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The Housing Market Impacts of Shale Gas Development

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RESOURCES FOR THE FUTURE

The Housing Market Impacts of Shale Gas Development

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Abstract

Using data from Pennsylvania and an array of empirical techniques to control for confounding factors, we recover hedonic estimates of property value impacts from nearby shale gas development that vary with water source, well productivity, and visibility. Results indicate large negative impacts on nearby groundwater-dependent homes, while piped-water-dependent homes exhibit smaller positive impacts, suggesting benefits from lease payments. Results have implications for the debate over regulation of shale gas development.

JEL Classification Numbers: Q32, Q33, Q50, Q53

Keywords: shale gas, groundwater, property values, hedonic models, nearest neighbor matching, differences-in-differences, triple differences

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1 Introduction

Technological improvements in the extraction of oil and natural gas from unconventional sources have transformed communities and landscapes and brought debate and controversy in the policy arena. Shale gas plays underlying the populated northeastern United States were thought to be uneconomical less than 10 years ago, but now contribute a major share of US gas supply.[1] Natural gas has been hailed as a bridge to energy independence and a clean future because of its domestic sourcing and, compared with coal and petroleum derivatives, its smaller carbon footprint and reduced emissions of other pollutants (e.g., particulates, sulfur dioxide, carbon monoxide, and nitrogen oxides). Yet opposition to unconventional methods of natural gas extraction has emerged, citing the potential for damages from methane leakage, water contamination, and local air pollution (see Mason et al., 2015, for a review).

Economic and environmental impacts may also arise from the "boomtown" phenomenon, where local areas facing shale development see increases in population, employment, business activity, and government revenues.[2] However, boomtowns may also suffer from negative social, economic, and environmental consequences such as increased crime rates, housing rental costs, and air pollution (Lovejoy, 1977; Albrecht, 1978; Freudenburg, 1982). Furthermore, the "boom" may be followed by a "bust" if benefits from shale gas development are only temporary. Local public goods might be expanded during the boom at considerable cost only to be later left underutilized, and sectors with better growth potential could contract during the boom, leaving the area worse off in the long run (i.e., the Dutch disease).

Properties surrounding shale gas development may experience growth or decline in value depending on whether the benefits of the activity outweigh the costs. Moreover, benefits and costs may be heterogeneous across housing types. For example, properties that rely on private water may suffer greater reductions in value when confronted with shale gas development if there is a risk of losing that water source. Access to a safe, reliable source of drinking water is an important determinant of a property's value; even

[1] In 2000, shale gas accounted for 1.6 percent of total US natural gas production; this rose to 4.1 percent in 2005, and by 2010, it had reached 23.1 percent (Wang and Krupnick, 2013). Natural gas from the Marcellus formation currently accounts for the majority of this production (Rahm et al., 2013) and can be attributed to advances in hydraulic fracturing, horizontal drilling, and 3-D seismic imaging.

[2] See, for example, Lillydahl et al. (1982) and Wynveen (2011). Employment effects from oil and gas development is an active area of research; specific to shale gas there are Weber (2012), Maniloff and Mastromonaco (2014), and Fetzer (2014).

a perceived threat to that access can have detrimental effects on housing prices. This is very important, as the potential for shale gas development to contaminate groundwater has been hotly debated.[3] Perceptions of the risks and benefits from drilling can vary with a variety of factors, including the density of drilling activity, environmental activism, economic activity, unemployment levels, and urban density (Theodori, 2009; Wynveen, 2011; Brasier et al., 2011). While there are valid arguments on both sides of the debate surrounding shale gas development, the question of whether the benefits outweigh the costs has not yet been answered. This paper uses hedonic theory to better understand these costs and benefits. Hedonic analysis exploits the tradeoffs between property characteristics (which also include neighborhood characteristics and amenities) and price made by homebuyers to value the former.[4] Measuring the impacts of shale gas activity on property values provides a convenient way to quantify its effects (whether real or perceived).

The impact of shale gas development on property values has become the focus of a growing body of literature. One of the first related papers (Boxall et al., 2005), while not a study of shale gas wells, finds a negative impact of wells emitting hydrogen sulfide (a lethal gas) on properties in Alberta, Canada. More recent studies have focused on shale gas, with Gopalakrishnan and Klaiber (2014) and Muehlenbachs et al. (2013) using data from Washington County, Pennsylvania. Gopalakrishnan and Klaiber (2014) find that proximity to shale gas wells diminishes property values across the board by a small amount while Muehlenbachs et al. (2013) find that a larger negative effect holds only for properties dependent on private-groundwater wells as a drinking water source. James and James (2014) find negative impacts in Weld County, Colorado, but Delgado et al. (2014) only find weak evidence of this in Lycoming and Bradford Counties, Pennsylvania. At the broader level, Boslett et al. (2014) finds that groundwater-dependent homes in New York positively value the possibility of shale gas development. Weber et al. (2014) find property values in Texas are higher in zip codes with shale, conjectured to be driven by local public finances.

A major obstacle to accurately estimating the impact of shale gas development on surrounding homes is the presence of correlated unobservables that may confound

[3]An example from Dimock, Pennsylvania, can be seen in these headlines: "Water Test Results Prove Fracking Contamination in Dimock," Riverkeeper.org, March 22, 2012, versus "Just Like We've Been Saying—Clean Water in Dimock," eidmarcellus.org, August 3, 2012. Under ambiguity aversion, such a debate would decrease the value of groundwater-dependent properties.

[4]See Appendix Sub-Section A.2 for a deeper discussion of the hedonic method as it applies to this paper.

identification. Shale gas wells are not located randomly, but may be placed in areas with features that aid in the drilling process, such as near a road or easement; unobservable property and neighborhood attributes may therefore be correlated both with proximity to wells and with the property value. Providing evidence suggesting that wells are not randomly assigned (see Figures 4 and 5), we highlight the importance of using variation in the price of a property over time to estimate the effect of a new nearby shale gas well. We are able to conduct this estimation by using a very long panel of property transactions spanning 1995 to 2012; other studies (with the exception of Muehlenbachs et al., 2013) estimate the impacts of shale gas wells by comparing values across different properties. Facilitated by data from across the Commonwealth of Pennsylvania, we employ a triple-difference (DDD) estimator, combined with a mix of fixed effects and treatment boundary techniques to deal with time invariant and time varying unobservables that may be correlated with proximity to shale gas wells or drinking-water source. Moreover, we show that similar results are obtained by utilizing a difference-in-differences-nearest-neighbor-matching (DDNNM) technique that does not rely on panel data variation for identification. By using a geographically expanded dataset of properties, we are able to measure economic impacts of drilling at the local level while controlling for macroeconomic effects (e.g., the Great Recession, outsourcing of manufacturing) at the county level. Finally, our long panel of property transactions creates a solid baseline for our DDD estimator prior to the onset of shale gas development.

Our results demonstrate that groundwater-dependent homes are, in fact, negatively affected by nearby shale gas development, indicating that the oft-debated risk to groundwater contamination has indeed materialized into a real impact. Similarly proximate homes that have access to publicly supplied piped water, on the other hand, appear to receive small benefits from that development. However, that benefit only comes from producing wells, suggesting that it reflects royalty payments to the homeowner from natural gas production. Recently drilled wells (i.e., drilled within the past year) do not contribute to this benefit, providing evidence that the drilling and hydraulic fracturing stages of shale gas development are the most disruptive. The burden of aesthetic disruptions is corroborated by the finding that the positive impacts are only driven by wells that are not in view of the property.

These results are particularly representative of the economic impacts of shale gas development in light of the fact that the Marcellus shale gas play is the largest in the country.[5] Given the amount of extraction that may occur in this region in the future, the effect on property values may have important implications for understanding the benefits and costs of a large scale shift towards domestic energy from shale gas.

Our paper proceeds as follows. Section 2 describes our methodology. Section 3 details our data, and Section 4 reports our empirical specifications and main results, with a summary of different property value impacts in Section 5. Section 6 concludes. Finally, we provide an appendix for online publication that describes (i) the sample cuts made to our dataset, (ii) hedonic theory, the simplifying assumptions that underlie most of the hedonic literature (including our analysis), and the problems that arise using panel data when the residential composition shifts over time, (iii) robustness checks over space and time, (iv) the impact of shale gas development on community sociodemographics, the frequency of sales, and new construction, and (v) geographical heterogeneity of the results.

2 Methodology

Our goal is to recover estimates of the non-marketed costs and benefits of shale gas wells by measuring their capitalization into housing prices. Houses are differentiated by proximity to wells and by water source—e.g., houses within 2km of a well that are dependent upon their own private groundwater wells as a source of drinking water versus houses at a similar range in public water service areas with access to piped water. In this paper we identify the differential impacts depending on well proximity and drinking water source.

2.1 Impact Categories

We categorize the impacts of nearby shale gas exploration and development on housing values as follows. (1) *Adjacency Effects*; this category refers to all of the costs and benefits associated with close proximity to a shale gas well that are incurred regardless of water source. Costs in this category may include noise and light pollution, local air pollution (McKenzie et al., 2012; Litovitz et al., 2013), alteration of the local landscape,

[5] See http://www.eia.gov/analysis/studies/usshalegas/ for a ranking of shale gas plays in terms of technically recoverable reserves.

and visual disamenities associated with drilling equipment and cleared land.[6] The most obvious benefit would be royalties and lease payments paid to the property owner for the extraction of the natural gas beneath their land.[7] It is possible to sever the mineral rights from the surface (property) rights, leaving future owners with no ability to profit from lease and royalty payments. The extent to which these rights have been severed throughout our sample is impossible to know without access to detailed data on leases and deeds, which we do not have. Thus, our estimates may find little to no positive impacts for homes located near shale gas wells because the rights may have been severed, and without knowing which properties currently hold their mineral rights, we are unable to capture the positive impact for those who do. Instead, our adjacency effect estimates an overall *net* effect: the benefits of lease payments for those households who may be receiving them (tempered by those unable to profit from the lease payments due to severed mineral rights) and the negative externalities of being located near a drilling site (excluding the externalities associated with the property depending on groundwater). (2) *Groundwater Contamination Risk* (GWCR); this category represents the additional cost capitalized into adjacent properties that are dependent upon groundwater. Our identification strategy assumes that this is the only additional impact of adjacency associated with reliance on groundwater.[8] If royalty rates do not vary with water source, then this should not impact our estimate

[6] Given that property values could be negatively affected by proximity to a shale gas well, one might wonder why a homeowner would be willing to lease their mineral rights to the gas company. In answering this question, it is important to note that refusing to lease out the mineral rights under one's property does not prevent a company from drilling on a neighbor's land, which would still expose the holdout-homeowner to development (and the potential, for example, of groundwater contamination). Horizontal drilling requires having the rights to drill under a large contiguous area, which implies that a critical mass of homeowners need to lease their mineral rights before drilling occurs. Homeowners may form coalitions to prevent drilling; however, unless there is a binding agreement between neighbors, each homeowner may have an incentive to deviate and lease their mineral rights to the gas companies. This may be particularly true if there is the possibility of a large up-front bonus payment. Conditional upon a neighbor's decision to sign a lease, therefore, leasing one's mineral rights will result in higher payoffs than holding out and still being exposed to the impacts of shale development. We may therefore expect to see groups of landowners choose to lease their rights although it might have been optimal for none of them to have done so.

[7] In Pennsylvania, upon signing their mineral rights to a gas company, landowners may receive two dollars to thousands of dollars per acre as an upfront "bonus" payment, and then a 12.5 percent to 21 percent royalty per unit of gas extracted. Natural Gas Forum for Landowners: Natural Gas Lease Offer Tracker, available at http://www.naturalgasforums.com/natgasSubs/naturalGasLeaseOfferTracker.php.

[8] Data on groundwater contamination resulting from shale gas development in Pennsylvania are not generally available to researchers or homeowners because there was no widespread testing of groundwater prior to the start of drilling. What we are measuring is therefore the cost associated with the *risk* of contamination *perceived* by homeowners.

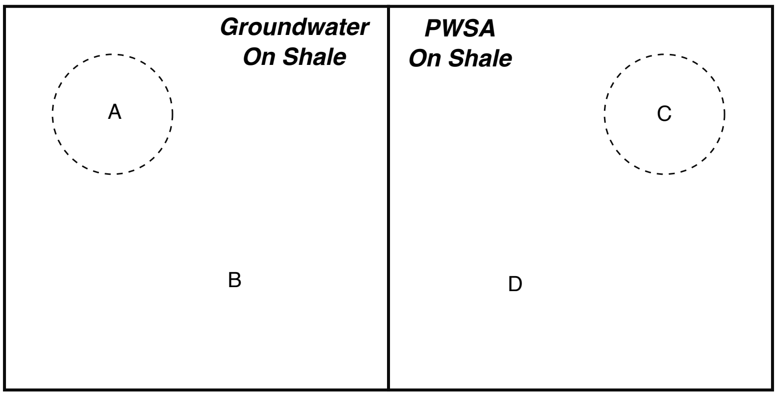

Figure 1: Types of Areas Examined

of GWCR.

In addition to these two direct impacts of shale gas activities on housing prices, there are broader *Vicinity Effects* that can also impact housing prices. These refer to the impacts of shale gas development on houses within a broadly defined area (e.g., 20km) surrounding wells and may include increased traffic congestion and road damage from trucks delivering fresh water to wells and hauling away wastewater, wastewater disposal (to the extent that is done locally), increased local employment and demand for local goods and services, and impacts on local public finance. We allow these vicinity effects to differ by drinking water source as water source may reflect jurisdictional boundaries that determine the extent to which a property might benefit from, for example, an impact fee.[9] Furthermore, there are *Macro Effects*, which are not specifically related to shale gas activity and are therefore assumed to be common to areas with and without a publicly provided drinking water source. Given the time period that we study, this impact category includes the housing bubble, the subsequent housing bust and national recession, impacts of globalization and jobs moving overseas, and other regional economic impacts.

Figure 1 is useful in describing our identification strategy, and we will refer to it in more detail in Section 4.2. Area *A* represents a buffer drawn around a well that defines adjacency. That buffer is located in an area dependent upon groundwater (GW)—

[9]Impact fees are taxes levied on drilled wells. The total amount of impact fees collected in PA through 2014 exceeded $850 million dollars, 60 percent of which is given to local counties and municipalities with wells. See http://stateimpact.npr.org/pennsylvania/tag/impact-fee/

i.e., outside the public water service area (PWSA). To choose the size of the buffer, we use two pieces of evidence. The first comes from Osborn et al. (2011) who find that drinking water wells within 1km of shale gas wells have higher concentrations of methane. Although their findings are not causally identified, this study has received much press attention and to date is one of the most frequently cited studies on the environmental impacts of shale gas development. Second, the distance of the horizontal portion of the well is approximately 1 mile (or 1.6km).[10] This implies that lease payments would be provided to homeowners located within this distance of a well.[11] We also vary the distance of the buffer to test our localized impact hypothesis, and find that distances less than 2km are most affected by proximity, thereby validating our hypothesis.

