

The Housing Market Impacts of Shale Gas Development[†]

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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 L71, Q35, Q53, R31)

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 north-eastern United States were thought to be uneconomical less than ten 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, Muehlenbachs, and Olmstead 2015 for a review).

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¹In 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.

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 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 trade-offs 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, Chan, and McMillan 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, Spiller, and Timmins (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, Spiller, and Timmins (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

² See, for example, Raimi and Newell (2014) and Wynveen (2011). Employment effects from oil and gas development is an active area of research; for papers specific to shale gas see Weber (2012); Maniloff and Mastrodonaco (2014); and Fetzer (2014).

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 online Appendix Section B for a deeper discussion of the hedonic method as it applies to this paper.

Delgado, Guilfoos, and Boslett (2014) only find weak evidence of this in Lycoming and Bradford Counties, Pennsylvania. At the broader level, Boslett, Guilfoos, and Lang (2014) find that groundwater-dependent homes in New York positively value the possibility of shale gas development. Weber, Burnett, and Xiarchos (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 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; many other studies 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,

⁵ See US Energy Information Administration (2011) for a ranking of shale gas plays in terms of technically recoverable reserves.

the effect on property values may have important implications for understanding the benefits and costs of a large scale shift toward domestic energy from shale gas.

Our paper proceeds as follows. Section I describes our methodology. Section II details our data, and Section III reports our empirical specifications and main results, with a summary of different property value impacts in Section IV. Section V concludes. Finally, we provide an online Appendix 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.

I. Methodology

Our goal is to recover estimates of the nonmarketed 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 2 km 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.

A. Impact Categories

We categorize the impacts of nearby shale gas exploration and development on housing values as follows:

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, 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

⁶Given 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.

⁷In Pennsylvania, upon signing their mineral rights to a gas company, landowners may receive \$2 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

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).

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 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., 20 km) 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 IIIB. Area A represents a buffer drawn around a well that defines adjacency. That buffer is located in an area dependent upon groundwater (GW), 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 1 km of shale gas wells have higher

extracted. Natural Gas Forum for Landowners: Natural Gas Lease Offer Tracker, http://www.naturalgasforums.com/lease_offers_tracker.php?action=resources (accessed September 17, 2015).

⁸Data 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.

⁹Impact fees are taxes levied on drilled wells. The total amount of impact fees collected in Pennsylvania through 2014 exceeded \$850 million dollars, 60 percent of which is given to local counties and municipalities with wells. See <https://stateimpact.npr.org/pennsylvania/tag/impact-fee/> (accessed September 17, 2015).

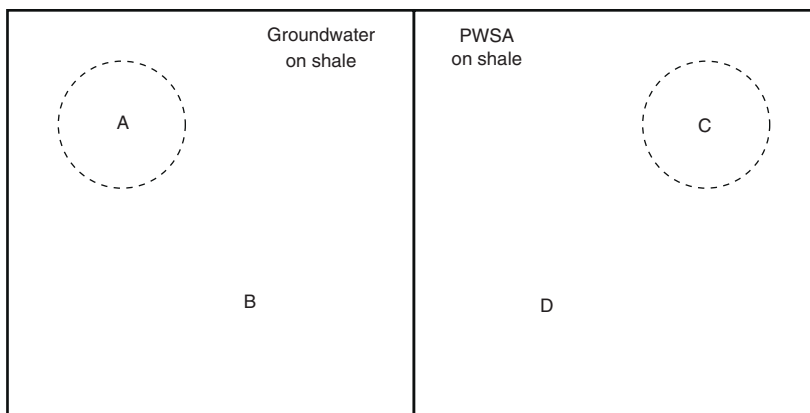


FIGURE 1. TYPES OF AREAS EXAMINED

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 1.6 km).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 2 km 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.

II. 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 US Geological Survey) as well as the properties sold.

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 (0.9 km) and 5,000 feet (1.5 km) (US Energy Information Administration 2013), but could be up to 10,684 feet (3.3 km) 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 1.6 km 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 online Appendix Section A for a description of how we constructed our final samples.

