Is the Shale Boom a Bust for Nearby Residents?

Evidence from Housing Values in Pennsylvania*

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Abstract

Profitable extraction of previously inaccessible shale gas reserves has led to rapid expansion of shale exploration across the United States. While there is much enthusiasm surrounding the benefits from this source of energy as a potential path to energy independence, very little is known about the environmental risks associated with this exploration activity. In this paper, we present one of the first empirical studies to measure the impact of early shale exploration as capitalized into surrounding property values. Our dataset combines real estate data, shale well data and land use data in Washington County, Pennsylvania from 2008 to mid-2010 to estimate the impact of shale activity on nearby housing values using a Box-Cox hedonic specification. We find that households are adversely impacted by shale gas exploration activity, but this impact depends on the proximity and intensity of shale activity and is largely transitory in duration. While the magnitude of the overall effect of an additional shale well within one mile from the property is modest (-0.8%) this impact is heterogeneous. The effect is larger for households located close to major highways and sourced with private well water. The impacts are larger and more persistent for properties surrounded by agricultural lands.

Keywords: Shale; Hedonic; Risk; Housing values

JEL Codes: Q51; Q53; Q40; Q33

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[*] Authorship equally shared. We would like to thank Brian Roe for his helpful comments and suggestions on earlier drafts of the paper. We would also like to thank participants at the AERE summer meetings for their comments and suggestions. All remaining errors are our own.

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1. Introduction

Exploration of previously inaccessible, domestic sources of energy contained in shale deposits has the potential to fundamentally change the energy makeup and outlook for the United States and global economy. Unlike traditional sources of shale exploration that date back to the 1800s, the recent enthusiasm surrounding shale gas exploration is largely a result of technological advancements that have enabled profitable extraction of subsurface shale resources. Beginning in 2005 with exploration of the Barnett Shale in Texas, innovations in the use of horizontal drilling and hydrofracturing techniques have ushered in a rapid expansion of shale gas exploration across the United States. In the Northeast United States, extraction of Marcellus shale gas began in Pennsylvania during the mid-2000s and quickly expanded in the following years.

The U.S Geological Survey estimates that Marcellus shale alone contains over 84 trillion cubic feet of undiscovered gas deposits. Exploration and development of the natural gas reserves contained in the Marcellus and Utica shale deposits in Ohio, Pennsylvania, West Virginia and New York is progressing rapidly and providing substantial private benefits to landowners, with typical lease payments upwards of $6,000 per acre and royalty payments near 20% (Downing, 2012). While the private benefits to landowners, and the potential for enhancing state revenues arising from these, has resulted in much enthusiasm there is very little information about the potential private and public costs associated with shale exploitation. In particular, the real and perceived environmental impacts associated with drilling techniques required to access this resource is a growing concern especially among nearby residents.

In the Marcellus Shale region of Pennsylvania, viable deposits of shale gas often occur at depths of one mile or deeper. The use of hydraulic fracturing and horizontal drilling have enabled profitable exploration of this resource, although their use has created considerable controversy stemming from perceived environmental and health risks. The process of fracturing shale and releasing natural gas to the surface uses large volumes of water, often between 2 million and 8 million gallons per well, mixed with additional chemicals which are forced into a well under pressure to create fissures allowing natural gas to flow out of the dense shale (Abdalla et al., 2012). A byproduct of the hydraulic fracturing process is the generation of wastewater to the surface of between 10 and 40 percent of the total water volume used in the process. This water is often laden with heavy metals, salts, hydrofracturing chemicals and other contaminants posing a serious environmental and health risk if not contained and disposed of properly. Furthermore, concerns over methane leaching into surrounding water supplies and the potential health risks associated with this effect on water quality have been raised in both the popular press ("Gasland") as well as in academic research (Osborn *et al.*, 2011, Warner *et al.*, 2012).

Shale exploration is likely to produce both winners and losers in a community[1]. Reliable estimates of the economic impacts on surrounding landowners are a necessary first step to better understand the economic impacts of this activity. Potential winners include subsurface mineral rights owners and communities that may benefit from increased tax revenues and provision of public goods or infrastructure by local authorities. The potential for losers exists if residents perceive environmental and water quality risks associated with shale gas exploration or experience more proximate negative impacts in the form of increased "visibility" in terms of increased noise, traffic, or nighttime lighting (NYSDEC, 2011). These negative effects are likely

[1] Losers in this context could be residents who are relatively worse off than their surrounding neighbors even when everyone in an area experiences gains. We leave this larger, regional, characterization of winners and losers for future research.

to vary spatially and temporally and are hypothesized to depend on the proximity of households to gas drilling activity.