Area B is located outside the adjacency buffer but is within the vicinity of a well and is located above the shale formation. Similarly defined regions of the PWSA area are labeled by C and D, respectively.

3 Data

We obtained transaction records of all properties sold in 36 counties in Pennsylvania between January 1995 and April 2012 from CoreLogic, a national real estate data provider. The data contain information on the transaction price (which we convert into 2012 dollars), exact street address, parcel boundaries, square footage, year built, lot size, number of rooms, number of bathrooms, and number of stories.[12] Figure 2 depicts the location of the Marcellus shale formation (obtained from the U.S. Geological Survey) as well as the properties sold in Pennsylvania.

To determine the date that wells are drilled, we use the Pennsylvania Department of Environmental Protection (PADEP) Spud Data as well as the Department of Conservation and Natural Resources (DCNR) Well Information System (the Pennsylvania

[10]Although electronic records of the location of the horizontal segment of the wellbores are not available, anecdotal evidence suggests that wellbores are typically between 3,000 feet (.9km) and 5,000 feet (1.5km) (US Energy Information Administration, 2013), but could be up to 10,684 feet (3.3km) which is the longest horizontal well in the Marcellus shale (O'Brien, 2013)).

[11]Of course, payments would only be made to those households whose property is located above the wellbore; while the pipes extend horizontally, they do not necessarily extend radially in all directions and therefore a portion of the homes located within 1.6km will not be entitled to a payment. Thus, the overall effect of proximity captures the combined impact on those houses that are eligible for payment and the remaining households who are not eligible.

[12]See Appendix Section A.1 for a description of how we constructed our final samples.

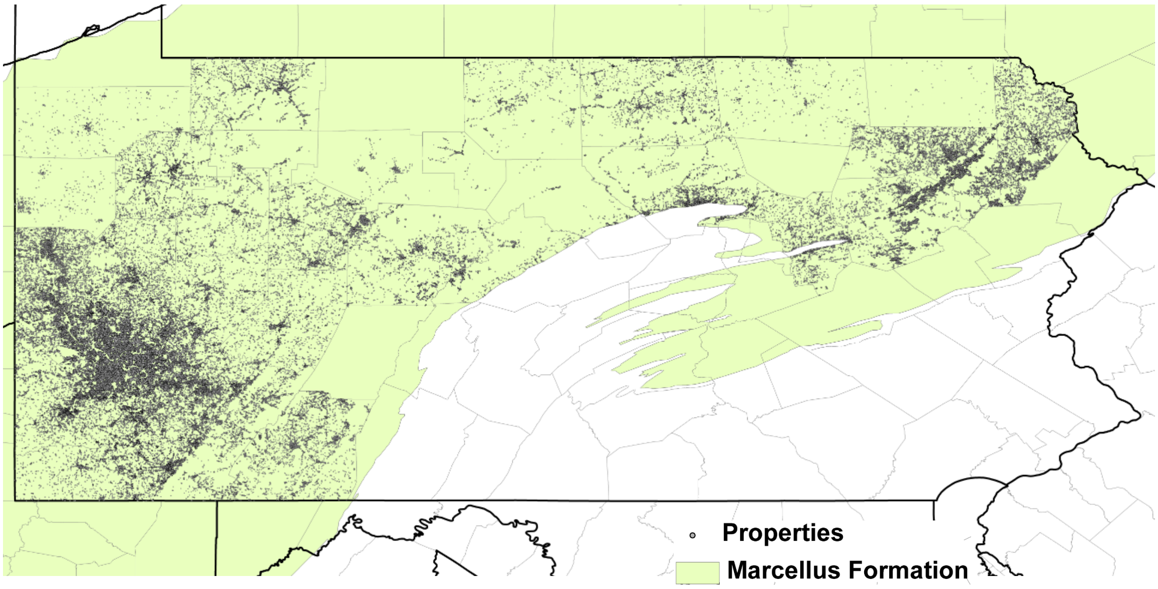

Figure 2: Property sales data from CoreLogic mapped with GIS on overlay of Marcellus Shale.

Internet Record Imaging System/Wells Information System [PA*IRIS/WIS]). Combining these two datasets provides us with the most comprehensive dataset on wells drilled in Pennsylvania that is available (for example, no other data distributors, such as IHS or Drillinginfo, would provide more comprehensive data than this).[13] The final dataset includes both vertical and horizontal wells, both of which produce similar disamenities, including risks of groundwater contamination.[14]

Because operators are able to drill horizontally underground, they can locate the tops of several wellbores close together at the surface, and radiate out the horizontal portion of the wellbore beneath the surface. Therefore, multiple wellbores can be drilled within meters of one another on the same "well pad," concentrating the surface disruption to a smaller space. Though the data do not group wellbores into well pads, we believe this is important to consider when estimating the effect of shale gas wells on nearby properties, as the impact from an additional wellbore is likely different from

[13]We corroborated this by comparing our data with data from Drillinginfo, a credible third source—we have 52 more wells than Drillinginfo and, because we have captured completion dates, we are able to use these when the "spud" dates are missing (which was the case for 847 wells). The spud date refers to the first day of drilling. Drillinginfo does not capture completion dates and thus provides a less complete data set than that which we use.

[14]Risk of improper well casing or cementing would be present in both vertical and horizontal wells.

the impact of an additional well pad. We therefore assume that any wellbore within a short distance of another wellbore is located on the same pad (specifically, any wellbore that is closer than 63m, or the length of an acre, to any other wellbore is designated to be in the same well pad).[15] We start with 6,260 wellbores, which we group into 3,167 well pads (with an average of 2 bores per pad and a maximum of 12). Using the geographic information system (GIS) location of the wells and the properties, we calculate counts of the number of well pads that have been drilled, within certain distances, at the time of the property sale. The PADEP also provides information on the GIS location of all permitted wells, which we use to count the number of wells that have been permitted but have not yet been drilled (only about 60% of the wells that have been permitted have been drilled). We can also use the date that the well was permitted to determine how long a permit has remained undrilled. We obtain the volume of natural gas produced for each wellbore from the PADEP's Oil & Gas Reporting Website.[16]

Pennsylvania has many hilly and mountainous areas as well as plateaus. Therefore, depending on where the property is located, a homeowner may or may not be able to see all the wells within the adjacency buffer. Following the methodology in Walls et al. (2013), who examine the property value of natural landscape views, we count the number of wells that are in view and not in view at the time of sale. To do so we use ArcGIS's Viewshed tool and an elevation map from the National Elevation Dataset (at a 30 meter resolution) to predict how far a 5-foot tall observer can see from all directions around the property.[17] From this we make a count of the visible wells within different radii at the time of the sale.

To identify properties that do not have access to piped drinking water, we utilize data on public water service areas. We obtained the GIS boundaries of the public water suppliers' service areas in Pennsylvania from the PADEP and assume that any property outside these boundaries is groundwater dependent.[18]

[15]During completion, a multi-well pad, access road, and infrastructure are estimated to encompass 7.4 acres in size; after completion and partial reclamation, a multi-well pad averages 4.5 acres in size (New York State Department of Environmental Conservation, 2011).

[16]The data are reported as annual quantities until 2009 and then semiannual from 2010 to 2012.

[17]Of course, this technology has limitations. It does not tell us whether the homeowner would be able to see the well from the top floor of a home or from the edge of the property; it also does not take into account obstructing vegetation or other houses. Finally, a taller person may better be able to see the well.

[18]There is not much financial assistance to households wishing to extend the piped water service area to their location. Doing so is a costly endeavor according to personal communication with the development manager at the Washington County Planning Commission, April 24, 2012.

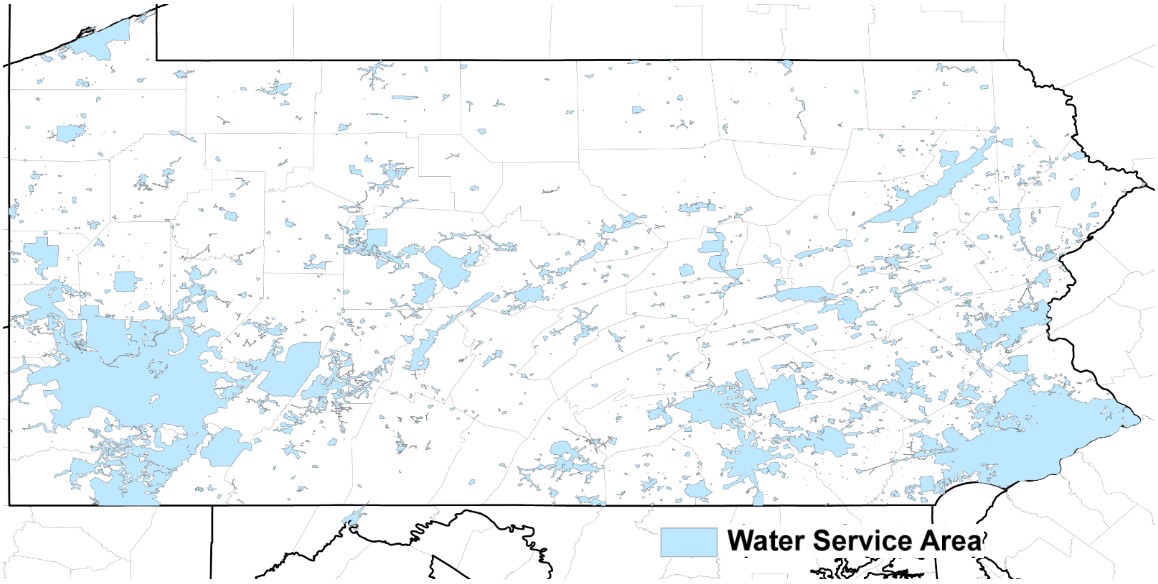

Figure 3: Public Water Service Areas in Pennsylvania

Figure 3 shows the PWSA areas – the unshaded areas are assumed to depend on private groundwater wells for their drinking water source. This figure demonstrates that PWSAs are scattered throughout the state and that there are large areas without access to piped water, further illustrating the importance of estimating the impacts of shale development on groundwater-dependent homes.

4 Empirical Strategy and Results

In this section, we estimate the impacts of close proximity to shale gas wells on property values. These effects can be positive, such as in the case that the property owner receives royalty or other lease payments from the gas company for the natural gas extracted from their property, or negative, given perceived impacts of groundwater contamination, noise, light, and air pollution, or the alteration of the local landscape. The siting of shale gas wells can be strategic on the part of gas companies and must be agreed to on part of the property owner, so it is also important to account for a wide range of unobservable attributes that may be correlated with both the property and proximity to the shale well. We first provide some evidence that our adjacency buffer correctly identifies localized impacts. We then begin our estimation section with a triple-difference technique that also makes use of properties on the boundary of the public water supply area. Finally, we show that similar results can be obtained from a difference-in-differences technique combined with a nearest-neighbor matching algorithm that does not rely on panel data variation for identification. Comparing the effect over time we find it to be similarly sized in different time periods, though cutting by sub-period reduces sample size and statistical significance. This points to our estimates being robust to the critique described by Kuminoff and Pope (2014), though only weakly so due to low statistical power.

4.1 Descriptive Evidence of Adjacency Effects and Groundwater Contamination Risk

Here we provide some evidence that the prices of groundwater-dependent houses are in fact affected by proximity to shale gas wells. We draw on a strategy similar to that employed by Linden and Rockoff (2008), which determines the point where a localized (dis)amenity no longer has localized impacts. For our application, this method compares the prices of properties sold after the drilling of a well to the prices of properties sold prior to drilling, and identifies the distance beyond which the well no longer has an additional effect.

In order to conduct this test, we create a subsample of properties that have been sold more than once and with at least one sale starting after the placement of only one well pad within 10km.[19] For each water source, we estimate two price functions based on distance to its nearest well pad—one using a sample of property sales that occurred *prior* to the well pad being drilled and the other using a sample of property sales that occurred *after* the well pad was drilled. The price functions are estimated with local polynomial regressions using as dependent variables the residuals from a regression controlling for county-year, quarter, and property characteristics.

Figure 4 depicts the results from the local polynomial regression when focusing on areas with access to piped water. This figure is in sharp contrast to Figure 5 which depicts areas without access to piped water. We see a sharp decline in property values of groundwater-dependent homes after a well is drilled within 2km; however, the prices

[19]For this exercise, we choose to only look at homes that have *one* well pad within 10km, as it would be difficult to separate the impact of the nearest well pad before and after the well pad is drilled if the home was already being impacted by another well pad drilled nearby. We chose 10km because finding properties with only one well pad within farther distances would reduce our sample size, while we think it is a reasonable assumption that vicinity impacts that are felt at more than 10km will be similar to those at 10km.

for groundwater-dependent properties farther than 2km from a well remain the same before and after it is drilled. This exercise demonstrates that adjacency impacts differ by drinking water source within 2km of a well, validating our usage of buffers less than 2km in distance. It also demonstrates the importance of controlling for unobserved characteristics that might be correlated with the siting of a well and the price of the property; in the case of public water service areas, properties that are the closest to a well are priced lower even before the well is drilled, while the opposite is true in groundwater-dependent areas.