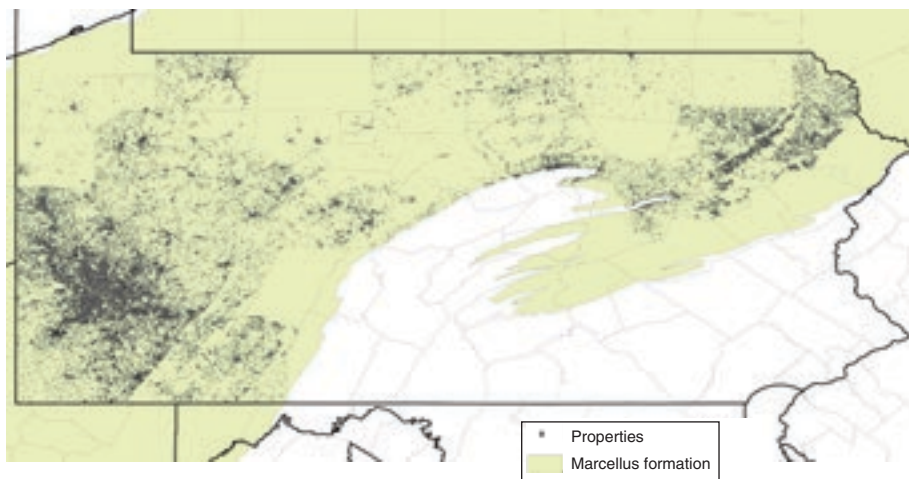


FIGURE 2. PROPERTY SALES DATA FROM CORELOGIC MAPPED WITH GIS ON OVERLAY OF MARCELLUS SHALE IN PENNSYLVANIA

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 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 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 63 m, 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

¹³We 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 dataset than that which we use.

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

¹⁵During 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).

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 percent 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 and 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, Kousky, and Chu (2013), who examine the property value of natural landscape views, we count the number of wells that are within eyesight 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

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.

III. 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

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

¹⁷Of 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.

¹⁸There 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.

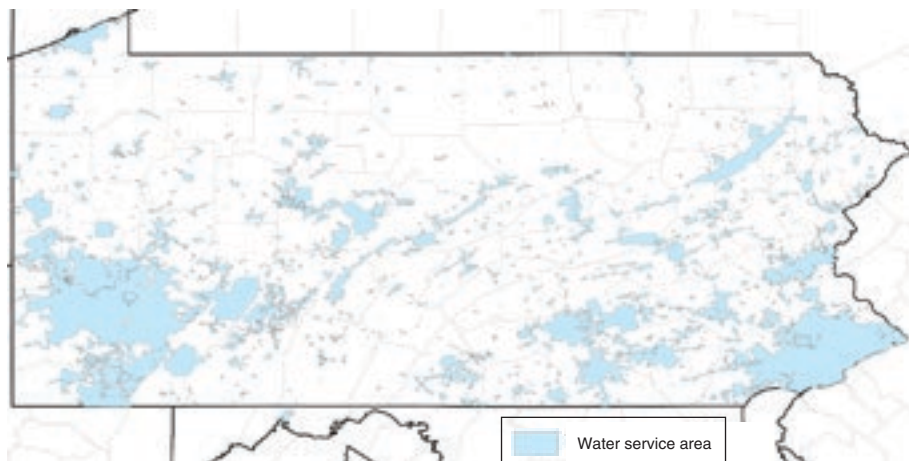


FIGURE 3. PUBLIC WATER SERVICE AREAS IN PENNSYLVANIA

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 subperiod 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.

A. 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 10 km.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

¹⁹For this exercise, we choose to only look at homes that have *one* well pad within 10 km, 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 10 km 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 10 km will be similar to those at 10 km.