In this paper, we measure the impact of early shale exploration as capitalized into property values using a Box-Cox hedonic pricing framework for the real estate market of single-family residential homes in Washington County, Pennsylvania. This county typifies the public debate over shale exploration and perceived environmental and health risks as many areas of the county have a high density of residents in close proximity to recent Marcellus Shale exploration activity, making it an ideal location to study the impacts of shale exploration on surrounding property values. Over time, this resource boom is likely to result in increased local and state revenues through income and property taxes as well as direct income to large landowners who have leased land to the oil and gas companies. Our focus on the early stages of activity is intended to limit the potential for positive externalities that could confound econometric estimates.

Previewing our results, we find evidence that households are negatively impacted by shale gas exploration activity, although this impact depends on the proximity and intensity of shale activity and diminishes over time, coinciding with the cessation of exploration activity. In particular, we find that shale activity disproportionately impacts households relying on well water, located closer to major highways, and located in more agricultural areas. We find that households relying on well-water and located within 0.75 miles of an active well site for which the drilling permit was acquired within 6 months experience a decrease in home values of 21.7%. This large impact mirrors similar findings by Muehlenbachs et al (2012) who find a large negative property value impact of -24% for households sourcing well water. However, we find that this large effect attenuates rapidly falling to -5.6% at a distance of 1 mile. In both our study and the Muehlenbachs et al (2012) study a comprehensive database on leased land is unavailable. This suggests that our results potentially include likely "winners" who own and may have leased subsurface mineral rights. To the extent we are unable to isolate these effects, the magnitude of any negative effects we find are likely to be understated and could be viewed as an upper bound.[2]

As shale gas exploration moves forward, both in the region and nationally, understanding the potential for expansion and the associated impacts on surrounding populations is a key component of effective policy. The next section briefly describes the study setting and shale exploration process underlying our identification strategy. Section three discusses the Box-Cox hedonic framework we employ in estimating the impact of shale exploration on nearby housing values. The fourth section describes the data and Marcellus Shale activity in our study area. The fifth section presents results from our econometric analysis and the sixth section concludes with a discussion of potential policy recommendations.

2. Shale exploration and identification strategy

It is well established that land and housing markets respond to changes in environmental conditions with prices adjusting to reflect differences in environmental quality and amenities across space. Since the introduction of the hedonic pricing method by Rosen (1974), hedonic models have become one of the most common tools used by economists to estimate the value (cost) of environmental (dis)amenities that are capitalized in property values. The hedonic price function decomposes the value of a residential property, itself a bundle of many individual attributes, into housing and environmental characteristics including property characteristics such as lot size, number of bedrooms and bathrooms, the age of the property, and type of construction;

[2] The positive effects of leasing would be unlikely to show up in property values if the subsurface mineral rights do not convey with the sale of property, which should limit this concern. Unfortunately, a comprehensive data set for subsurface mineral rights is not available to explore this issue further.

neighborhood characteristics such as quality of the school district, crime rate, and proximity to city services; and environmental amenities such as air or water quality (Leggett and Bockstael, 2000), amount and quality of open space nearby (Abbott and Klaiber, 2011), proximity to amenities such as beaches and beach quality (Gopalakrishnan et al., 2011); and disamenities such as proximity to industrial waste disposal (Smith and Desvousges, 1986) or agricultural activity (Ready and Abdalla, 2005).

Credible identification of the impact of an environmental attribute of concern depends on the ability to control for unobservable factors that may confound the estimates of the treatment effect in a quasi-experimental setting (Parmeter and Pope 2013). For example, in our current study we might be concerned whether potential buyers perceived the presence of shale activity prior to purchasing the home. In what follows, we briefly describe the setting in which buyers and sellers operate before turning attention to our econometric specification.