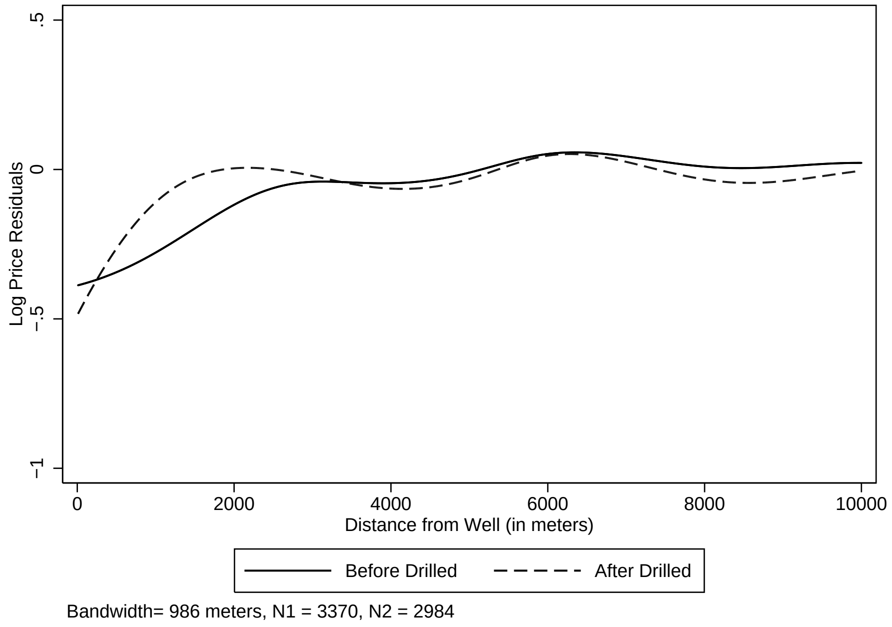

Figure 4: Price Gradient of Distance from Future/Current Well, using Public Water Service Areas

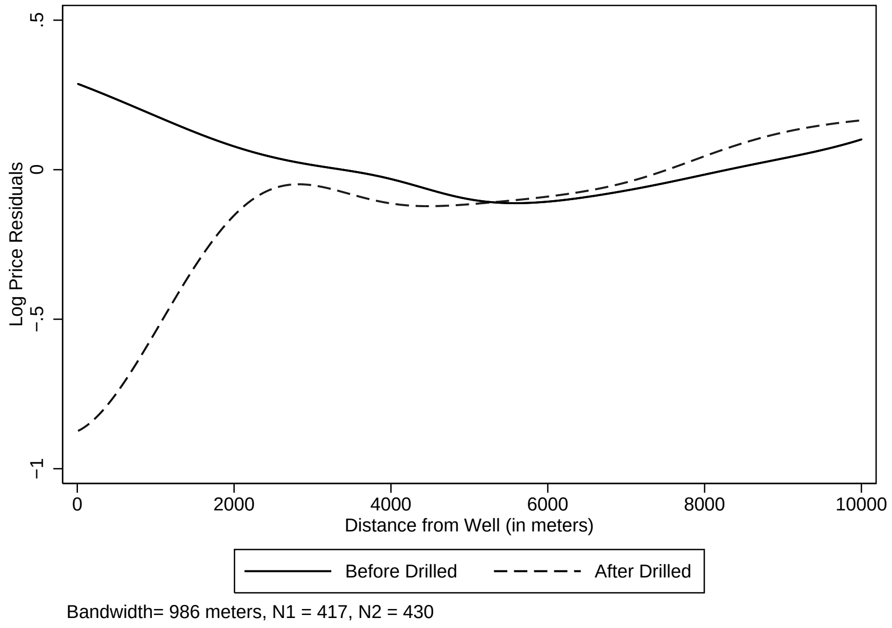

Figure 5: Price Gradient of Distance from Future/Current Well, using Groundwater-Dependent Areas

4.2 Triple-Difference (DDD) Estimation of GWCR

Considering the impact categories described in Section 2.1 and in Figure 1, we begin by defining the components of the change in a *particular* property's value over time (ΔP) in each area:

$$\begin{aligned}
\Delta P_A &= \Delta\text{Adjacency} + \Delta\text{GWCR} + \Delta\text{Vicinity}_{GW} + \Delta\text{Macro} \\
\Delta P_B &= \Delta\text{Vicinity}_{GW} + \Delta\text{Macro} \\
\Delta P_C &= \Delta\text{Adjacency} + \Delta\text{Vicinity}_{PWSA} + \Delta\text{Macro} \\
\Delta P_D &= \Delta\text{Vicinity}_{PWSA} + \Delta\text{Macro}
\end{aligned} \tag{1}$$

where, for example, ΔGWCR refers to the change in price attributable to groundwater contamination risk from new wells in area A. We differentiate vicinity effects by drinking water source: $\Delta\text{Vicinity}_{GW}$ refers to the vicinity impact on groundwater-dependent homes, while $\Delta\text{Vicinity}_{PWSA}$ refers to the vicinity impact on PWSA homes. Our strategy for identifying adjacency effects uses a difference-in-differences (DD) estimator:

$$\Delta\text{Adjacency}_{\text{DD}} = [\Delta P_C - \Delta P_D]$$

where the first difference, "Δ," reflects the change in price of a particular house (e.g., accompanying the addition of a new well pad). The second difference compares the change in prices for PWSA properties adjacent to shale gas development to the change in prices of PWSA properties not adjacent to development. For the PWSA homes, this differences away vicinity and macro effects that are common across C and D. Because vicinity effects may differ by drinking water source, we can only difference these away by looking within water sources; hence, our adjacency regressions rely only on PWSA homes. Furthermore, note that the corresponding equation for GW homes results in both adjacency and groundwater contamination risk:

$$(\Delta\text{Adjacency} + \Delta\text{GWCR})_{\text{DD}} = [\Delta P_A - \Delta P_B]$$

Therefore, to estimate the effect of perceived groundwater contamination risk, we must then difference away the effects across PWSA and GW areas by implementing the following triple-difference (DDD) estimator:

$$\Delta\text{GWCR}_{\text{DDD}} = [\Delta P_A - \Delta P_B] - [\Delta P_C - \Delta P_D]$$

Similar to the expression for adjacency, in this expression, Δ reflects the first difference, the change in the price of a particular house accompanying the addition of a new well pad. The second difference compares the change in prices inside each adjacency buffer to the change in prices outside of that buffer. This second difference differences away relevant vicinity and macro effects, leaving only GWCR and adjacency effects. The third (and final) difference differences those double-differences, eliminating adjacency effects and leaving only GWCR from a new well pad.

In order to conduct this estimation, we define our impact variable given the results of our adjacency test in Section 4.1. In most of the specifications, we look at well pads rather than wellbores to estimate adjacency effects. To identify GWCR we focus on well pads because we are capturing perceptions of contamination risk. When a pad is cleared and drilling begins, it is unlikely that drilling a second wellbore on that pad will have the same impact on property values as did the initial pad. Essentially, we assume that the perception of groundwater contamination risk will be the same regardless of the number of wellbores located on a well pad.[20]

In deriving our empirical specification based on the preceding intuition, we begin by considering the price of house i at time t as a function of all well pads ($k = 1,2,...K$), a house fixed effect (μ_i), a fixed effect that varies with both geography (i.e., either county or census tract) and year (ν_{it}), and a temporal fixed effect indicating the quarter (q_t):

$$\ln P_{it} = \alpha_0 + \sum_{k=1}^{K} \rho_{ik} w_{kt} + \mu_i + \nu_{it} + q_t + \epsilon_{it} \tag{2}$$

where k indexes the well and K is the total number of wells in Pennsylvania; $w_{kt} = 1$ if well pad k has been drilled by time t (in a sensitivity analysis we differentiate between wells that are merely drilled and actually producing); and ρ_{ik} translates the presence of well w_{kt} into an effect on house price based on its proximity. We can decompose Equation (2) by dividing the well pads into those that are within 20km and those outside of 20km:

$$\ln P_{it} = \alpha_0 + \sum_{k=1}^{K} \alpha_1 d_{ik}^{<20} w_{kt} + \sum_{k=1}^{K} \lambda_1 d_{ik}^{>20} w_{kt} + \mu_i + \nu_{it} + q_t + \epsilon_{it}$$

where $\rho_{ik} = \alpha_1 d_{ik}^{<20} + \lambda_1 d_{ik}^{>20}$, $d_{ik}^{<20} = 1$ if well pad k is within 20km of house i (= 0

[20] We test this assumption with a specification that uses wellbores rather than pads and find that wellbores do not significantly affect the estimate of GWCR, lending credence to our assumption that the marginal impact of an extra wellbore is insignificant.

otherwise), and $d_{ik}^{>20}$ is defined in a similar manner for wells outside of 20km distance of a house. Here, we simplify things by assuming that $\lambda_1 = 0$:

$$\ln P_{it} = \alpha_0 + \alpha_1 \sum_{k=1}^{K} d_{ik}^{<20} w_{kt} + \mu_i + \nu_{it} + q_t + \epsilon_{it}$$

We can take a further step by allowing the effect to be different for nearby wells, transforming this equation into a difference-in-difference estimator by adding a term interacting the initial proximity regressor (the presence of a well within 20km) with an indicator for the well being within a short distance of the property (in this case, we refer to the short distance—or adjacency buffer— as being 2km but the same equation holds for buffers of smaller and larger sizes):

$$\ln P_{it} = \alpha_0 + \alpha_1 \sum_{k=1}^{K} d_{ik}^{<20} w_{kt} + \alpha_3 \sum_{k=1}^{K} d_{ik}^{<20} d_{ik}^{<2} w_{kt} + \mu_i + \nu_{it} + q_t + \epsilon_{it} \tag{3}$$

It is important to note that wells within 2km are also within 20km, which implies that $d_{ik}^{<20} d_{ik}^{<2} = d_{ik}^{<2}$. Finally, we transform the regression into a triple-difference estimator by interacting the terms with a dummy variable (GW_i) that equals one if the property is groundwater-dependent:

$$\begin{aligned}\ln P_{it} = \alpha_0 + \alpha_1 \sum_{k=1}^{K} d_{ik}^{<20} w_{kt} + \alpha_2 GW_i \sum_{k=1}^{K} d_{ik}^{<20} w_{kt} + \\ \alpha_3 \sum_{k=1}^{K} d_{ik}^{<2} w_{kt} + \alpha_4 GW_i \sum_{k=1}^{K} d_{ik}^{<2} w_{kt} + \mu_i + \nu_{it} + q_t + \epsilon_{it}\end{aligned}$$

In this regression, the effect of adjacency is measured by α_3, which appears in the following expression:

$$ADJACENCY = \sum_{k=1}^{K} \alpha_3 d_{ik}^{<2} w_{kt}$$

Finally, α_4 identifies GWCR as part of the following term:

$$GWCR = \alpha_4 d_{ik}^{<2} GW_i \sum_{k=1}^{K} w_{kt}$$

For the sake of simplicity, we define the following well pad count variables for 20 and

2km:

$$(\text{Pads in 20km})_{it} = \sum_{k=1}^{K} d_{ik}^{<20} w_{kt}$$

$$(\text{Pads in 2km})_{it} = \sum_{k=1}^{K} d_{ik}^{<2} w_{kt}$$

With these terms defined, we can rewrite our estimating equation in the following way:

$$\ln P_{it} = \alpha_0 + \alpha_1(\text{Pads in 20km})_{it} + \alpha_2 GW_i(\text{Pads in 20km})_{it} + \alpha_3(\text{Pads in 2km})_{it} + \alpha_4 GW_i(\text{Pads in 2km})_{it} + \mu_i + \nu_{it} + q_t + \epsilon_{it} \quad (4)$$

Referring back to Figure 1, the coefficients correspond to the areas A, B, C, and D in the following way:

$$\begin{aligned} \Delta P_A &= \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 \\ \Delta P_B &= \alpha_1 + \alpha_2 \\ \Delta P_C &= \alpha_1 + \alpha_3 \\ \Delta P_D &= \alpha_1 \end{aligned}$$

This implies the following:

$$\begin{aligned} &\Delta P_A - \Delta P_C = \alpha_2 + \alpha_4 \\ &\Delta P_B - \Delta P_D = \alpha_2 \\ &(\Delta P_A - \Delta P_C) - (\Delta P_B - \Delta P_D) = \alpha_4 \end{aligned}$$

Thus, α_4 is the triple-difference measure of groundwater contamination risk associated with the proximity of a shale gas well. Furthermore, α_3 is the double-difference measure of adjacency which can be identified by running a regression with only PWSA homes (i.e., only homes located in areas C and D), as $\Delta P_C - \Delta P_D = \alpha_3$.

As mentioned earlier, unobservables can affect the estimated impact of proximity to shale gas wells on property values. Our double and triple-differencing strategies control for many of these unobservables: property fixed effects (μ_i) control for any time-invariant unobservables at the house level; the number of pads within 20km (both alone and interacted with GW dummy- i.e., α_1 and α_2) control for vicinity effects; and county $\times$ year or census tract $\times$ year fixed effects (i.e., ν_{it}) control for time-varying unobservables at the local and macro levels. In addition to these controls, we implement a sample restriction designed to minimize differences in time-varying unobservables across the GW and PWSA subsamples. In particular, we limit our sample to only properties located in a narrow band around the PWSA boundary—1000m on either side, ignoring houses on the GW side within 300m (to avoid potential miscoding of PWSA houses as GW houses).[21] GW and PWSA houses may be very different on average, although these structural differences are captured by property fixed effects. Time-varying unobservable differences in GW and PWSA houses are, conversely, more likely to result from changing neighborhood attributes. In particular, we would expect neighborhood attributes to be very different across GW and PWSA houses located far from the boundary—some of the GW houses are in very rural areas while some of the PWSA houses are in urban areas. By limiting our DDD analysis to houses along the PWSA boundary, we still allow for variation in water source while geographically restricting neighborhoods to be more homogenous.[22] Figure 6 demonstrates the PWSA boundary sample for an example county, Armstrong County, Pennsylvania. Table 1 shows that property characteristics do differ between the full sample and the boundary subsample (we find a statistically significant difference in means for all variables).

We provide simple evidence that restricting our sample to the band surrounding the PWSA boundary functions as intended. In particular, using data from years prior to the onset of hydraulic fracturing, we check to see if time-varying differences in groundwater-dependent and PWSA properties exist when restricting to the boundary sample.[23] Controlling for property fixed effects, county $\times$ year fixed effects, and quarter fixed effects, we regress log price on an interaction between an indicator for groundwater dependence and the year of sale. We estimate this regression equation first using the full sample and then using only properties in the band surrounding the PWSA boundary. If the boundary sample is able to successfully control for time-varying differences between groundwater and PWSA houses, we would expect to see the coefficients on the interaction term become insignificant using the boundary sample. We run an F-test of joint significance of the coefficients on the interaction terms and

[21]Our final results are robust to removing 300m on the PWSA side as well; doing so, we find an even larger decrease in values of GW-dependent homes and a statistically significant increase in PWSA homes.

[22]PWSA boundaries may overlap natural or political boundaries, such as the border of a town or county. Then for example, GW houses might receive differentially more revenues from taxes (in Pennsylvania revenues come from impact fees paid per well) and see more improvements in local schools etc. These are vicinity effects and therefore it is important to let vicinity effects differ by water source.

[23]We choose all years before and including 2005 because 99.6% of the wells were drilled after 2005.