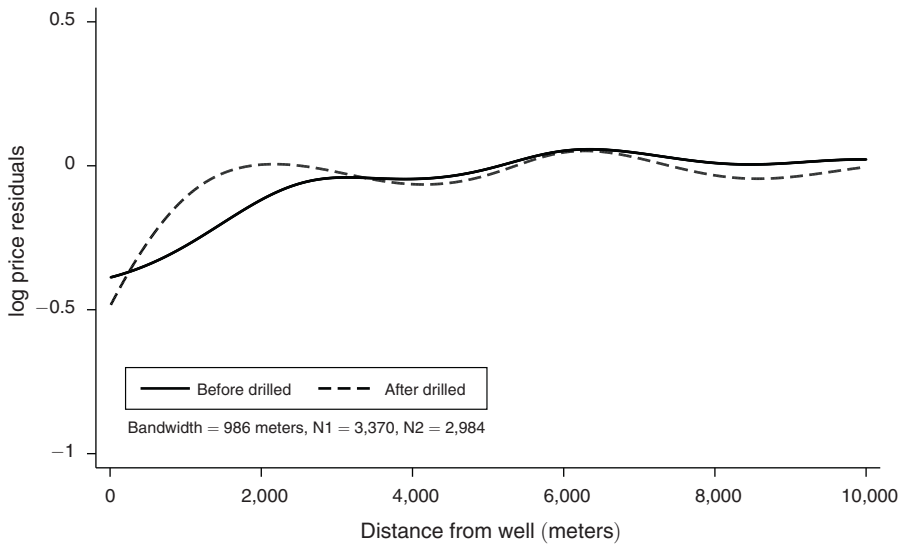


FIGURE 4. PRICE GRADIENT OF DISTANCE FROM FUTURE/CURRENT WELL, USING PUBLIC WATER SERVICE AREAS

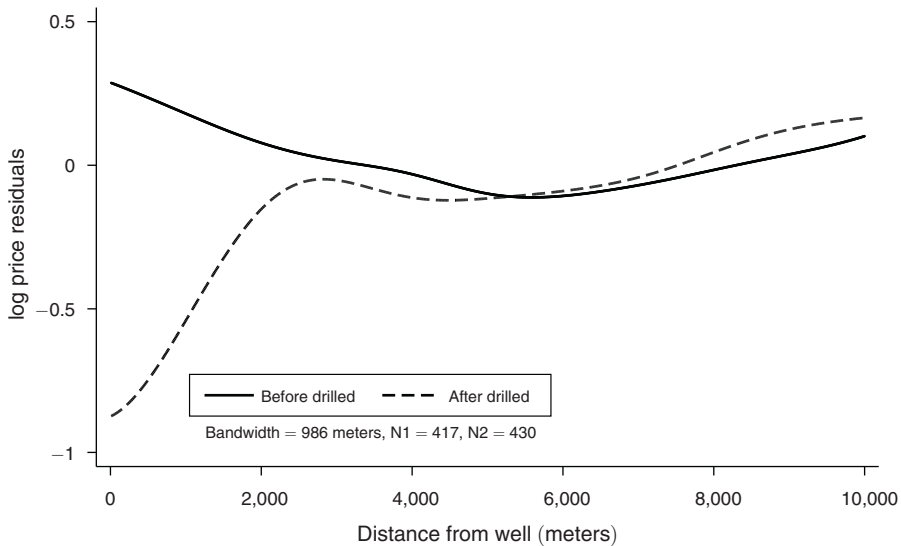


FIGURE 5. PRICE GRADIENT OF DISTANCE FROM FUTURE/CURRENT WELL, USING GROUNDWATER-DEPENDENT AREAS

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 2 km; however, the prices for groundwater-dependent properties farther than 2 km from a well remain the same before and after it is drilled. This exercise demonstrates that

adjacency impacts differ by drinking water source within 2 km of a well, validating our usage of buffers less than 2 km 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.

B. Triple-Difference (DDD) Estimation of GWCR

Considering the impact categories described in Section IA 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:

$$(1) \quad \begin{aligned} \Delta P_A &= \Delta Adjacency + \Delta GWCR + \Delta Vicinity_{GW} + \Delta Macro \\ \Delta P_B &= \Delta Vicinity_{GW} + \Delta Macro \\ \Delta P_C &= \Delta Adjacency + \Delta Vicinity_{PWSA} + \Delta Macro \\ \Delta P_D &= \Delta Vicinity_{PWSA} + \Delta Macro, \end{aligned}$$

where, for example, $\Delta GWCR$ 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: $\Delta Vicinity_{GW}$ refers to the vicinity impact on groundwater-dependent homes, while $\Delta Vicinity_{PWSA}$ refers to the vicinity impact on PWSA homes. Our strategy for identifying adjacency effects uses a difference-in-differences (DD) estimator:

$$\Delta Adjacency_{DD} = [\Delta P_C - \Delta P_D],$$

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 difference 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:

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

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:

$$\Delta GWCR_{DDD} = [\Delta P_A - \Delta P_B] - [\Delta P_C - \Delta P_D].$$

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 IIIA. 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 ($k = 1, 2, \dots, K$), 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):

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

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 20 km and those outside of 20 km:

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

where $\rho_{ik} = \alpha_1 d_{ik}^{<20} + \lambda_1 d_{ik}^{>20}$, $d_{ik}^{<20} = 1$ if well pad k is within 20 km of house i ($= 0$ otherwise), and $d_{ik}^{>20}$ is defined in a similar manner for wells outside of 20 km 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

²⁰We 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.

interacting the initial proximity regressor (the presence of a well within 20 km) 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 2 km but the same equation holds for buffers of smaller and larger sizes):

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

It is important to note that wells within 2 km are also within 20 km, 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 1 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:

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

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

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

For the sake of simplicity, we define the following well pad count variables for 20 and 2 km:

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

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

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

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

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 20 km (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—1,000 m on either side, ignoring houses on the GW side within 300 m (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 homogeneous.²² Figure 6 demonstrates the PWSA boundary sample for an example county, Armstrong County, Pennsylvania. Table 1 shows that property

²¹ Our final results are robust to removing 300 m 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.

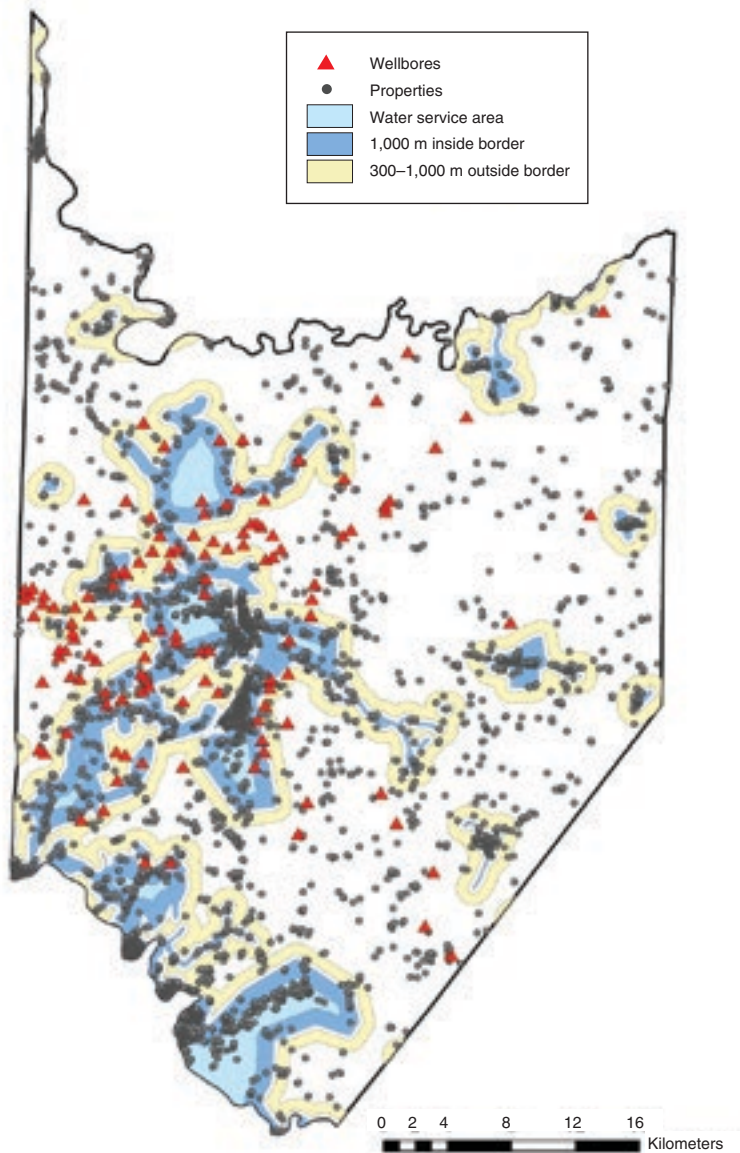


FIGURE 6. EXAMPLE INDICATING THE 1,000 M BOUNDARY INSIDE AND 300–1,000 M BOUNDARY OUTSIDE OF PUBLIC WATER SERVICE AREAS IN ARMSTRONG COUNTY, PENNSYLVANIA