Shale exploration activity begins when a shale gas company acquires subsurface mineral rights from a landowner. When horizontal drilling techniques are employed, a single well pad can hold up to 8 individual wells, extending up to 1 mile underground in each direction. Prior to drilling activity, mineral rights must be acquired from all owners of the land that a well passes through. Pennsylvania code 58 P.S. § 601.201 requires that drilling operators "must send notice of drilling to the owner of the surface estate upon which drilling is to occur and to surface landowners or water purveyors who have water supplies within 1,000 feet of the proposed well location." This ensures that current owners are aware of pending activity surrounding their property even if they are not involved in the leasing activities.

After securing leases for all land on which drilling operations are to occur either at the surface or subsurface in the case of horizontal wells, companies must obtain drilling permits, usually from a state environmental agency, which are priced by wellbore length in Pennsylvania and typically cost under $5,000.[3,4] At this stage, on-site preparations begin, which include construction or improvement of access roads, construction of a well pad to hold equipment, assembling retention ponds for water needed for hydraulic fracturing, and ultimately erecting a drilling rig. The final steps include drilling operations, hydraulic fracturing, and ultimately the reclamation of the well-pad area after the cessation of drilling activities.

For credible identification of shale related impacts on housing values, establishing that prospective buyers and sellers were likely aware of pending and ongoing shale activity is paramount. To highlight public awareness of Marcellus shale activity more generally, a LexisNexis search of "Marcellus Shale" spanning the years 2008 through 2010 found the two largest newspapers in the Pittsburgh region, the Pittsburgh Post-Gazette and Pittsburgh Tribune-Review, ran a combined 1,246 articles covering shale related topics. This high level of visibility in public media is reflective of the widespread interest and awareness of the growing shale exploration activities in the area. For prospective homebuyers, we hypothesize that awareness of more proximate shale exploration is likely to occur through one of three mechanisms. First, prior to and during exploration activity, truck traffic in the area is likely to be greatly increased. It is estimated that a horizontal well experiences an average of 230 one-way heavy truck trips and an additional 230 one-way light truck trips prior to actual drilling (spud date), and an average of 1,145 one-way heavy truck trips and 830 one-way light truck trips by the completion of activity (NYSDCE, 2011). A survey of Pennsylvania residents in October 2009 reported that 63% of respondents in areas with high drilling activity reported significantly increased traffic and congestion associated with trucks compared to just 12% in less impacted areas (Schafft, 2012).

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[3] For an example of a lease template in use in the neighboring state of OH and common to the area, see http://ohioline.osu.edu/als-fact/pdf/Leasing_Farmland_Oil_Gas.pdf.

[4] http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-87960/8000-PM-OOGM0001%20Instructions.pdf

In addition to truck traffic, the second “visible” aspect of shale exploration is an increase in the associated noise likely to alert existing and perspective homebuyers of nearby activity. Studying various stages of the shale exploration process, NYSDCE found decibel levels of 58 decibels at 1000 feet and 52 decibels at 2000 feet, the furthest extent reported, during the well pad construction period compared to baseline ambient rural noise levels of approximately 30 decibels at night. During the horizontal well drilling period, which occurs 24 hours a day, decibel levels were 50 and 44 at 1000 feet and 2000 feet, respectively. During the fracturing process decibel levels were 78 and 72 at the 1000 and 2000-foot range, respectively. Overall, this suggests that in many rural areas the noise associated with shale exploration would be readily apparent at least up to half a mile from an active well pad.

Finally, visibility of an oil and gas rig is likely to indicate nearby activity, even in the relatively hilly and forested areas of Washington County, PA. With heights of up to 150 feet (NYSDCE), drilling rigs are likely to be seen from long distances. Upadhyay and Bu (2010) explore this issue in Bradford County, PA, which is similar in terms of hilly and wooded landscape to Washington County, and report good visibility in many cases at up to 1 mile from the well site. They also note that the use of horizontally placed lighting at night makes distant sights more visible, particularly in relatively dark rural areas. Taken together, the combination of these three measures of visibility to perspective homebuyers suggests that this activity is readily apparent if located within 1 mile of a well site during the site preparation and drilling operations stage of exploration.

3. Hedonic framework

The hedonic framework represents an individual’s utility as a concave function of a bundle of attributes that are capitalized in property values and a composite numeraire commodity.