Table 1: Summary Statistics by Sample

	Full Sample		**Boundary Subsample**	
	Mean	(Std. Dev.)	Mean	(Std. Dev.)
Transaction Price (k 2012 Dollars)	134	(98.4)	120	(92.1)
Age of House	55.7	(32.1)	61.3	(34.9)
Total Living Area (1000 sqft)	1.59	(.67)	1.54	(.634)
No. Bathrooms	1.82	(.852)	1.68	(.799)
No. Bedrooms	2.96	(.933)	2.91	(.984)
Lot Size (acres)	.578	(3.9)	.53	(4.5)
Distance to nearest MSA (km)	22.3	(12.4)	26.4	(13.4)
Groundwater Dependent	.0771	(.267)	.0563	(.231)
Distance to Closest Well Pad (km)	11.7	(5.35)	11.2	(5.5)
Pads in 1km	.00329	(.081)	.00596	(.113)
Pads in 1.5km	.00855	(.164)	.015	(.226)
Pads in 2km	.0178	(.289)	.0314	(.401)
Pads in 20km	4.73	(18.1)	5.11	(21)
Pads in View in 1km	.000474	(.024)	.000844	(.0325)
Pads in View in 1.5km	.00113	(.0425)	.0022	(.0599)
Pads in View in 2km	.00189	(.0671)	.00368	(.0955)
Producing Pads in 1km	.00263	(.0736)	.0049	(.104)
Producing Pads in 1.5km	.00694	(.152)	.0127	(.214)
Producing Pads in 2km	.0147	(.274)	.0273	(.388)
Observations	229,946		66,327	

Notes: Samples are same as those used in our main estimation (i.e., only include properties that were sold more than once during the sample period). The boundary subsample includes only properties in the narrow band on either side of the border of the public water service area.

find that for the full sample, they are jointly significant (p-value of 0.057), while for the boundary sample, they are not (p-value of 0.412). This demonstrates that our boundary sample controls for time-varying unobservable differences across groundwater and PWSA homes, while the full sample maintains potentially confounding unobservables in the regression. Moreover, the boundary sample contains sufficient variation (e.g., in water source) to estimate our triple-difference specification. Thus, our boundary sample is used in our preferred specification.

Having defined the PWSA boundary sample, we restrict our attention to those homes located within this region in order to clearly identify the GWCR in our triple-difference estimation. Using this sample, results show that the GWCR effect is negative, large, and statistically significant.

In the top panel of Table 2 we present results from the regression with county $\times$ year fixed effects and in the bottom panel we instead include census tract $\times$ year fixed effects.[24] The *overall* impact of adding a well pad within a certain distance of a groundwater-dependent property is not just the GWCR, but also the positive (although

[24] Census tract $\times$ year fixed effects are generally preferred as they control for spatial heterogeneity at a fine level of resolution. However, tract fixed effects also soak up a lot of variation in house prices and make it more difficult to identify other parameters of interest. In any case, it is important to note that, qualitatively, the effects on property values are robust across the two specifications.

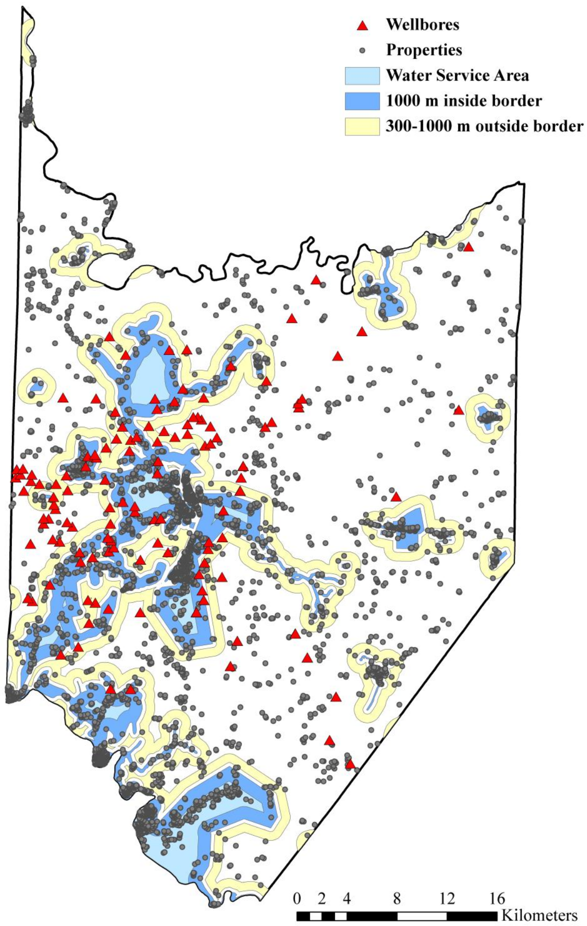

Figure 6: Example Indicating the 1000m Boundary Inside and 300-1000m Boundary Outside of Public Water Service Areas in Armstrong County, Pennsylvania

sometimes statistically insignificant) adjacency effect. It is interesting to see how the effects differ as we change the size of the adjacency buffer. Focusing on the boundary sample in Table 2, we show that very near a well (within 1km), we see much larger negative impacts from GWCR (-16.5%) and insignificant positive adjacency impacts (2.6%), where the summation of the two coefficients implies a statistically significant drop of 13.9% (p-value of .051) for groundwater-dependent homes.[25] Moving to a larger buffer (from 1km to 1.5km) a statistically significant positive impact from well pads starts to emerge (perhaps because wells at farther distances contribute less to negative

[25] While these net impacts may seem large, Throupe et al. (2013)'s contingent valuation study in Texas and Florida shows a 5-15% decrease in property bid values for homes located near shale gas wells, with larger negative impacts for homes very close to a well, dependent on groundwater, and in an area with less of a history of shale gas exploration.

impacts such as noise and light pollution). At a larger buffer the negative impact on GW homes also diminishes to 9.9%. The results imply that adding an extra well within 1.5km causes GW homes to lose 6.5% of their value (bordering statistical significance with a p-value of .09), with -9.9% being due to the risk of groundwater contamination, and +3.4% due to the positive impact of lease payments and other adjacency impacts. Finally, farther from a well (at 2km) there are no longer significant negative impacts of proximity for groundwater-dependent homes; this is intuitive, as we would expect that being located farther from a well would decrease the perception of groundwater contamination risk. For PWSA homes, on the other hand, the *net* positive benefits are smaller at 2km relative to 1.5km; this is likely the result of fewer homes at this distance receiving lease payments. At larger buffer sizes there are larger numbers of wells within the buffer, therefore the diminishing impacts from additional wells could also be driven by non-linear effects.

4.3 Difference-in-Difference Estimation of Adjacency Effect

To investigate the positive effects of adjacency to shale gas wells in more detail, we next focus only on properties that have access to piped water (i.e., any property located in areas C and D). This allows us to identify the adjacency effect in the absence of any concerns over GWCR, via a difference-in-difference estimation.[26] Table 3 displays how the impacts of shale gas development depend on characteristics of that development, using different regression specifications and distances (1km, 1.5km, and 2km) as adjacency buffers.[27]

First, because the topography of Pennsylvania varies across the state, we have variation in the number of wells that are visible to a 5ft individual looking 360 degrees around a property. Panel A of Table 3 shows that the positive impact of being adjacent to a well is driven by those wells that are not in view of the property. The positive effects from lease payments appear to be offset largely by visual disamenities, as the coefficient on wells in view is statistically insignificant.

We next examine whether the positive results are indeed driven by royalties from gas production by including as regressors the count of wells that are producing and the

[26]In this analysis, we include all properties located within the PWSA area. By excluding the GW-dependent properties, there are no concerns about unobservable attributes correlated with being located in a GW or PWSA area, and therefore we no longer need to focus on the boundary sample when estimating adjacency effects.

[27]Buffers extended to 3km are found in Table A2 in the Appendix.

Table 2: Log Sale Price on Well Pads

	$K \leq 1$km		$K \leq 1.5$km		$K \leq 2$km	
	Full	Boundary	Full	Boundary	Full	Boundary
	(1)	(2)	(3)	(4)	(5)	(6)
	Panel A: County-Year Fixed Effects					
Pads in Kkm	.028	.026	.029**	.034*	.016**	.018*
	(.025)	(.035)	(.014)	(.02)	(6.9e-03)	(.01)
(Pads in Kkm)*GW	-.062	-.165**	-.042*	-.099***	-.023	-.013
	(.046)	(.072)	(.025)	(.036)	(.02)	(.052)
Pads in 20km	-7.8e-04***	-8.1e-04	-8.3e-04***	-9.3e-04*	-8.4e-04***	-9.4e-04*
	(3.0e-04)	(5.3e-04)	(3.0e-04)	(5.5e-04)	(3.0e-04)	(5.6e-04)
(Pads in 20km)*GW	6.6e-04	2.0e-03***	7.0e-04	2.0e-03***	7.1e-04	1.7e-03**
	(4.7e-04)	(7.0e-04)	(4.9e-04)	(6.8e-04)	(5.2e-04)	(6.8e-04)
Property Effects	Yes	Yes	Yes	Yes	Yes	Yes
County-Year Effects	Yes	Yes	Yes	Yes	Yes	Yes
Quarter Effects	Yes	Yes	Yes	Yes	Yes	Yes
n	229,946	66,327	229,946	66,327	229,946	66,327
p-value ($\alpha_3 + \alpha_4 = 0$)	.414	.051	.544	.090	.740	.919
Avg. Pads in Kkm	.003	.006	.009	.015	.018	.031
Avg. Pads in 20km	4.725	5.108	4.725	5.108	4.725	5.108
	Panel B: Census Tract-Year Fixed Effects					
Pads in Kkm	.016	.030	.020	.026	.009	.019
	(.046)	(.055)	(.021)	(.027)	(.014)	(.015)
(Pads in Kkm)*GW	-.036	-.137	-.050	-.107***	-.021	.001
	(.071)	(.093)	(.039)	(.037)	(.027)	(.092)
Pads in 20km	-2.7e-04	5.1e-04	-3.0e-04	4.7e-04	-3.1e-04	4.3e-04
	(.001)	(.002)	(.001)	(.002)	(.001)	(.002)
(Pads in 20km)*GW	.001	.002	.001	.002	.001	.001
	(.001)	(.001)	(.001)	(.001)	(.001)	(.001)
Property Effects	Yes	Yes	Yes	Yes	Yes	Yes
Census Tract-Year Effects	Yes	Yes	Yes	Yes	Yes	Yes
Quarter Effects	Yes	Yes	Yes	Yes	Yes	Yes
n	229,946	66,327	229,946	66,327	229,946	66,327
p-value ($\alpha_3 + \alpha_4 = 0$)	.774	.320	.442	.125	.647	.861
Avg. Pads in Kkm	.003	.006	.009	.015	.018	.031
Avg. Pads in 20km	4.725	5.108	4.725	5.108	4.725	5.108

Notes: Each column in each panel represents a separate regression. Dependent variable in all regressions is the log sale price. Independent variables are the counts of wells at different distances from the property, drilled before the sale, as well as interactions with an indicator for whether the property is dependent on groundwater (GW). The boundary sample restricts the full sample to include only properties in a narrow band around the border of the public water service areas. Robust standard errors are clustered by census tract. *** Statistically significant at the 1% level; ** 5% level; * 10% level.

count that are not producing. In the data, 42% of wells that have been drilled have not produced anything as of 2012. Unproductive wells are typically left inactive because the cost to permanently plug and abandon the wells is very high and there is little incentive to do so (Muehlenbachs, 2015). In the data only 52 wells, or less than 1% of the wells, have been permanently plugged and abandoned; therefore, examining the margin of whether a well is producing is more appropriate than examining the margin of whether a well is permanently plugged and abandoned. In Panel B we show that the positive adjacency impacts are driven by producing wells. This result is intuitive, as production would result in royalty payments to the homeowner and the closer the well, the more likely the owner is to receive payments.[28]

Our final specification in Panel C explores the timing of the drilling of the wells: in particular, we estimate whether newly drilled wellbores (i.e., bores drilled within 12 months prior to the sale of the home) affect property values more than older bores. When examining timing we focus on wellbores because they can be sequentially added to well pads and therefore an old well pad with a new wellbore being drilled on it would look similar to a new well pad. Results show that the positive impact from proximity only holds for old wellbores within 1.5km and 2km, while newer bores have an insignificant, negative impact. This lends some evidence that disruptions from the drilling and hydraulic fracturing process (such as increased truck traffic and noise from drilling and hydraulic fracturing) reduce the positive benefits associated with lease payments. At a very close distance, 1km, there is no positive effect felt from old drilled wells; however there is a positive effect from permits, implying that expectations for drilling have positive implications for property values in close proximity.[29]

[28]In another specification, not shown, the amount of natural gas produced by the wells (as measured as total natural gas production in the year of sale) also increases property values.

[29]This provides some evidence that homeowners expect future drilling to occur, which implies that there may be some attenuation bias given future expectations. However, formally modeling these expectations of drilling is outside the scope of this research, both in terms of data and computational requirements. See Bayer et al. (2011) for a description of the method and data needed to conduct such an estimation. We maintain the simpler (and more transparent) static hedonic framework in this paper, but note that it is likely that estimated treatment effects will be muted to the extent that buyers of houses unexposed to wells consider the likelihood of future exposure.

Table 3: Adjacency Effects

	K=1km	K=1.5km	K=2km
	(1)	(2)	(3)
	ln(price)	ln(price)	ln(price)
A. Log Sale Price on Well Pads in View			
Visible Well Pads in Kkm	1.1e-03	-.019	.019
	(.072)	(.058)	(.035)
Not-Visible Well Pads in Kkm	.03	.036***	.015**
	(.028)	(.013)	(6.5e-03)
Pads in 20km	-6.0e-04*	-6.4e-04*	-6.5e-04*
	(3.3e-04)	(3.3e-04)	(3.3e-04)
B. Log Sale Price on Productive Wells			
Unproductive Pads in Kkm	-.052	-.043	-.054*
	(.077)	(.035)	(.03)
Producing Pads in Kkm	.044**	.038***	.02***
	(.02)	(.013)	(5.8e-03)
Pads in 20km	-6.0e-04*	-6.4e-04*	-6.3e-04*
	(3.3e-04)	(3.3e-04)	(3.3e-04)
C. Log Sale Price on Timing of Wellbores			
Old Bores (drilled > 365 days) in Kkm	.021	.023**	.011**
	(.018)	(9.8e-03)	(4.4e-03)
New Bores (drilled ≤ 365 days) in Kkm	-4.4e-03	-9.7e-03	-3.3e-04
	(.029)	(.013)	(8.0e-03)
Old Undrilled Permits (> 365 days) in Kkm	.055**	.022	.011
	(.025)	(.014)	(.012)
New Undrilled Permits (≤ 365 days) in Kkm	.04*	7.2e-03	7.2e-03
	(.023)	(.014)	(7.9e-03)
Pads in 20km	-6.0e-04*	-6.2e-04*	-6.3e-04*
	(3.3e-04)	(3.3e-04)	(3.3e-04)
Property Effects	Yes	Yes	Yes
County-Year Effects	Yes	Yes	Yes
Quarter Effects	Yes	Yes	Yes
n	212,207	212,207	212,207

Notes: Dependent variable is log sale price. Each panel has three separate regressions, one per column. Regressors are the count of wells (or annual natural gas production) within Kkm, depending on the column. The sample used includes only properties that are in piped water service areas. Robust standard errors are clustered by census tract. *** Statistically significant at the 1% level; ** 5% level; * 10% level.