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

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

TABLE 1—SUMMARY STATISTICS BY SAMPLE

	Full sample		Boundary subsample	
	Mean	SD	Mean	SD
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 (1,000 sq ft)	1.59	(0.67)	1.54	(0.634)
No. bathrooms	1.82	(0.852)	1.68	(0.799)
No. bedrooms	2.96	(0.933)	2.91	(0.984)
Lot size (acres)	0.578	(3.9)	0.53	(4.5)
Distance to nearest MSA (km)	22.3	(12.4)	26.4	(13.4)
Groundwater dependent	0.0771	(0.267)	0.0563	(0.231)
Distance to closest well pad (km)	11.7	(5.35)	11.2	(5.5)
Pads in 1 km	0.00329	(0.081)	0.00596	(0.113)
Pads in 1.5 km	0.00855	(0.164)	0.015	(0.226)
Pads in 2 km	0.0178	(0.289)	0.0314	(0.401)
Pads in 20 km	4.73	(18.1)	5.11	(21)
Pads in view in 1 km	0.000474	(0.024)	0.000844	(0.0325)
Pads in view in 1.5 km	0.00113	(0.0425)	0.0022	(0.0599)
Pads in view in 2 km	0.00189	(0.0671)	0.00368	(0.0955)
Producing pads in 1 km	0.00263	(0.0736)	0.0049	(0.104)
Producing pads in 1.5 km	0.00694	(0.152)	0.0127	(0.214)
Producing pads in 2 km	0.0147	(0.274)	0.0273	(0.388)
Observations	229,946		66,327	

Notes: Samples are the 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.

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 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

²⁴Census 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

TABLE 2—LOG SALE PRICE ON WELL PADS

	$K \leq 1$ km		$K \leq 1.5$ km		$K \leq 2$ km	
	Full (1)	Boundary (2)	Full (3)	Boundary (4)	Full (5)	Boundary (6)
<i>Panel A. County-year fixed effects</i>						
Pads in K km	0.028 (0.025)	0.026 (0.035)	0.029** (0.014)	0.034* (0.02)	0.016** (6.9e-03)	0.018* (0.01)
(Pads in K km) × GW	-0.062 (0.046)	-0.165** (0.072)	-0.042* (0.025)	-0.099*** (0.036)	-0.023 (0.02)	-0.013 (0.052)
Pads in 20 km	-7.8e-04*** (3.0e-04)	-8.1e-04 (5.3e-04)	-8.3e-04*** (3.0e-04)	-9.3e-04* (5.5e-04)	-8.4e-04*** (3.0e-04)	-9.4e-04* (5.6e-04)
(Pads in 20 km) × GW	6.6e-04 (4.7e-04)	2.0e-03*** (7.0e-04)	7.0e-04 (4.9e-04)	2.0e-03*** (6.8e-04)	7.1e-04 (5.2e-04)	1.7e-03** (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
Observations	229,946	66,327	229,946	66,327	229,946	66,327
p -value ($\alpha_3 + \alpha_4 = 0$)	0.414	0.051	0.544	0.090	0.740	0.919
Avg. pads in K km	0.003	0.006	0.009	0.015	0.018	0.031
Avg. pads in 20 km	4.725	5.108	4.725	5.108	4.725	5.108
<i>Panel B. Census tract-year fixed effects</i>						
Pads in K km	0.016 (0.046)	0.030 (0.055)	0.020 (0.021)	0.026 (0.027)	0.009 (0.014)	0.019 (0.015)
(Pads in K km) × GW	-0.036 (0.071)	-0.137 (0.093)	-0.050 (0.039)	-0.107*** (0.037)	-0.021 (0.027)	0.001 (0.092)
Pads in 20 km	-2.7e-04 (0.001)	5.1e-04 (0.002)	-3.0e-04 (0.001)	4.7e-04 (0.002)	-3.1e-04 (0.001)	4.3e-04 (0.002)
(Pads in 20 km) × GW	0.001 (0.001)	0.002 (0.001)	0.001 (0.001)	0.002 (0.001)	0.001 (0.001)	0.001 (0.001)
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
Observations	229,946	66,327	229,946	66,327	229,946	66,327
p -value ($\alpha_3 + \alpha_4 = 0$)	0.774	0.320	0.442	0.125	0.647	0.861
Avg. pads in K km	0.003	0.006	0.009	0.015	0.018	0.031
Avg. pads in 20 km	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.