(1) $$U_{ij}^{k} = U(c, X_i, N_j, Z_{ij}, \alpha^k)$$

Households are assumed to have different preferences, α^k with the utility of an individual, k, choosing house i in neighborhood j dependent on characteristics of the property (X_i), neighborhood or location specific characteristics (N_j), environmental attributes that can vary by home and neighborhood (Z_{ij}), and a composite numeraire commodity (c) . Households maximize utility subject to a budget constraint and bid prices up or down until an equilibrium price schedule is obtained as a function of preferences, housing and location attributes as given by

(2) $$P_{ij} = P_{ij}\left(\beta, X_i, N_j, Z_{ij}\right).$$

To estimate the model econometrically, researchers must specify a functional form for 2 and assume an error structure. We use a Box-Cox regression to determine the appropriate transformation for the dependent variable, house sale price, as that has been shown to improve performance of hedonic specifications when combined with spatial fixed effects (Kuminoff et al., 2010). The general Box-Cox functional form is given by:

(3) $$\frac{P_{ij}^{\theta} - 1}{\theta} = \beta_0 + \beta_1 X_i + \gamma \boldsymbol{Z_{ij}} + \delta_{jt}\left(N_j * T_t\right) + \varepsilon_{ij}$$

where θ is the transform parameter, X_i includes property characteristics such as number of rooms, number of stories, built-up area (sq ft.), age of the property, presence of a garage, pool, distance to Pittsburgh, and distance to the nearest road. To distinguish the impact of shale exploration from other confounding unobserved factors that are specific to the area, we include location by sale year fixed effects ($N_j * T_t$) at the level of the municipalities, which correspond closely to census tracts in our study area.[5]

Recent advances in the hedonic method for estimation of environmental values have focused on spatial and temporal variation in environmental amenities, and therefore the need to control for the spatial and temporal extent of capitalization of these values (Kuminoff *et al.*, 2010). Previous studies have separately explored spatial extents of capitalization of environmental and land use characteristics (Geoghegan et al. 1997; Paterson and Boyle, 2002; Anderson and West, 2006; Abbott and Klaiber, 2010), and timing of sales relative to the introduction of a hazardous waste site (Michaels and Smith, 1990). When considering the impact of shale activity, inclusion of spatial-temporal fixed effects enables us to control for unobservable factors that affect housing values within each municipality and sale year combination. Allowing unobservables to differ from year to year within each municipality ensures that identification of effects associated with shale exploration is not driven by changes in baseline conditions over time that are common across a municipality. Identification comes from differences in shale activity around houses located within a municipality selling during the same year (represented by Z_{ij}). Figure 1 provides a map of transactions and municipalities in our study area.

A challenge in this analysis is that shale exploration is relatively recent and was not widespread until early 2008. In exploring this early effect we are limited by the number of shale gas wells and the small sample of residential properties in close proximity to shale development. In addition, differences in intensity of development across well pads are important because a

[5] For robustness, we also carried-out analysis using block group by sale year fixed effects and report those in the appendix. In our study area we observe transactions in 59 census tracks, 63 municipalities, and 162 block groups during the years 2008 through 2010.

single well pad may contain up to 8 horizontal wells due to the directional nature of horizontal drilling (Abdalla et al., 2012). It is likely that the impact of shale activity depends on both the proximity to the drilling site and the intensity of the surrounding activity as increasing numbers of wells increases the visibility and potential effects of gas wells to prospective buyers. We therefore include the number of horizontal shale wells within specific distance bands and time windows around each property sale as an explanatory variable. In the hedonic price function, the coefficient γ_1 represents the marginal impact of an additional shale well within a given distance buffer and time window on property values. Box-Cox estimation results shown in Table 4 indicate that a square root transformation is most appropriate given our data as revealed by the estimated transformation coefficient of 0.4843. As such, we estimate conditional regressions assuming a transformation coefficient of $\theta = 0.5$ for all subsequent results.[6] Marginal willingness to pay measures associated with shale exploration for the average homeowner in our sample are calculated as

(4) $$MWTP(Z_{ij}) = \frac{\partial P_{ij}}{\partial Z_{ij}} = \sqrt{\overline{P}}\ \hat{\gamma}\ .$$

4. Data

Marcellus Shale gas exploration began in Southwestern Pennsylvania during the mid-2000s and rapidly expanded by the end of the decade. We use data from Washington County, a county to the south of Pittsburgh and exploit the close proximity of housing transactions to shale activity for econometric identification in our analysis (Figure 1). In our study area widespread shale activity began in 2008, with much of this activity located near residential homes. Our

[6] For comparison, we also estimated semi-log models that assume a transformation of theta = 0, a common functional form used in the literature, and find qualitatively similar results. Results are available upon request.

econometric specification requires data on housing transactions, well locations and timing, surrounding land use, as well as additional controls for source of water and municipalities. The following sub-sections describe each of these components.