4.4 Difference-in-Differences Nearest-Neighbor Matching (DDNNM)

In this section, we find similar GWCR and adjacency results using techniques that do not rely on panel data variation. In the DDD strategy we relied on intertemporal variation in price; however, as described by Kuminoff and Pope (2014) these estimates would be biased if the hedonic gradient shifts over time. The essence of that argument is that methods based on using panel variation (i.e., to control for time-invariant unobserved property or neighborhood attributes) will fail to accurately describe the slope of the hedonic price function (and, hence, preferences) if the residential composition changes over time, causing the equilibrium price function to move. Their argument is summarized in our discussion of the hedonic method, found in the online appendix. In this subsection, we describe an alternative estimator that relies on cross-sectional data but uses the logic of differences-in-differences in conjunction with matching techniques to achieve identification. We restrict matches to be within the same year; although the estimate is an average over time, it therefore only relies on within-year variation. We focus on results that use the average of these within-year estimates over time as our sample sizes are small when we consider year-by-year estimates. However, dividing the sample into two time periods (early and late) provides weak evidence of a stable gradient.

The fundamental problem of causal inference is the inability to observe a treated observation in its untreated state and vice-versa; in the current setting, we fail to observe the price of a house located in close proximity to a well pad were that same house instead located farther away ("same," in this context, is in terms of both house and neighborhood attributes, both time-invariant and variant). Panel data techniques are frequently used to control for time-invariant unobserved house attributes that may be correlated with the (dis)amenity of interest.

Matching estimators impute counterfactual observations by pairing treated houses with similar houses from a control group.[30] The effect of treatment is then found by averaging across the price differences for matched pairs. More detail on the techniques involved in matching estimators can be found in Abadie and Imbens (2002), Abadie and Imbens (2006), Abadie and Imbens (2011), and Abbott and Klaiber (2011); our main specification uses the nearest-neighbor matching technique.

The key to the success of this type of matching estimator is to structure the problem so that unobservable house and neighborhood attributes are not correlated with treatment status. We do so here by limiting the control sample in certain dimensions and by requiring exact matches in other dimensions.[31] In particular, the nearest-neighbor

[30]For more background on the advantages of matching compared to parametric hedonic methods, see Cochran and Rubin (1973), Rubin (1974), Rosenbaum and Rubin (1983), Rubin and Thomas (1992), and Heckman et al. (1998).

[31]It is important to note that there may exist residual impacts of shale gas development for homes that are not immediately adjacent to a shale gas well. For example, homes that depend on piped water may face some level of drinking water contamination if the public water source is contaminated; while rivers and streams have been found to be affected by shale gas development (see Olmstead et al., 2013) there have yet to be any studies of the impacts on tap water. Key to our identification is that outside of a clearly defined adjacency buffer, the homes are not only less likely to be affected by shale gas development but also that these homes will be equally affected by development regardless of location (i.e., the contamination of publicly-sourced piped-drinking water is not correlated with adjacency).

matching algorithm allows us to require exact matches in the geographic dimension (i.e., census tract) to control for neighborhood unobservables, and in the temporal dimension (i.e., transaction year) to control for time-varying unobservables. We restrict the matches to be exact in these dimensions to help control for various forms of unobservables that might otherwise bias our results. Moreover, we limit the sample to include only houses that we expect to be in a relatively homogenous neighborhood within each census tract. Thus, we (1) limit our analysis to only houses that are within 6km of a well pad (defining the treatment buffer to be 1, 1.5, or 2km given evidence of a small adjacency buffer found in Section 4.1), (2) require exact matches by census tract, (3) require exact matches by year of sale, and (4) perform the analysis separately for groundwater and PWSA houses. The idea behind these restrictions is that houses within 6km of a well pad in the same census tract that rely on the same water source will be located in similar neighborhoods, thereby reducing unobservables that may be correlated with the location of the property. Requiring exact matching by year of sale will further eliminate differences in unobservables that vary from year to year at this level of the neighborhood.

The nearest neighbor matching algorithm is used to recover an estimate of the average treatment effect on the treated (ATT), or the impact on price from moving a non-adjacent house inside the adjacency buffer. In Figure 1, this corresponds to a move from B to A for groundwater houses, and from D to C for PWSA houses. We now show that, by differencing these ATT estimates, we are able to recover an estimate of GWCR.

We begin by defining the price of properties in each of the four areas in Figure 1 in a cross-sectional analogue of Equation 1. Rather than using the change in price of a particular property over time (i.e., Δ), we focus on cross-sectional differences in prices. Our nearest neighbor matching algorithm applied to groundwater houses yields an estimate of the GWCR combined with the adjacency effect: $P_A - P_B = GWCR + Adjacency$ (hence, P_A is the price of a house in area A, etc.). Applied to PWSA houses, it yields an estimate of the adjacency effect alone: $P_C - P_D = Adjacency$. Differencing these two estimates leaves us with an estimate of the GWCR:

$$\text{GWCR}_{\text{DDNNM}} = (P_A - P_B) - (P_C - P_D)$$

The results of the nearest neighbor matching procedure are reported in Table 4. The first two rows report the point estimates and 90% confidence intervals for PWSA houses using 1, 1.5, and 2km treatment buffers. The next two rows report comparable figures for groundwater houses. In all cases, the difference-in-differences estimate of the GWCR effect based on these estimates is negative. In the case of the 1.5km treatment buffer, the DD estimate is large (-11.6%) and significant at the 10% level. The Kuminoff and Pope critique emphasizes that the temporal average gradient may not always provide a policy-relevant measure of welfare. However, dividing the sample by properties sold before 2010 (Panel B) and properties sold in 2010 or after (Panel C), the coefficients are similar across time periods though insignificant (potentially due to smaller sample sizes of treated wells in each distinct time period). Therefore, our results weakly address the Kuminoff and Pope critique. Importantly, we also show that, relying on within-year variation yields an average effect over time that is similar to the DDD effect that we get using intertemporal variation.[32,33]

[32] While the DDNNM point estimate is larger than the DDD estimate, it is important to note that the DDNNM confidence intervals overlap the DDD estimate. Furthermore, it is unlikely that we would be able to recover exactly the same results, given that the DDD estimator utilizes property fixed effects and the boundary sample, while the DDNNM estimate does not.

[33] In further supporting evidence provided in the online Appendix, we show that neighborhood characteristics are not found to have changed in an economically significant manner with the introduction of shale gas.

Table 4: Log Sale Price on Groundwater Contamination Risk of Well Pads from a Matching Estimator

	Panel A: All Years		
Sample	1km	1.5km	2km
PWSA (*n= 9,278*)	0.002	0.024	-0.013
	(-0.08, 0.08)	(-0.03, 0.08)	(-0.05, 0.03)
GW (*n= 1,869*)	-0.070	-0.092	-0.030
	(-0.18, 0.04)	(-0.18, -0.01)	(-0.11, 0.05)
$GWCR_{DD}$	-0.072	-0.116	-0.016
	(-0.21, 0.06)	(-0.22, -0.02)	(-0.10, 0.07)

	Panel B: Before 2010		
Sample	1km	1.5km	2km
PWSA (*n= 3,541*)	0.113	0.032	0.052
	(-0.04, 0.26)	(-0.08, 0.14)	(-0.02, 0.13)
GW (*n= 807*)	0.046	-0.083	-0.040
	(-0.12, 0.21)	(-0.21, 0.05)	(-0.14, 0.06)
$GWCR_{DD}$	-0.067	-0.115	-0.092
	(-0.29, 0.16)	(-0.28, 0.05)	(-0.22, 0.04)

	Panel C: 2010 and later		
Sample	1km	1.5km	2km
PWSA (*n= 5,737*)	-0.059	0.004	-0.046
	(-0.15, 0.03)	(-0.06, 0.06)	(-0.09, 0.00)
GW (*n= 1,062*)	-0.104	-0.082	-0.032
	(-0.24, 0.04)	(-0.20, 0.03)	(-0.13, 0.07)
$GWCR_{DD}$	-0.044	-0.087	0.014
	(-0.21, 0.12)	(-0.21, 0.04)	(-0.10, 0.13)

Notes: Samples comprise all houses within 6km of a well pad (Panel A), within 6km and sold before 2010 (Panel B), and within 6km and sold in 2010 or later (Panel C). Each house in the treatment buffer is matched with 4 houses in the control sample. Exact match required on year of sale and census tract. Matching also based on house attributes (lot size, square footage, number of bedrooms, number of bathrooms, and year built). Treatment buffer size varies between 1 and 2km. Bias adjustment equation contains all house attributes. 90% confidence intervals reported in parentheses.

5 Summary of Impacts

Using a variety of empirical methodologies, we demonstrate that the risk of groundwater contamination negatively affects house values in the 1-1.5km range. Although data are not available to measure the impact of actual groundwater contamination, the perception of these risks is large, causing important, negative impacts on groundwater-dependent properties near wells.

While it is clear that the perceived risk of groundwater contamination negatively impacts property values, homes that rely on piped water may in fact benefit from being adjacent to drilled and producing wells. These results appear to be driven by royalty payments (or expectations of royalties) from productive wells. However, it is evident from how the results change when we use different sized adjacency buffers that the positive impacts from being in close proximity to a well diminish as that distance becomes very small. The overall positive impacts are net impacts of being near a well; i.e., net of any negative environmental externality (such as light and noise pollution from drilling) that is common to all properties regardless of drinking water source. Thus, even homes with piped water are better off being slightly farther from a well, as long as they are able (i.e., not too far) to capitalize on lease payments. Consistent with the increase in property values being due to royalties and lease payments, we find that the property value increase is driven by producing wells. We also find that this positive finding is explained by wells that were drilled over a year prior to the sale, most likely because disruptions such as truck traffic, the drilling rig, and hydraulic fracturing equipment are present in the first year of a well's life. Coinciding with the visual disamenity of a shale gas well, we only find these positive effects for wells that are not visible from the property.

Similarly, for groundwater-dependent homes, the negative impacts of adjacency are large when the property is very close (1.5km or closer) to a shale gas well, and become more negative the closer a home gets to a shale gas well. We find that the costs of groundwater contamination risk are large and significant (ranging from -9.9% to -16.5%), suggesting that there could be large gains to the housing market from regulations that reduce the risk. Using the estimated net impact from adjacency and GWCR and data on the houses sold in the most recent year (April 2011 to April 2012), we calculate the average annual loss for groundwater-dependent homes within 1.5km of a well to be \$30,167.[34] The average annual loss for GW properties is larger than the average annual gain for piped-water properties within 1.5km of a shale gas well (\$4,802).[35] Furthermore, it is important to keep in mind that our estimates do not

[34]This value is calculated using all groundwater-dependent properties that are within 1.5km of a well and sold between April 2011 and April 2012. For these properties, the number of well pads in 1km and between 1 and 1.5km are combined with the adjacency and GWCR coefficients from our boundary sample (columns 2 and 4, in the first panel of Table 2).

[35]This is calculated using properties that have access to piped water, are within 1.5km of a well, and are sold in the most recent year of our data. If we also include properties within 2km of a well and include coefficients from column 6 for properties within 1.5km and 2km of a well, the groundwater losses are smaller on average while the piped-water properties have similar gains (i.e., the average loss for GW homes within 2km of a well is \$16,059 compared to gains for PWSA homes on average of \$5,070.

fully capture the total costs associated with groundwater contamination risk. Owners of groundwater-dependent homes may purchase expensive water filters to clean their drinking water when faced with a shale gas well nearby; whole home filters can cost thousands of dollars.[36] To the extent that our estimates do not capture adaptation costs, our estimates will be a lower bound to the actual costs incurred by homeowners located near shale gas wells, implying that contamination risk reduction can have very large benefits to nearby homes.

The use of the properties in the band surrounding the PWSA boundary (relative to using the full sample of homes) demonstrates that failing to control for unobservable attributes that vary with location can result in an underestimation of the negative impacts on groundwater-dependent homes. This is intuitive. Rural groundwater-dependent neighborhoods may be different in unobservable but important ways when compared with more urban PWSA neighborhoods, and these differences might vary over time. Using a sample containing both PWSA and GW homes, but specifically limited to be within the PWSA boundary, helps to reduce the potential for these unobserved neighborhood differences to bias our results while still permitting comparison based on water source.

6 Conclusion

Development of shale deposits has become increasingly widespread due to advances in technology that allow for the inexpensive enhanced extraction of natural gas. This rapid expansion in development has generated ample debate about whether the benefits from a cleaner domestic fuel and the accompanying economic development outweigh the local negative impacts associated with the extraction technology. This paper addresses many of these questions by measuring the net capitalization of benefits and costs of shale gas development at various levels of proximity and water source exposure.

The ability of shale gas development to impact nearby groundwater sources has been a major point of discussion. We estimate the local impacts on groundwater-dependent homes to be large and negative, which is not surprising given the attention the media has been placing on this potential risk. As groundwater contamination

[36]These water filters can cost about $1,480/year for a family of four (http://www.ezclearwater.com/wordpress/tag/whole-house-water-filtration-system/) Given the cost to adjacent groundwater-dependent homes is near $30,000, this implies a yearly cost of approximately $1,500 under a 20 year mortgage, which aligns with the price of installing a filter to clean the drinking water.

can cause severe economic hardship on homes without access to piped water, the perception that a nearby shale gas well will cause irreversible harm to an aquifer can have significant effects on nearby property values. These forces are beginning to show up in the way housing markets located on shale plays operate – e.g., recent evidence that major national mortgage lenders are refusing to make loans for properties in close proximity to shale gas wells, and that insurance providers are refusing to issue policies on those houses.[37]

However, shale gas development can also bring positive impacts to small towns through increased employment opportunities, economic expansion and, importantly, lease payments to the holders of mineral rights. Our estimates suggest that there are localized benefits to homes that are adjacent to producing wells, once the drilling stage is complete. We find that the negative impacts of development occur during the active portion of drilling activities; minimizing concerns with aesthetic aspects of drilling (such as truck traffic and land clearing) may thus help to improve the benefits of shale gas development.

Therefore, while we find small benefits from being in close proximity to shale gas wells, we find strong evidence of localized costs borne particularly by groundwater-dependent homes. As these negative impacts are based on perceptions of groundwater contamination risk rather than actual risk or contamination levels, better understanding the probability of groundwater contamination would be valuable.