***Significant at the 1 percent level.

**Significant at the 5 percent level.

*Significant at the 10 percent level.

(although 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 1 km), we see much larger negative impacts from GWCR (-16.5 percent) and insignificant

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.

positive adjacency impacts (2.6 percent), where the summation of the two coefficients implies a statistically significant drop of 13.9 percent (p -value of 0.051) for groundwater-dependent homes.²⁵ Moving to a larger buffer (from 1 km to 1.5 km) a statistically significant positive impact from well pads starts to emerge (perhaps because wells at farther distances contribute less to negative impacts such as noise and light pollution). At a larger buffer the negative impact on GW homes also diminishes to 9.9 percent. The results imply that adding an extra well within 1.5 km causes GW homes to lose 6.5 percent of their value (bordering statistical significance with a p -value of 0.09), with -9.9 percent being due to the risk of groundwater contamination, and $+3.4$ percent due to the positive impact of lease payments and other adjacency impacts. Finally, farther from a well (at 2 km) 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 2 km relative to 1.5 km; 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 nonlinear effects.

C. 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 (1 km, 1.5 km, and 2 km) 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 5 ft 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 count that are not producing. In the data, 42 percent 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

²⁵ While these net impacts may seem large, Throupe, Simons, and Mao's (2013) contingent valuation study in Texas and Florida shows a 5–15 percent 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.

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 3 km are found in Table C2 in the online Appendix.

TABLE 3—ADJACENCY EFFECTS

	<i>K</i> = 1 km (1)	<i>K</i> = 1.5 km (2)	<i>K</i> = 2 km (3)
	ln(price)	ln(price)	ln(price)
<i>Panel A. log sale price on well pads in view</i>			
Visible well pads in <i>K</i> km	1.1e-03 (0.072)	-0.019 (0.058)	0.019 (0.035)
Not-visible well pads in <i>K</i> km	0.03 (0.028)	0.036*** (0.013)	0.015** (6.5e-03)
Pads in 20 km	-6.0e-04* (3.3e-04)	-6.4e-04* (3.3e-04)	-6.5e-04* (3.3e-04)
<i>Panel B. log sale price on productive wells</i>			
Unproductive pads in <i>K</i> km	-0.052 (0.077)	-0.043 (0.035)	-0.054* (0.03)
Producing pads in <i>K</i> km	0.044** (0.02)	0.038*** (0.013)	0.02*** (5.8e-03)
Pads in 20 km	-6.0e-04* (3.3e-04)	-6.4e-04* (3.3e-04)	-6.3e-04* (3.3e-04)
<i>Panel C. log sale price on timing of wellbores</i>			
Old bores (drilled > 365 days) in <i>K</i> km	0.021 (0.018)	0.023** (9.8e-03)	0.011** (4.4e-03)
New bores (drilled ≤ 365 days) in <i>K</i> km	-4.4e-03 (0.029)	-9.7e-03 (0.013)	-3.3e-04 (8.0e-03)
Old undrilled permits (> 365 days) in <i>K</i> km	0.055** (0.025)	0.022 (0.014)	0.011 (0.012)
New undrilled permits (≤ 365 days) in <i>K</i> km	0.04* (0.023)	7.2e-03 (0.014)	7.2e-03 (7.9e-03)
Pads in 20 km	-6.0e-04* (3.3e-04)	-6.2e-04* (3.3e-04)	-6.3e-04* (3.3e-04)
Property effects	Yes	Yes	Yes
County-year effects	Yes	Yes	Yes
Quarter effects	Yes	Yes	Yes
Observations	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 *K* km, 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.

*** Significant at the 1 percent level.

** Significant at the 5 percent level.

* Significant at the 10 percent level.

52 wells, or less than 1 percent 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

²⁸In 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.

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 1.5 km and 2 km, 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, 1 km, 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

D. 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.

²⁹This 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.