4.1 Housing transactions

Housing transactions data were purchased from Dataquick, a private data vendor, spanning January 2008 through October 2010. Unlike much of the country, the Pittsburgh metro experienced relatively stable prices over this time period. The metro level housing price index was 1.249 in the first quarter of 2008 and rose slightly to 1.299 by the end of 2010 (Davis and Palumbo, 2007).[7] The transactions dataset contains a complete set of housing characteristics, sales prices, and sales dates as well as location and address information for each transaction. Structural characteristics include square footage, lot size, bedrooms, baths, stories, year built, presence of a garage, presence of a fireplace, and presence of a pool. After removing non-arm's length transactions and data with missing attributes or extreme outliers for structural characteristics our sample consisted of 4,128 housing transactions.

To locate these properties in space, we used the address information included in the transactions data that consisted of street number, street name, municipality, and zip code to geocode each transaction using the publicly available Yahoo geocoding engine.[8] After eliminating 189 transactions that were unable to be geocoded and an additional 293 transactions that were poorly geocoded, not matching street names or addresses and falling outside of the

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[7] Their MSA level data series is updated and maintained at http://www.lincolninst.edu/subcenters/land-values/metro-area-land-prices.asp.

[8] For comparison, we also used Google's online geocoding tool which revealed a median difference in location of 125 feet. This difference is largely explained by Yahoo locating properties at streets and Google attempting to locate them at parcel centroids. Further manual inspection revealed several large outliers in the Google results where zip codes were not matched correctly. Yahoo employs a hierarchical match which ensures zip codes match for all of our transactions.

reported zip code in the assessor data, we obtained a final estimation sample of 3,646 single-family residential transactions. Summary statistics for these are shown in table 1 and largely conform to our prior expectations about the rural/suburban nature of this area. In particular, the average home has a sales price slightly under $150,000 with an average square footage of 1,659 and is located on 0.61 acres of land. The relatively large acreage for the average home reflects the rural/suburban character of much of the county.

The resulting geocoded transactions are shown in figure 2 overlaid on municipalities. This figure shows that a large number of transactions are located in close proximity to the county seat, Washington, at the intersection of interstates 79 and 70 as well as further north along Interstate 79 in Canonsburg and along the Allegheny County line in the northeast section of the county. Using the geocoded property locations, we formed several supplemental data elements using ArcGIS including distance to the nearest highway or interstate and distance to downtown Pittsburgh.

Information on the location of water services and municipality boundaries was obtained from PASDA, a clearing house for spatial data maintained by Pennsylvania State University which assembles data from local governments across the state. Information on statewide boundaries for public water service providers is provided by the Pennsylvania Department of Environmental Protection. This information was attached to each transaction by overlaying the shapefiles with the geocoded transactions points in ArcGIS. In total, our transactions fall across 67 municipalities and approximately 91% of our transactions are in a water provider's coverage area (Figure 3).

4.2 Shale exploration activity

Data on Marcellus shale gas activity were obtained from the Pennsylvania Department of Environmental Protection and include information on both permitting of wells and the actual drilling of shale gas wells across the state. Historically, many oil and gas wells in Pennsylvania were of the "vertical" type where a single vertical well shaft is drilled to access the resource, usually at shallow depths. In this analysis we focus only on the impacts of horizontal wells for two reasons. Horizontal drilling has now become the most common technique prevalent in Pennsylvania, enabling oil and gas companies to access shale at greater depths and across larger areas. Second, the significant public discourse over health and environmental risks to residents is associated with hydraulic fracturing associated with horizontal wells. Because a large portion of the visible shale gas activity occurs between permitting and the beginning of drilling operations, typically with increased truck traffic over several months, we are interested in identifying the likely time period in which this activity becomes apparent to nearby residents and prospective homebuyers. Using both drilling and permitting data from the Pennsylvania Department of Environmental Protection, we merged each data source to attach the permit date to each drilled well in our study area. In our study area the average time from permit acquisition to the spud date, or the date that drilling begins, is between 3 and 4 months (Table 2). Considering that drilling and hydrofracturing activities occur over 6 to 12 weeks, this suggests that the majority of the visible activity associated with shale exploration occurs in a 6-month time window beginning at the permitting date. We use this date in our subsequent analysis.[9]