[37]For example, "Fracking Boom Gives Banks Mortgage Headaches," *American Banker*, August 19, 2013, or "Couple Denied Mortgage Because of Gas Drilling," *WTAE, Pittsburgh's Action News*, May 08, 2012.

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A Appendix (For Online Publication)

A.1 Sample Cuts

We start with 731,169 unique observations of sales that have information on the location of the property. After excluding properties without a listed price, a price in the top or bottom 1% of all prices, and properties sold more than once in a single year, we are left with 626,637 sales observations. Of these, there are 604,074 properties designated as a single family residence, rural home site, duplex, or townhouse; our main specifications only include these properties in order to estimate the impact on (likely) owner-occupied homes, rather than properties that are more likely transient or rented.[38] Furthermore, we want to include in our main specification only homes that were sold from one person to another (i.e., excluding made-to-order homes), thus we drop approximately 30,203 properties that were sold in the year built.[39] After eliminating new homes, of the remaining 573,871 sales, 229,946 are repeat sales—a necessary condition for including property fixed effects. For specifications that instead rely on observed housing attributes (specifically, our Linden and Rockoff-type figures), not all properties report a full slate of housing characteristics; out of our 573,871 sale sample, only 379,649 have information on all property characteristics.

A.2 Hedonic Method

Rosen (1974) established the connection between individual preferences and the hedonic price function, allowing the researcher to interpret the hedonic gradient as the marginal willingness to pay for an incremental change in a non-marketed house or neighborhood attribute. In the context of our application, $P(W)$ represents the hedonic price relationship describing how prices vary with exposure to increasing numbers of wells, *ceteris paribus*. Rosen describes how the hedonic price function is formed by the equilibrium of buyers and sellers sorting to one another in the marketplace. In Figure A1, buyers A and B are represented by indifference curves (U_1^A, U_1^B, U_2^A, U_2^B); each represents combinations of price and shale gas well exposure that yield a constant level of utility. Sellers X and Y are described by offer curves (O_1^X, O_1^Y, O_2^X, O_2^Y), each of which represents combinations of price and well exposure that yield a constant level of profit. The hedonic price function is formed by the envelope of these indifference and offer curves.

Individuals choose a house that maximizes utility. For individual A, who neither likes paying a lot for a house nor (for the purposes of this discussion) wants exposure to shale gas wells, this is accomplished by reaching the indifference curve lying farthest to the southwest. Considering the constraint formed by the hedonic price function, utility is maximized at point A^*, where that individual achieves utility U_1^A. Individual B similarly maximizes utility at B^*. The fundamental insight of the hedonic method is that, at A^* and B^*, the slope of the price function is equal to the slope of each individual's indifference curve at that point. That slope describes the individual's willingness to give up consumption of other goods in exchange for a marginal reduction in exposure to nearby wells. This is how the literature typically defines marginal willingness to pay (MWTP); we will do the same.[40]

Of course, the value of MWTP defined by the slope of the price function at the level of well exposure chosen by the individual represents just one point on the individual's indifference curve. If we were to trace out each individual's MWTP at each point on a particular indifference curve, we would end up with functions for each individual like those shown in

[38] Though CoreLogic provides an indicator for whether the property is owner-occupied, this variable is not consistently reported by all counties. We exclude properties listed as a hotel, motel, residence hall, or transient lodging.

[39] Results are similar if these homes are included. We return to the question of new home construction in response to shale gas development in Appendix Section A.7.

[40] Other measures of value used in the literature include compensating and equivalent variations in income. CV or EV can be calculated both in a partial equilibrium context, where individuals' housing choices and equilibrium prices are not updated, and in a general equilibrium context, where they are updated to reflect re-optimization and subsequent market re-equilibration.

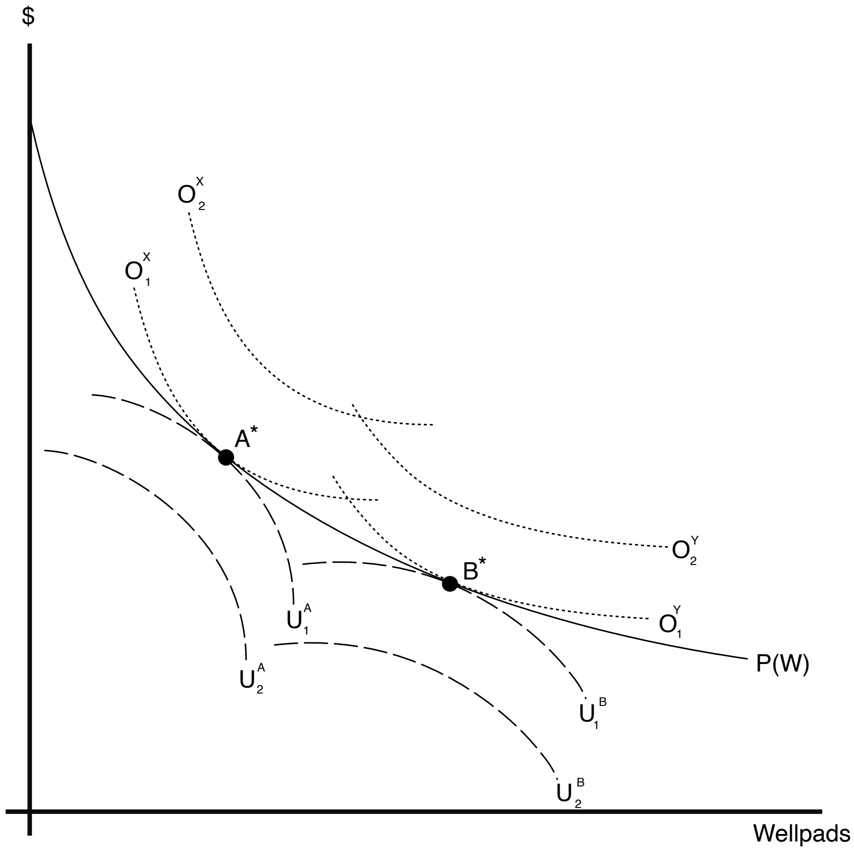

Figure A1: Formation of the Hedonic Price Function

Figure A2.

With cross-sectional data, the hedonic gradient (i.e., the slope of the hedonic price function) therefore only identifies one point on each MWTP function. This is the crux of the identification problems detailed by Brown and Rosen (1982) and Mendelsohn (1985). Endogeneity problems also arise in the effort to econometrically recover these functions; for a discussion, see Bartik (1987) and Epple (1987). More recent literature dealing with the recovery of MWTP functions includes Ekeland et al. (2004), Bajari and Benkard (2005), Heckman et al. (2010), and Bishop and Timmins (2012).

With few exceptions, the applied hedonic literature has not estimated heterogeneous MWTP functions, but has instead relied on a strong assumption to simplify the problem—in particular, that preferences are homogenous and are therefore represented by the hedonic price function itself. Using price levels as the dependent variable (so that the hedonic gradient is a horizontal line that represents the MWTP function for all individuals) yields the

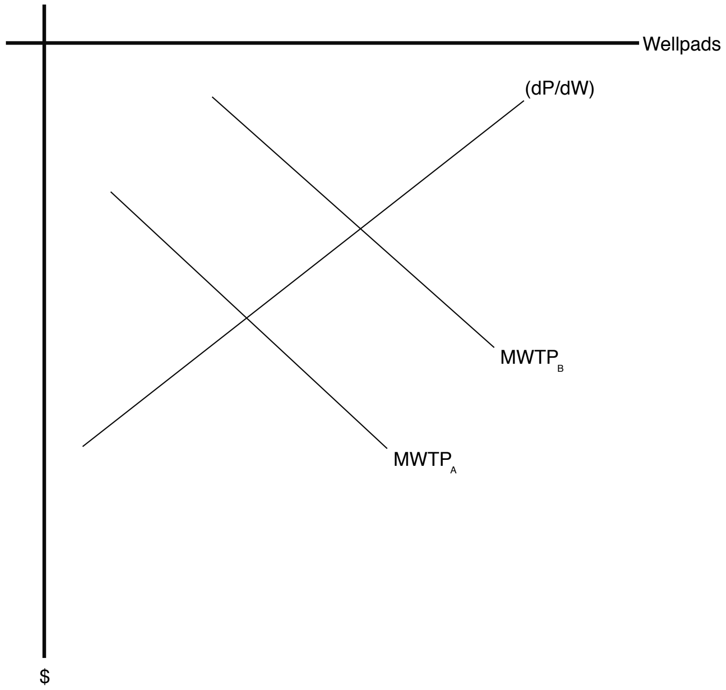

Figure A2: Marginal Willingness to Pay

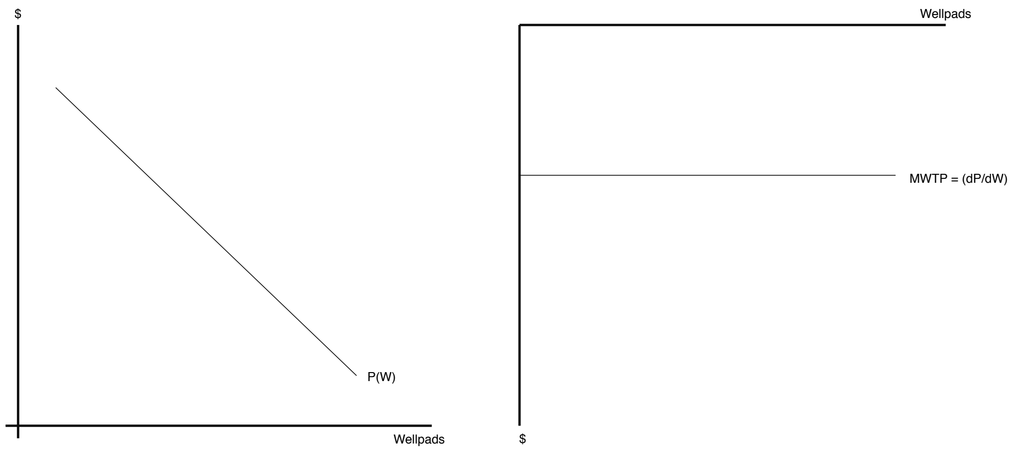

Figure A3: Marginal Willingness to Pay—Simplification simple estimate of MWTP in Figure A3, and avoids the difficulties associated with recovering estimates of MWTP discussed above (using log prices, these become non-linear functions, but also allow us to recover a simple estimate of MWTP without having to estimate the MWTP function). This has allowed attention to be focused instead on recovering unbiased estimates of the hedonic price function. This literature is vast and includes applications dealing with air quality (Chay and Greenstone, 2005; Bajari et al., 2010; Bui and Mayer, 2003; Harrison Jr and Rubinfeld, 1978; Ridker and Henning, 1967), water quality (Walsh et al., 2011; Poor et al., 2007; Leggett and Bockstael, 2000), school quality (Black, 1999), crime (Linden and Rockoff, 2008; Pope, 2008b), and airport noise (Andersson et al., 2010; Pope, 2008a). Our application is most similar in spirit to papers that have examined locally undesirable land uses (LULUs): Superfund sites (Greenberg and Hughes, 1992; Kiel and Williams, 2007; Greenstone and Gallagher, 2008; Gamper-Rabindran and Timmins, 2013), brownfield redevelopment (Haninger et al., 2012; Linn, 2013), commercial hog farms (Palmquist et al., 1997), underground storage tanks (Zabel and Guignet, 2012), cancer clusters (Davis, 2004), and electric power plants (Davis, 2011). Our estimation strategy described above draws upon insights from many of these papers. We follow the literature and specify a log-linear hedonic price function. As in these other papers, the smaller the change in the (dis)amenity, the better this function will approximate the true partial equilibrium welfare effect.

Of particular importance for our analysis is the discussion in Kuminoff and Pope (2014). They highlight the fact that the change in price over time (which allows for the use of differencing strategies to control for time-invariant unobservables) will only yield a measure of the willingness to pay for the corresponding change in the attribute being considered under a strong set of assumptions. These assumptions include those described above (i.e., linear hedonic price function, common MWTP function). In addition, the hedonic price function must not move over the time period accompanying the change in the attribute. If it does, as in Figure A4, the change in the price (δP) accompanying the change in well pad exposure (δW) may provide a poor approximation of the slopes of either of the hedonic price functions. [41] In the right panel of Figure A4, $\left|\frac{\Delta P}{\Delta W}\right|$ (i.e., the dashed line) $<$ $\left|\frac{dP}{dW}\right|$ (i.e., the solid line).

Determining whether or not the hedonic price function has moved over time is difficult; in particular, it requires having some way of recovering an unbiased estimate of the hedonic price function without exploiting time variation. As a check on our DDD results, we provide an alternative strategy for recovering the impact of groundwater contamination risk (double-difference nearest neighbor matching) that avoids using time variation. In the following sub-section of the appendix, we also provide an indication of how much of a problem shifting gradients present for our double- and triple-difference strategies by looking at the extent to which neighborhood sociodemographics change because of fracking. If they change a lot, preferences of the local population will likely be altered as well, and caution would be advised when interpreting our results as measures of welfare rather than simple capitalization effects. We note here, however, that the changes we find attributable to shale gas development are quite small.

[41] Even if the hedonic price function remains stationary over time, the change in price accompanying the change in an amenity will not accurately describe the slope of the price function if that function is non-linear. The problem becomes more severe the larger the change in the amenity being considered. Many papers in the hedonics literature described above consider non-marginal changes. Our estimation looks at small, marginal changes in the number of wells adjacent to a property.

