seven to twelve completed wells					−0.010	[0.013]	0.002	[0.015]
Thirteen or more completed wells					0.006	[0.026]	0.020	[0.027]
Ring 3 — between 5001 and 6500 ft								
One or more completed wells	−0.010	[0.007]	−0.001	[0.008]				
One to six completed wells					−0.010	[0.007]	−0.005	[0.007]
Seven to twelve completed wells					0.001	[0.011]	0.016	[0.012]
Thirteen or more completed wells					−0.008	[0.016]	0.018	[0.014]
Construction well effects								
Ring 1 — within 3500 ft								
One or more construction wells	−0.022***	[0.008]	−0.018**	[0.009]				
One to six construction wells					−0.020**	[0.008]	−0.018**	[0.009]
Seven to twelve construction wells					−0.047	[0.035]	−0.024	[0.038]
Thirteen or more construction wells					−0.099**	[0.046]	−0.064	[0.048]
Ring 2 — between 3501 and 5000 ft								
One or more construction wells	−0.010**	[0.005]	−0.010*	[0.006]				
One to six construction wells					−0.009*	[0.005]	−0.011**	[0.005]
Seven to twelve construction wells					0.005	[0.025]	0.004	[0.028]
Thirteen or more construction wells					0.065	[0.071]	0.070	[0.079]
Ring 3 — between 5001 and 6500 ft								
One or more construction wells	−0.004	[0.006]	−0.004	[0.006]				
One to six construction wells					−0.000	[0.006]	−0.003	[0.006]
Seven to twelve construction wells					−0.031	[0.019]	−0.019	[0.019]
Thirteen or more construction wells					−0.051	[0.039]	−0.030	[0.035]
Quarter fixed effects	Yes		Yes		Yes		Yes	
ZIP code fixed effects	Yes		Yes		Yes		Yes	
ZIP code * quarter fixed effects	No		Yes		No		Yes	
N	124,003		124,003		124,003		124,003	
R^2	0.838		0.846		0.836		0.845	

Notes: All specifications include property characteristics and amenity effects. Standard errors are clustered at the ZIP code level. *, **, and *** denote significance at the 0.10, 0.05, and 0.01 level, respectively.

Table 4
Standard hedonic method: Contagion effect for nearby unconventional and conventional wells on transaction price.

Dependent variable = ln(sales price)								
Specification:	(6)		(7)		(8)		(9)	
	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.
Unconventional well effects								
Ring 1 — within 3500 ft								
One or more unconventional wells	−0.038***	[0.011]	−0.030**	[0.012]				
One to six unconventional wells					−0.041***	[0.011]	−0.035***	[0.012]
Seven to twelve unconventional wells					−0.029**	[0.014]	−0.018	[0.016]
Thirteen or more unconventional wells					0.011	[0.029]	0.033	[0.034]
Ring 2 — between 3501 and 5000 ft								
One or more unconventional wells	−0.013*	[0.007]	−0.007	[0.008]				
One to six unconventional wells					−0.013*	[0.007]	−0.009	[0.007]
Seven to twelve unconventional wells					−0.008	[0.012]	0.007	[0.013]
Thirteen or more unconventional wells					−0.002	[0.017]	0.026	[0.023]
Ring 3 — between 5001 and 6500 ft								
One or more unconventional wells	−0.010	[0.008]	−0.002	[0.008]				
One to six unconventional wells					−0.010	[0.007]	−0.004	[0.007]
Seven to twelve unconventional wells					−0.006	[0.012]	0.011	[0.013]
Thirteen or more unconventional wells					−0.015	[0.019]	0.016	[0.017]
Conventional Well Effects								
Ring 1 — within 3500 ft								
One or more conventional wells	0.012	[0.019]	0.009	[0.020]				
One to six conventional wells					0.007	[0.014]	0.003	[0.015]
Seven to twelve conventional wells					−0.048	[0.098]	−0.058	[0.099]
Thirteen or more conventional wells					−0.125	[0.121]	−0.143	[0.123]
Ring 2 — between 3501 and 5000 ft								
One or more conventional wells	−0.002	[0.021]	−0.004	[0.021]				
One to six conventional wells					−0.004	[0.018]	−0.006	[0.019]
Seven to twelve conventional wells					−0.000	[0.048]	−0.010	[0.048]
Thirteen or more conventional wells					0.075	[0.071]	0.068	[0.070]
Ring 3 — between 5001 and 6500 ft								
One or more conventional wells	−0.001	[0.013]	−0.000	[0.013]				
One to six conventional wells					−0.002	[0.012]	−0.003	[0.012]
Seven to twelve conventional wells					0.073**	[0.036]	0.069*	[0.039]
Thirteen or more conventional wells					0.090*	[0.052]	0.083	[0.054]
Quarter fixed effects	Yes		Yes		Yes		Yes	
ZIP code fixed effects	Yes		Yes		Yes		Yes	
ZIP code*Quarter fixed effects	No		Yes		No		Yes	
N	127,556		127,556		127,556		127,556	
R^2	0.836		0.845		0.837		0.845	

Notes: All specifications include property characteristics and amenity effects. Standard errors are clustered at the ZIP code level. *, **, and *** denote significance at the 0.10, 0.05, and 0.01 level, respectively.

caveats. We have a relatively short time period which leads to a small sample of properties sold more than once, about 15,000 properties. We are also concerned about investors "flipping" or making very quick significant improvements to these properties, which we cannot observe; therefore, we limit our sample to those properties that have at least 6 months between sales.[22] Lastly, external validity to the larger housing market is reduced because homes selling more than once may be different than homes that sold only once.