We also explore a range of spatial and temporal buffers to examine the persistence of our results across space and time. Summary statistics for the number of shale gas wells and the

[9] We also conducted the analysis using the spud date but found that the use of this date led to a general loss of significance across all models. This loss of significance likely reflects the failure to capture the full effects of shale gas activity on surrounding homes and led us to instead rely on permit dates. Econometric results using the spud date are shown in the appendix.

number of residential properties (treated observations) at each time and distance threshold are shown in Table 3. Extending the spatial buffer to 2 miles and temporal window to 12 months reveals an average number of shale gas wells of 0.63 across all homes with a maximum of 19 wells located within those cutoffs for at least one home. This large number of nearby wells drops to a maximum of only 7 wells when using a 0.75-mile cutoff and 6-month window. The large numbers of wells are reflective of the horizontal nature of drilling activity. While multiple wells can originate from a single location, as the number of wells increase, the size of the drilling operation and amount of associated traffic and "visibility" to homeowners is likely to increase as well. For this reason, focusing on the total count of wells captures important differences across space and time that would be overlooked if we consider only proximity to activity.

4.3 Surrounding land use

The final data component consists of land use data obtained from the USGS 2006 National Land Cover Database (NLCD). Using these data, we calculated percentages of land cover within 1 mile of each house in our transactions data for the categories of agriculture, forest, water, commercial, industrial, residential, and miscellaneous. Summary statistics, shown in table 1, reflect the relatively low-density rural nature of much of Washington County with an average of 27.5% of surrounding land from each home classified as agriculture and a further 29.5% of surrounding land classified as forested lands.

Shale gas exploration largely occurs in agricultural areas resulting from the presence of easier access and fewer landowners to negotiate leases. For our econometric analysis, identifying and controlling for these surrounding land use is important. In addition to controlling for surrounding land use, the presence of specific land use types may also influence the "visibility" of shale gas activity in this area. In particular, it is likely that high percentages of surrounding agricultural land may make activity more visible and could also influence expectations about the extent and location of future activity.

5. Results

Using a Box-Cox regression to determine the appropriate functional form, we estimated several versions of the hedonic price function in Equation 3. We then use a square root transformation suggested by the Box-Cox regression, and define the dependent variable in all subsequent models as $\frac{P_{ij}^{0.5}-1}{0.5}$ (Table 4). To establish a baseline model for comparison, all our econometric models include variables describing housing characteristics, surrounding land use, distance to Pittsburgh, and spatial-temporal fixed effects. In addition, we define several explanatory variables associated with shale exploration that are also common to all model specifications and intended to capture the localized effect of shale activity. The first of these variables is a measure of the total number of shale wells within a specified distance and time cutoff from a property. The second variable captures the proximity of households located near shale development to major highways, as highways are likely to be heavily utilized by truck traffic accessing well sites and may indicate a greater visibility and potential disruption associated with nearby shale activity. This variable is formed as an interaction between the number of shale wells and inverse distance to major highway. The use of inverse distance gives this term an interpretation that a negative coefficient reflects a lower willingness to pay associated with more proximate (temporally and spatially) locations.

The baseline models reported in Table 4 employ a spatial cutoff of 1 mile between shale wells and surrounding property transactions. We further restrict attention to shale wells for which a permit had been acquired no more than six months prior to the sale of the property, and that were subsequently drilled. All the housing characteristics have the expected sign, and the land use variables reveal significant and intuitive results for surrounding land use categories relative to the omitted category of residential development. For our main results characterizing shale development, we find a negative coefficient of -3.2608 associated with the count measure of shale wells, which is significant at a 1% level. While proximity to a major road does not have a significant impact on an average property in our sample, the negative and significant coefficient of -3.2663 for the interaction of well count with proximity to major roadway indicates that an increase in the number of active shale wells disproportionately impacts residents located closer to major roadways.

The impact of shale gas activity on particular subsets of the broader housing market is captured through the inclusion of an interaction between the number of shale wells and the source of water supply to identify the marginal effect of shale activity on a property that uses private well water. To explore the potential risk due to lower water quality, we control for the source of drinking water by including an indicator variable for whether the property is provided with public water supply or private well water.