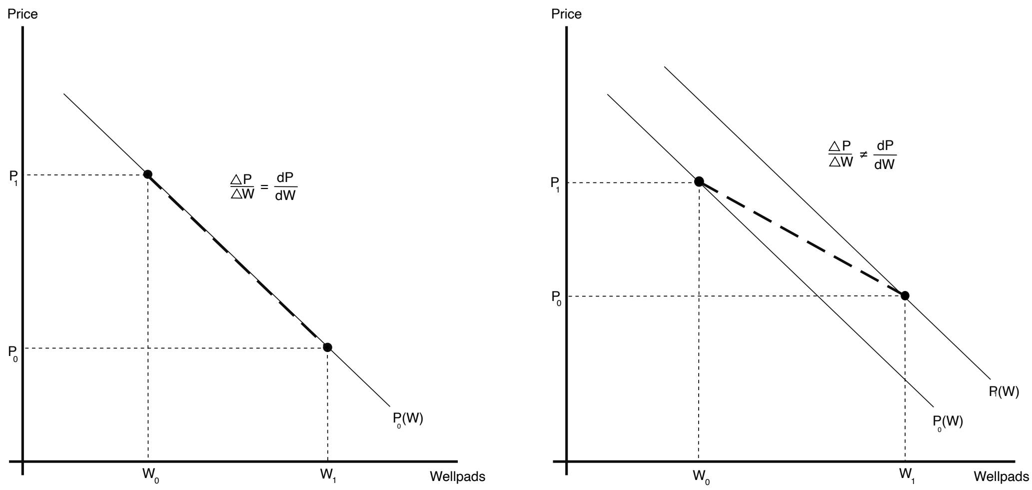

Figure A4: Time-Varying $P(W)$

A.3 Groundwater Contamination Risk and Adjacency Impacts Beyond k=2km

In this subsection, we extend Tables 2 and 3 to include regressors of the counts of wells at 2.5km and 3km. At farther distances, an additional well has a smaller effect on PWSA properties and no impact on GW properties (the last four columns of Table 2). We see that the adjacency impacts remain the same or decrease with radii larger than 2km in the case of the different types of adjacent wells (last two columns of Table 3). That an additional well has a smaller impact the farther from well, could be driven by farther wells having a smaller impact, but also by non-linear effects because there are more wells found in larger radii. We cannot rule out that the impact that well pads have on properties is non-linear in the number of well pads. We do not have enough variation in the number of well pads to reliably estimate non-linear effects. Restricting the sample to only those properties that eventually have at most one well within 2km (not shown), we do not have significance with a radius of 1km (possibly due to the small sample size) and find much larger impacts with radii of 1.5km and 2km than in our main table.

Table A1: Log Sale Price Well Pads

	$K\leq$1km		$K\leq$1.5km		$K\leq$2km		$K\leq$2.5km		$K\leq$3km	
	Full	Bound.	Full	Bound.	Full	Bound.	Full	Bound.	Full	Bound.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Pads in Kkm	.028	.026	.029**	.034*	.016**	.018*	.012**	.014*	.011***	9.9e-03*
	(.025)	(.035)	(.014)	(.02)	(6.9e-03)	(.01)	(4.9e-03)	(7.2e-03)	(3.4e-03)	(5.6e-03)
(Pads in Kkm)*GW	-.062	-.165**	-.042*	-.099***	-.023	-.013	-.013	-7.0e-03	-.01	-.012
	(.046)	(.072)	(.025)	(.036)	(.02)	(.052)	(.014)	(.029)	(9.7e-03)	(.023)
Pads in 20km	-7.8e-04***	-8.1e-04	-8.3e-04***	-9.3e-04*	-8.4e-04***	-9.4e-04*	-8.7e-04***	-1.0e-03*	-9.0e-04***	-1.0e-03*
	(3.0e-04)	(5.3e-04)	(3.0e-04)	(5.5e-04)	(3.0e-04)	(5.6e-04)	(3.0e-04)	(5.7e-04)	(3.0e-04)	(5.7e-04)
(Pads in 20km)*GW	6.6e-04	2.0e-03***	7.0e-04	2.0e-03***	7.1e-04	1.7e-03**	7.0e-04	1.7e-03**	7.1e-04	1.9e-03***
	(4.7e-04)	(7.0e-04)	(4.9e-04)	(6.8e-04)	(5.2e-04)	(6.8e-04)	(4.9e-04)	(6.7e-04)	(5.0e-04)	(6.8e-04)
Property Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
County-Year Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Quarter Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
n	229,946	66,327	229,946	66,327	229,946	66,327	229,946	66,327	229,946	66,327
p-value ($\alpha_3+\alpha_4=0$)	.414	.051	.544	.090	.740	.919	.935	.817	.950	.928
Avg. Pads in Kkm	.003	.006	.009	.015	.018	.031	.031	.055	.048	.081
Avg. Pads in 20km	4.725	5.108	4.725	5.108	4.725	5.108	4.725	5.108	4.725	5.108

Notes: This table extends the first panel of Table 2 to radii beyond K=2km. Dependent variable is log sale price and each column represents a separate regression. The independent variables in the regressions vary by the size of the radius Kkm around each property, used to count the number of adjacent well pads present before the sale. The boundary sample restricts the full sample to include only properties in a narrow band around the border of the public water service areas. Robust standard errors are clustered by census tract. *** Statistically significant at the 1% level; ** 5% level; * 10% level.

Table A2: Adjacency Effects

	K=1km	K=1.5km	K=2km	K=2.5km	K=3km
	(1)	(2)	(3)	(4)	(5)
	ln(price)	ln(price)	ln(price)	ln(price)	ln(price)
A. Log Sale Price on Well Pads in View					
Visible Well Pads in Kkm	1.1e-03	-.019	.019	.018	6.0e-03
	(.072)	(.058)	(.035)	(.02)	(.012)
Not-Visible Well Pads in Kkm	.03	.036***	.015**	.011**	.011***
	(.028)	(.013)	(6.5e-03)	(4.6e-03)	(3.4e-03)
Pads in 20km	-6.0e-04*	-6.4e-04*	-6.5e-04*	-6.8e-04**	-7.1e-04**
	(3.3e-04)	(3.3e-04)	(3.3e-04)	(3.4e-04)	(3.4e-04)
B. Log Sale Price on Productive Wells					
Unproductive Pads in Kkm	-.052	-.043	-.054*	-.03	6.7e-03
	(.077)	(.035)	(.03)	(.022)	(.02)
Producing Pads in Kkm	.044**	.038***	.02***	.014***	.011***
	(.02)	(.013)	(5.8e-03)	(4.5e-03)	(3.3e-03)
Pads in 20km	-6.0e-04*	-6.4e-04*	-6.3e-04*	-6.4e-04*	-7.0e-04**
	(3.3e-04)	(3.3e-04)	(3.3e-04)	(3.4e-04)	(3.4e-04)
C. Log Sale Price on Timing of Wellbores					
Old Bores (drilled > 365 days) in Kkm	.021	.023**	.011**	.011***	9.6e-03***
	(.018)	(9.8e-03)	(4.4e-03)	(3.3e-03)	(2.6e-03)
New Bores (drilled $\leq$ 365 days) in Kkm	-4.4e-03	-9.7e-03	-3.3e-04	-6.0e-03	-1.9e-03
	(.029)	(.013)	(8.0e-03)	(6.3e-03)	(5.2e-03)
Old Undrilled Permits (> 365 days) in Kkm	.055**	.022	.011	9.8e-03	6.4e-03
	(.025)	(.014)	(.012)	(8.9e-03)	(7.0e-03)
New Undrilled Permits ($\leq$ 365 days) in Kkm	.04*	7.2e-03	7.2e-03	2.0e-03	-1.3e-03
	(.023)	(.014)	(7.9e-03)	(5.9e-03)	(4.9e-03)
Pads in 20km	-6.0e-04*	-6.2e-04*	-6.3e-04*	-6.4e-04*	-6.8e-04**
	(3.3e-04)	(3.3e-04)	(3.3e-04)	(3.4e-04)	(3.4e-04)
Property Effects	Yes	Yes	Yes	Yes	Yes
County-Year Effects	Yes	Yes	Yes	Yes	Yes
Quarter Effects	Yes	Yes	Yes	Yes	Yes
n	212,207	212,207	212,207	212,207	212,207

Notes: This table extends Table 3 to radii beyond K=2km. Dependent variable is log sale price. Each panel has three separate regressions, one per column. Regressors are the count of wells (or annual natural gas production) within Kkm, depending on the column. The sample used includes only properties that are in piped water service areas. Robust standard errors are clustered by census tract. *** Statistically significant at the 1% level; ** 5% level; * 10% level.

A.4 Event Study using the Timing of Drilling

In this subsection we create event-study graphs similar to Greenstone and Hanna (2014) for four types of properties, in which the event examined is the drilling of the first well. We create indicators for each of the years before and after the first well is drilled for properties that are adjacent to a well (within 2km) and properties that are nearby but not adjacent (within 2-10km). We separate the sample into subsamples depending on whether the property is at some point in time adjacent ("treated") or only nearby ("control") and whether the property has access to piped water or is dependent on groundwater. For each subsample, we run separate regressions of logged property values on the dummies indicating how many years (before or after) there are between the sale and drill date. Because the timing of the drilling varies across different properties we can identify year fixed effects as well the coefficients on the dummies and so we can control for year effects and quarter effects. Figures A5 and A6 plot the coefficients on each of the dummies (in which the omitted category is the dummy indicated the property was sold seven years before the first well). These figures are useful to demonstrate that there are no differential trends between the treatment and control groups in the years prior to the drilling. In the pre-period, the coefficients on the years prior to drilling are statistically insignificant in all subsamples. In the years after drilling, we have statistical significance on GW properties in the treatment group in the second year after drilling. Similar to Table 3, Panel C, these estimates suggest that there is a delay in the impacts. This implies that our main estimation, by considering the effect on adjacent GW houses in all years after drilling (including the year directly after drilling), may be understating the size of the total effect. However, similar to the Linden and Rockoff (2008) approach, this test is using a particular sample (i.e., only looking at homes exposed to a well pad within 10km) which is not necessarily representative of all homes affected by proximate wells. Therefore, our preferred specification comes from the estimation on the full set of well pads, the boundary sample, and the triple difference.

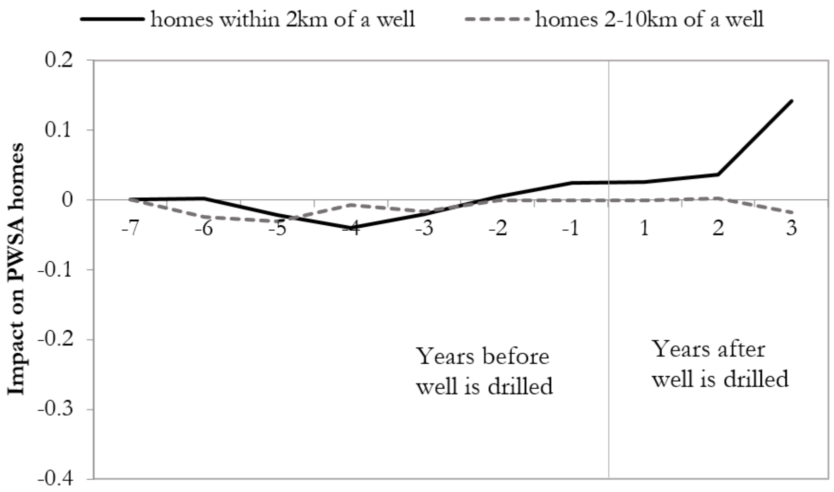

Figure A5: Years Since First Well Drilled for Properties with Access to Piped Water

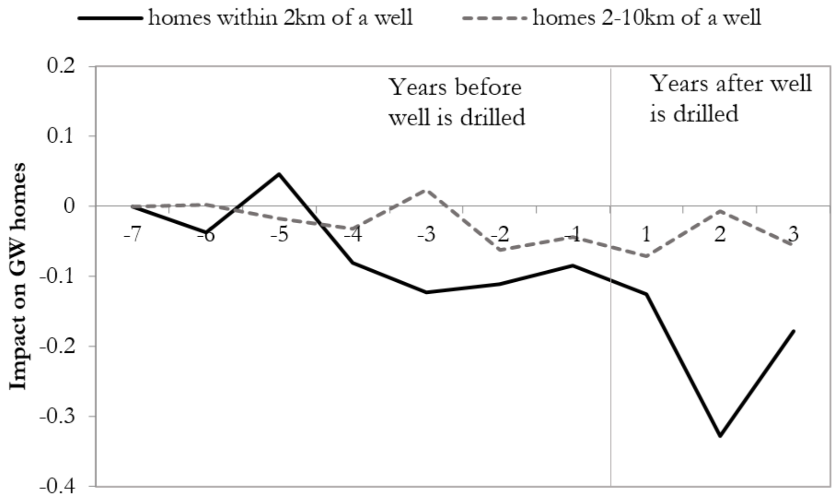

Figure A6: Years Since First Well Drilled for Properties Dependent on Groundwater

A.5 Effects on Sociodemographics

In this subsection, we examine the effect of shale gas development on sociodemographic attributes at the census-tract level. As described in Section A.2, if the hedonic price function moves over time, the change in price accompanying a change in exposure to shale gas may provide a poor approximation of the slope of the hedonic price function. Kuminoff and Pope

(2014) discuss a number of conditions that must hold in order for this not to be a concern. One important requirement is that the preferences of local residents for exposure to wells do not change over time. If preferences are a function of residents' attributes, a simple check can be performed by examining how tract-level sociodemographics change with changes in exposure. To examine how sociodemographics changed over time, we compare 2000 and 2012 using census tract information on neighborhood attributes compiled by SimplyMap, a national data mapping software tool.[42] SimplyMap combines information from decennial censuses, the American Community Survey Public Use Microdata Samples, the Annual Demographic Survey, Current Population Reports, numerous special Census reports, and information from the US Postal Service to create estimates for key sociodemographic variables at the census tract level. Table A3 describes the results of this analysis. In particular, we regress the change in 33 tract-level attributes, X, over the period 2000 to 2012 on the change in the number of cumulative wellbores within 20km of the centroid of the census tract in 2012.[43]

$$(X_{i,2012} - X_{i,2000}) = \rho \, bores20_{i,2012} + \epsilon_i$$

The first column reports the variable name, and the second column reports the mean of that variable in 2012. The third column reports the coefficient on wellbores, ρ, and the fourth column reports the percent change in the variable in question over the period 2000 to 2012 attributable to the average change in the number of wells in the corresponding vicinity of each census tract.

Out of the 33 variables that we consider, 23 have statistically significant wellbore effects. While statistical significance may be a cause for concern, very few of these effects are *economically* significant. In particular, considering the actual change in well exposure in each census tract over this period, the average of the resulting changes in tract attributes was no larger than 1% for any variable. Changes in neighborhood composition induced by shale gas development are, therefore, quite small. While this is not sufficient to rule out shifts in the hedonic price function over time, it is evidence in favor of a MWTP, as opposed to a simple capitalization effect, interpretation of our DDD results.

[42]http://geographicresearch.com/simplymap/. Access through the Duke University Library.

[43]Recall that cumulative wellbores is everywhere equal to zero in 2000.