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 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. Performing nearest-neighbor matching on house attributes, 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 homogeneous neighborhood within each census tract. Thus, we (i) limit our analysis to only houses that are within 6 km of a well pad (defining the treatment buffer to be 1, 1.5, or 2 km given evidence of a small adjacency buffer found in Section IIIA); (ii) require exact matches by census tract; (iii) require exact matches by year of sale; and (iv) perform the analysis separately for groundwater and PWSA houses. The idea behind these restrictions is that houses within 6 km 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 nonadjacent 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

³⁰For 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, Ichimura, and Todd (1998).

³¹It 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).

TABLE 4—LOG SALE PRICE ON GROUNDWATER CONTAMINATION RISK OF WELL PADS FROM A MATCHING ESTIMATOR

Sample	1 km	1.5 km	2 km
<i>Panel A. All years</i>			
<i>PWSA</i> ($n = 9,278$)	0.002 (-0.08, 0.08)	0.024 (-0.03, 0.08)	-0.013 (-0.05, 0.03)
<i>GW</i> ($n = 1,869$)	-0.070 (-0.18, 0.04)	-0.092 (-0.18, -0.01)	-0.030 (-0.11, 0.05)
<i>GWCR_{DD}</i>	-0.072 (-0.21, 0.06)	-0.116 (-0.22, -0.02)	-0.016 (-0.10, 0.07)
<i>Panel B. Before 2010</i>			
<i>PWSA</i> ($n = 3,541$)	0.113 (-0.04, 0.26)	0.032 (-0.08, 0.14)	0.052 (-0.02, 0.13)
<i>GW</i> ($n = 807$)	0.046 (-0.12, 0.21)	-0.083 (-0.21, 0.05)	-0.040 (-0.14, 0.06)
<i>GWCR_{DD}</i>	-0.067 (-0.29, 0.16)	-0.115 (-0.28, 0.05)	-0.092 (-0.22, 0.04)
<i>Panel C. 2010 and later</i>			
<i>PWSA</i> ($n = 5,737$)	-0.059 (-0.15, 0.03)	0.004 (-0.06, 0.06)	-0.046 (-0.09, 0.00)
<i>GW</i> ($n = 1,062$)	-0.104 (-0.24, 0.04)	-0.082 (-0.20, 0.03)	-0.032 (-0.13, 0.07)
<i>GWCR_{DD}</i>	-0.044 (-0.21, 0.12)	-0.087 (-0.21, 0.04)	0.014 (-0.10, 0.13)

Notes: Samples comprise all houses within 6 km of a well pad (panel A), within 6 km and sold before 2010 (panel B), and within 6 km and sold in 2010 or later (panel C). Each house in the treatment buffer is matched with four 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 2 km. Bias adjustment equation contains all house attributes. 90 percent confidence intervals reported in parentheses.

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:

$$GWCR_{DDNNM} = (P_A - P_B) - (P_C - P_D).$$

The results of the nearest neighbor matching procedure are reported in Table 4. The first two rows report the point estimates and 90 percent confidence intervals for PWSA houses using 1, 1.5, and 2 km 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 1.5 km treatment buffer, the DD estimate is large (-11.6 percent) and significant at the 10 percent 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 statistically 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}

IV. Summary of Impacts

Using a variety of empirical methodologies, we demonstrate that the risk of groundwater contamination negatively affects house values in the 1–1.5 km 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 (1.5 km 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 percent to –16.5 percent), 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 1.5 km of a well to be \$30,167.³⁴ The average

³²While 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.

³³In 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.

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

annual loss for GW properties is larger than the average annual gain for piped-water properties within 1.5 km of a shale gas well (\$4,802).³⁵ Furthermore, it is important to keep in mind that our estimates do not 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.

V. 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 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

³⁵This is calculated using properties that have access to piped water, are within 1.5 km of a well, and are sold in the most recent year of our data. If we also include properties within 2 km of a well and include coefficients from column 6 for properties within 1.5 km and 2 km 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 2 km of a well is \$16,059 compared to gains for PWSA homes on average of \$5,070).

³⁶These water filters can cost about \$1,480/year for a family of four (<http://www.ezclearwater.com/wordpress/tag/whole-house-water-filtration-system/>, accessed September 17, 2015). 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.

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.

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³⁷For 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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