Table 5 presents the estimation of Eq. (2) for four different specifications. In all specifications we estimate a price index by including the standard matrix for sales dates where the first transaction in the pair takes value −1 and the second takes 1. The specifications differ based on the scope of the price index. Specification 1 takes Tarrant County as a whole and finds significant impacts of proximity to hydraulically fractured wells in each ring on transaction price. The magnitudes are very similar to the hedonic results. Because we do not imagine that the entire county constitutes the local housing market, we focus the price index down to the city-level in specification 2 and find significant reductions in sales price for homes with wells in rings 1 and 2.[23] Narrowing further, we estimate the price index for each of Tarrant County's 43 cities in specifications 3 and 4. These are the preferred specifications and we find significant impacts on transaction prices when homes have wells or one pad within rings 1 and 2. The magnitudes suggest that prices are reduced by 1.8% and 1.6% for the existence of a well in ring 1 and ring 2, respectively.[24] Evaluated at the mean sales price for the repeat sales sample ($176,065) the effect translates to a reduction of $2817 to $3169. Pad effects are of similar size; however, there is also evidence that three pads within 3500 ft significantly reduces transaction price. The magnitude of this effect is larger, 3.4% or $5986.

7. Conclusion

This paper uses over 120,000 house transactions in Tarrant County, TX to show that houses nearby hydraulically fractured natural gas wells are sold at lower prices than other houses. The reduction in price is largest for homes within 3500 ft of a well or pad, approximately 1.5–3.5% of a house's value on average. During construction of the natural gas wells, the houses within 5000 ft see an additional reduction in house value on average of about 1 to 2%. It should be kept in mind that this estimate represents the cost to property net of any benefits (lease payments), and is unconditional of water source. Comparing

[22] We have tried longer holding times and while the transaction count is reduced the magnitude and significance of the results largely remain unchanged.

[23] For example there are 18 different school districts represented in our sample. To the extent that localities differ in the effect that hydraulic fracturing has on home values, our estimates represent a weighted average of these heterogeneous effects.

[24] The estimates of 1.6 to 1.8% reduction are similar to estimates in the census tract hedonic estimates in Table C2.

Table 5
Repeat sales method.

Dependent variable = ln(sales price$_{t+\tau}$ / sales price$_t$)								
Specification:	(1)		(2)		(3)		(4)	
	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.
Hydraulic Fracturing Effects								
Ring 1 — within 3500 ft								
One or more wells	−0.027***	[0.007]	−0.013***	[0.005]	−0.018***	[0.006]		
One to six wells							−0.018***	[0.005]
Seven to twelve wells							−0.010	[0.011]
Thirteen or more wells							−0.034**	[0.014]
Ring 2 — between 3501 and 5000 ft								
One or more wells	−0.027***	[0.007]	−0.014***	[0.005]	−0.016***	[0.006]		
One to six wells							−0.013***	[0.004]
Seven to twelve wells							−0.008	[0.007]
Thirteen or more wells							−0.013	[0.009]
Ring 3 — between 5001 and 6500 ft								
One or more wells	−0.011	[0.007]	0.000	[0.004]	0.003	[0.005]		
One to six wells							−0.001	[0.007]
Seven to twelve wells							0.018*	[0.010]
Thirteen or more wells							−0.026	[0.021]
Local price index level	Tarrant County		School district		City		City	
N	15,412		15,412		15,412		15,412	
R^2	0.118		0.231		0.256		0.257	

Notes: The local price index is calculated by including the standard indicator matrix for sales date; the largest level and starting point is the entire county then to the school district level and finally to the city level (43 cities in Tarrant County). The minimum days between sales is 180 days. Repeat sales with appreciation rates higher than 10% per quarter and sold within two years are removed. Repeat sales with appreciation rates higher than 8% per quarter and with hold times greater than 2 years are removed. Standard errors are clustered at the city level. *, **, and *** denote significance at the 0.10, 0.05, and 0.01 level, respectively.

unconventional to conventional drilling, it is the unconventional horizontal wells that drive the negative effects.

The realization of negative spillover effects is important for understanding regulatory trends. A 3.5% reduction in property values amounts to property destruction in Tarrant County of $753 million from 2005 to 2011. The most conservative repeat sales estimate of 1.3% reduction yields $280 million in net property destruction. These losses are less than the $2.54 billion in assessed mineral values, but far from insignificant. Our measured effect is the net effect of the average benefits and costs to homeowners in our sample.

In reality, there is likely substantial heterogeneity in the benefits of hydraulic fracturing to homeowners, with owners of split estates (those without mineral rights) receiving less of the benefits than those who do own the mineral rights. Because many of the mineral rights owners have addresses outside the state,[25] we can surmise that the local electorate has not received the full benefits of hydraulic fracturing, yet they have been exposed to the full costs. It is not surprising, then, that the electorate has organized in favor of increased regulation. In 2013, Dallas, TX (Tarrant County's neighbor to the east) passed a city ordinance restricting hydraulically fractured wells from locating within 1500 ft of homes, schools, churches, and other protected sites. In 2014, Denton, TX (just north of Tarrant County, TX) went one step further and passed a city ordinance prohibiting the operation of hydraulically fractured wells. In 2015, the state of Texas responded by outlawing the type of ordinance passed in Denton. Tarrant County has comparatively extensive publically available mineral lease information and will be an important location for informing research on the effect of split estates on property values as well as understanding the political economy of hydraulic fracturing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eneco.2016.11.010.

[25] Tarrant Appraisal District, MNRL file downloaded Aug 1, 2014.

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