Table A3: Change in Sociodemographic Characteristics, 2000-2012

Variable	Mean in 2012	Coefficient on Wellbores	Average % Δ from Wells
Household Income per Capita	30,080.30	-2.45E0	-0.154
Household Median Vehicles	1.803	1.30E-4***	0.071
Median Age	39.09	5.83E-3***	0.156
Median Age (Female)	40.294	5.19E-3***	0.135
Median Age (Male)	37.706	6.87E-3***	0.189
Population	3,964.24	-6.05E-1***	-0.291
% Asian	0.059	-6.25E-5***	-0.009
% Associate Degree	0.055	3.10E-5***	0.000
% Bachelor's Degree	0.122	-2.24E-6	0.000
% Black	0.155	-6.62E-6	0.000
% Family	0.784	-1.59E-5	0.000
% Female	0.515	-2.39E-5***	0.000
% High School	0.211	2.74E-5***	0.000
% Hispanic	0.131	-9.98E-5***	-0.004
% In Group Quarters	0.034	6.69E-6	0.001
% Less Than High School	0.093	-3.46E-5***	0.000
% Male	0.485	2.39E-5***	0.000
% Married, Female	0.202	-2.91E-5***	0.000
% Married, Male	0.204	-3.52E-5***	0.000
% Non-Family	0.182	9.22E-6	0.000
% Occupation, Construction	0.034	-1.05E-5**	0.000
% Occupation, Farming	0.002	-1.17E-6	0.000
% Occupation, Management	0.068	-1.07E-5	0.000
% Occupation, Production	0.054	-9.87E-6*	0.000
% Occupation, Professional	0.107	8.36E-7	0.000
% Occupation, Sales and Office	0.111	1.11E-5	0.000
% Occupation, Service	0.092	-1.81E-5**	0.000
% Other Race	0.052	5.56E-5***	0.013
% Some College	0.115	2.43E-5***	0.000
% Speaks English	0.728	1.16E-4***	0.000
% Urban	0.835	-9.92E-6***	0.000
% White	0.701	7.68E-5***	0.000
% White, Non-Hispanic	0.643	1.33E-4***	0.000

Note: % Δ from Wells is calculated as the average across census tracts of (Δ Wellbores*Coefficient on Wellbores)/(Mean in 2012)*100.

A.6 Effects on Likelihood of Transaction

Here we investigate whether shale gas development within 20km affects the number of properties that are sold in a census tract. The concern is that drilling activity may affect the likelihood of a transaction, so that our sample of observed sales will be selected based upon the drilling exposure treatment. Using aggregated CoreLogic data, we regress the log of the annual number of transactions in each census tract on exposure to shale gas development within 20km of the tract centroid, including year and census tract fixed effects. We find that the effect of cumulative well pads is small and statistically insignificant for the number of properties sold (Table A4). This is also true if we only focus on census tracts that are majority-piped-water areas or census tracts that are majority-groundwater areas. We therefore do not worry about sample selection in our housing transactions data induced by the well exposure treatment.

Table A4: Log Number of Sales on Drilling Activity

	All Census Tracts	>50% PWSA Census Tracts	≥50% Groundwater Census Tracts
	(1)	(2)	(3)
	ln(# Sales)	ln(# Sales)	ln(# Sales)
Pads in 20km	3.77e-04	2.81e-04	5.87e-04
	(3.32e-04)	(3.87e-04)	(9.11e-04)
County-Year Effects	Yes	Yes	Yes
Census Tract Effects	Yes	Yes	Yes
n	19,283	16,353	2,930

Notes: Dependent variable is the log annual number of properties sold in a census tract, calculated using the property sales data. Each column represents a separate regression, differing based on the sample used: all census tracts in the data, census tracts that are mostly piped-water, and census tracts that are mostly groundwater. Regressor is the cumulative count of well pads drilled within 20km of the centroid of the census tract in the year of observation. Standard errors are clustered by census tract.

A.7 Effects on Likelihood of New Construction

In this section, we perform two tests to investigate whether new construction associated with shale gas development may be driving down the size of the positive vicinity effect we find during the period around drilling. In particular, a strong increase in new housing supply may result in a failure to find any increase in prices in spite of a positive vicinity effect. Using CoreLogic data, we check first to see if the likelihood of a transaction for a newly constructed property is a function of exposure to cumulative well pads within 20km at the time of sale.[44] In particular, we run a regression at the property level, where the dependent variable is equal to one if the sale refers to a newly constructed house, and zero otherwise; the regression includes the count of well pads within 20km from the census tract, the count interacted with groundwater, census tract fixed effects and year fixed effects. Results are reported in Column (1) in Table A5—we find that cumulative well pads are weakly negatively correlated with the likelihood of a transaction being a new construction.

Table A5: New Construction on Drilling Activity

	Using All Property Sale Data
	Indicator (New=1)
Pads in 20km	-4.0e-04*
	(2.2e-04)
(Pads in 20km)*GW	2.5e-04
	(1.5e-04)
Census Tract Effects	Yes
County-Year Effects	Yes
Quarter Effects	Yes
n	634,820

Notes: The sample includes all properties sold in the property sales data; dependent variable equals 1 if the property was a new building, zero otherwise. Regressor is the count of wellbores (or well pads) that have been drilled within 20km of the property at the time of sale.

[44] Whereas we had dropped new construction homes from our previous analyses, we reintroduce them to the dataset here. If we were to include newly constructed homes in our previous analyses, our findings would not change.

A.8 Heterogeneity across Geography

The largest population center above the Marcellus shale in Pennsylvania is found in the Pittsburgh metropolitan area in the Southwest. Here we investigate whether the results are being driven by the Southwest, given that most of the properties in our sample are from this area.[45] In the first panel of Table A6 we show that indeed the results from the Southwest subsample are very similar to the findings in our main table (Table 2). However, when restricting the sample to counties in the Northeast we also find somewhat similar results; properties that depend on private groundwater wells are negatively affected when in close proximity to shale gas development. We do not see a positive impact on PWSA properties when focusing on the Northeast and there are a couple of potential reasons for this. In the Northeast, 60% of the wells within 1.5km of properties sold in 2012 were not producing any gas, whereas in the Southwest, only 39% of the wells were not producing. Pipeline infrastructure is more developed in the Southwest making marginal wells more profitable, but perhaps more important for production is that in the western part of the Southwest, natural gas production is "wet," meaning that alongside the methane production are natural gas liquids (ethane, butane, propane, and pentane). In the Northeast, the natural gas is "dry," containing primarily methane. Over this time period, natural gas liquids have obtained a higher price than methane, making wells in the Southwest more profitable than in the Northeast. If we divide the sample instead into counties with and without wet gas, the distinction between the estimates is even larger (Table A7).[46] Areas with natural gas liquids have statistically significant increases in value when in close proximity to shale gas, even at a 1km distance. Properties in the PWSA boundary sample that are groundwater-dependent, see a smaller increase than PWSA properties. Properties in areas without natural gas liquids, do not see an increase in value, and those dependent on groundwater see a large decrease.

[45] Southwest counties included are Allegheny, Armstrong, Beaver, Butler, Fayette, Greene, Indiana, Lawrence, Somerset, Washington, and Westmoreland.

[46] We used a map with an approximation of the line dividing wet and dry Pennsylvania to designate counties as either with wet gas or without. See http://www.marcellus.psu.edu/images/Wet-Dry_Line_with_Depth.gif.

Table A6: Log Sale Price on Well Pads by Geographic Subsamples

	$K\leq$1km		$K\leq$1.5km		$K\leq$2km	
	Full	Boundary	Full	Boundary	Full	Boundary
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Properties in the Southwest						
Pads in Kkm	.027	.026	.029**	.035*	.016**	.018*
	(.025)	(.035)	(.014)	(.02)	(6.8e-03)	(.011)
(Pads in Kkm)*GW	-.043	-.162**	-.024	-.092**	9.0e-03	3.3e-03
	(.054)	(.075)	(.025)	(.038)	(.018)	(.053)
Pads in 20km	-7.9e-04**	-7.5e-04	-8.4e-04**	-8.9e-04	-8.5e-04***	-9.1e-04
	(3.2e-04)	(6.4e-04)	(3.3e-04)	(6.6e-04)	(3.3e-04)	(6.8e-04)
(Pads in 20km)*GW	6.7e-05	2.0e-03**	7.2e-05	2.0e-03**	-6.7e-05	1.6e-03*
	(5.8e-04)	(9.3e-04)	(6.0e-04)	(9.1e-04)	(6.1e-04)	(9.0e-04)
Property Effects	Yes	Yes	Yes	Yes	Yes	Yes
County-Year Effects	Yes	Yes	Yes	Yes	Yes	Yes
Quarter Effects	Yes	Yes	Yes	Yes	Yes	Yes
n	199,344	52,986	199,344	52,986	199,344	52,986
p-value ($\alpha_3 + \alpha_4 = 0$)	0.766	0.075	0.814	0.174	0.119	0.692
Avg. Pads in Kkm	0.003	0.007	0.009	0.018	0.019	0.038
Avg. Pads in 20km	5.051	5.634	5.051	5.634	5.051	5.634
Panel B: Properties in Northeast						
Pads in Kkm	-5.9e-03	-.013	-.018	-9.2e-03	-3.5e-03	3.9e-03
	(.112)	(.115)	(.053)	(.064)	(.038)	(.039)
(Pads in Kkm)*GW	-.059	-.225	-.048	-.464**	-.08*	-.149*
	(.12)	(.194)	(.066)	(.233)	(.043)	(.088)
Pads in 20km	-1.2e-03*	-1.0e-03	-1.2e-03*	-1.0e-03	-1.2e-03*	-1.1e-03
	(6.3e-04)	(6.8e-04)	(6.5e-04)	(7.0e-04)	(6.7e-04)	(7.4e-04)
(Pads in 20km)*GW	1.7e-03**	2.0e-03*	1.9e-03**	2.3e-03**	2.3e-03***	2.5e-03**
	(7.2e-04)	(1.1e-03)	(7.5e-04)	(1.1e-03)	(8.4e-04)	(1.2e-03)
Property Effects	Yes	Yes	Yes	Yes	Yes	Yes
Census Tract-Year Effects	Yes	Yes	Yes	Yes	Yes	Yes
Quarter Effects	Yes	Yes	Yes	Yes	Yes	Yes
n	28,068	11,762	28,068	11,762	28,068	11,762
p-value ($\alpha_3 + \alpha_4 = 0$)	0.287	0.225	0.128	0.047	0.002	0.043
Avg. Pads in Kkm	0.002	0.001	0.006	0.003	0.013	0.008
Avg. Pads in 20km	2.729	3.286	2.729	3.286	2.729	3.286

Notes: Each column in each panel represents a separate regression. Dependent variable in all regressions is the log sale price. Independent variables are the counts of wells at different distances from the property, drilled before the sale, as well as interactions with an indicator for whether the property is dependent on groundwater (GW). First panel only includes properties in the Southwest and the second panel only includes properties in the Northwest and Northeast. The boundary sample restricts the full sample to include only properties in a narrow band around the border of the public water service areas. Robust standard errors are clustered by census tract. *** Statistically significant at the 1% level; ** 5% level; * 10% level.

Table A7: Log Sale Price on Well Pads by Geographic Subsamples: Abundance of Natural Gas Liquids

	$K \leq 1$km		$K \leq 1.5$km		$K \leq 2$km	
	Full	Boundary	Full	Boundary	Full	Boundary
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Properties in Wet-Gas Counties						
Pads in Kkm	.063**	.071**	.052***	.057**	.024***	.026**
	(.032)	(.03)	(.018)	(.022)	(9.1e-03)	(.012)
(Pads in Kkm)*GW	-.067	-.201***	-.027	-.11***	4.3e-03	-3.5e-03
	(.053)	(.075)	(.026)	(.037)	(.019)	(.054)
Pads in 20km	-1.3e-03***	-2.1e-03*	-1.3e-03***	-2.2e-03**	-1.3e-03***	-2.2e-03**
	(4.2e-04)	(1.1e-03)	(4.3e-04)	(1.1e-03)	(4.3e-04)	(1.1e-03)
(Pads in 20km)*GW	-1.0e-04	2.1e-03**	-1.4e-04	2.1e-03**	-2.5e-04	1.6e-03
	(6.3e-04)	(1.0e-03)	(6.6e-04)	(1.0e-03)	(6.7e-04)	(1.0e-03)
Property Effects	Yes	Yes	Yes	Yes	Yes	Yes
County-Year Effects	Yes	Yes	Yes	Yes	Yes	Yes
Quarter Effects	Yes	Yes	Yes	Yes	Yes	Yes
n	165,421	42,126	165,421	42,126	165,421	42,126
p-value ($\alpha_3 + \alpha_4 = 0$)	0.937	0.102	0.216	0.225	0.076	0.688
Avg. Pads in Kkm	0.003	0.008	0.007	0.017	0.015	0.035
Avg. Pads in 20km	4.160	4.569	4.160	4.569	4.160	4.569
Panel B: Properties in Dry-Gas Counties						
Pads in Kkm	-.026	-.121	-6.1e-03	-.024	1.7e-03	-2.7e-03
	(.035)	(.073)	(.01)	(.026)	(5.8e-03)	(.016)
(Pads in Kkm)*GW	-.033	-.151	-.074*	-.421*	-.078***	-.121*
	(.079)	(.197)	(.041)	(.214)	(.026)	(.07)
Pads in 20km	-6.0e-05	1.6e-04	-6.1e-05	1.2e-04	-1.0e-04	3.0e-05
	(4.1e-04)	(5.0e-04)	(4.1e-04)	(5.1e-04)	(4.1e-04)	(5.6e-04)
(Pads in 20km)*GW	1.3e-03**	1.7e-03*	1.5e-03**	2.0e-03**	1.8e-03***	2.1e-03**
	(5.7e-04)	(9.5e-04)	(5.9e-04)	(9.8e-04)	(6.5e-04)	(1.0e-03)
Property Effects	Yes	Yes	Yes	Yes	Yes	Yes
Census Tract-Year Effects	Yes	Yes	Yes	Yes	Yes	Yes
Quarter Effects	Yes	Yes	Yes	Yes	Yes	Yes
n	64,525	24,201	64,525	24,201	64,525	24,201
p-value ($\alpha_3 + \alpha_4 = 0$)	0.414	0.141	0.049	0.037	0.003	0.063
Avg. Pads in Kkm	0.004	0.003	0.012	0.011	0.026	0.025
Avg. Pads in 20km	6.174	6.047	6.174	6.047	6.174	6.047

Notes: Each column in each panel represents a separate regression. Dependent variable in all regressions is the log sale price. Independent variables are the counts of wells at different distances from the property, drilled before the sale, as well as interactions with an indicator for whether the property is dependent on groundwater (GW). First panel only includes properties that are in counties that have natural gas liquids and the second panel only includes properties in counties without any natural gas liquids. The boundary sample restricts the full sample to include only properties in a narrow band around the border of the public water service areas. Robust standard errors are clustered by census tract. *** Statistically significant at the 1% level; ** 5% level; * 10% level.

Appendix References

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