In addition to potential ground water risks it is likely that the perception of additional future drilling would reasonably be capitalized into housing values. It has been noted in previous research that expectations about future land use patterns can influence the value of open space (Smith *et al.* 2002; Irwin, 2002). One might expect that potential future shale exploration activity and the visibility of current activity are both likely enhanced in agricultural areas. We test for heterogenous impacts associated with agricultural land use by including an interaction between the percentage of surrounding agricultural lands and counts of shale gas wells.

Including these interaction terms, the environmental attributes of interest shown in equation (3) are expanded to include $\left(z_{ij}, \left(z_{ij} \times L_i^{AG}\right), \left(z_{ij} \times X_i^{WATER}\right)\right)$ in the baseline model where shale activity is measured within 1 mile from the property and within 6 months from the sale date. Results, presented in the second column of table 4, show that the impact of shale activity is largely captured by the interaction effects, with no significant baseline effect remaining. We found a negative and significant effect of additional shale activity on properties that rely on well water (-15.1122) and on properties surrounded by agricultural land (-17.4935). While the average impact of shale activity is small, the effect on rural homes is significant and large.[10] We continue to find a negative and statistically significant impact of roadway proximity interacted with shale well counts (-1.0096), although the magnitude of this effect is smaller.

To allow easier interpretation of these effects, the marginal willingness to pay to avoid additional shale well is reported in Table 8 for all our model specifications.[11] These calculations are based on the average property in our sample, with a sales price of $148, 401. For the models including interaction terms shown in column 2 of Table 4, the implied marginal effect of an additional shale well depends on both the interaction and level terms. The first row of Table 8 presents marginal willingness to pay estimates associated with our baseline specification and the subsequent rows report these effects for the expanded model including land use and water source interactions with well counts for specified levels of the interaction variables.

[10] In the appendix Table A4 we also report results for the inclusion of an interaction between large lots (>5 acres) and count of wells. We are unable to include additional interactions in this specification due to high degrees of collinearity.

[11] As shown by Bayer et al [2007] taste-based sorting suggests that virtually all hedonic estimates are likely to be biased. This sorting bias implies that hedonic estimates recover the average willingness to pay for households choosing to live near (dis)amenities. In our application, where we expect close proximity to active shale wells is a disamenity, sorting suggests that our estimates are reflective of the average willingness to pay for households with the least aversion to shale gas wells as those are the households likely to choose to locate near active wells, all else equal. As such, our estimates may understate the magnitude of any potential negative impacts and could be viewed as an upper bound.

Results reveal a marginal willingness to pay of $-1256 to avoid the negative impact of an additional shale well within one mile from an average house in our baseline model. For the interaction models, the sign and magnitude of this effect depends critically on the location of the home. For homes on public water supplies with little (<20%) surrounding agricultural lands, this effect is a positive $1576. Moving the same home to a more agricultural area (80%) reveals a negative impact of $-2467. If that home in an agricultural region relies on private well water, it will see a loss of $-8288 while the same home with private well water in a less agricultural area (20%) will experience a loss of $-4244. These results highlight the importance of accounting for a variety of heterogeneous effects in describing the potential for winners and losers to emerge associated with shale development.

5.2. Spatial and temporal persistence

To this point, our econometric specifications have focused exclusively on shale wells permitted within 6 months prior to a house sale and located within one mile of a home. To examine the persistence of these effects both across space and time, we vary the spatial and temporal buffers and analyze the impact of changes in these assumptions on our results. We expect that potential buyers are likely to perceive considerable risks that are capitalized while activity is ongoing, but upon completion of exploration activity risk perceptions and the associated visibility of nearby wells diminish. If risk perceptions vary over time, as this suggests, we would expect to see any potential negative impacts, transmitted through risk perceptions, attenuate over time. Similarly, as we move farther away from the likely range of perceived risks in space, the effects of shale gas activity as capitalized into housing values are also likely to attenuate.

Table 5 reports these results for the baseline model (specification 3) as well as additional specifications with distance ranges of 0.75, 1 mile, and 2 miles and temporal windows of 6 months and 12 months. We find that the impact of additional wells is largest with a coefficient on well count of -7.8891 for properties that are located within 0.75 miles of the activity, and for which permits were acquired within 6 months from the sale date. This negative impact attenuates both across space and time. The coefficient is insignificant beyond 1 mile regardless of temporal window used and is insignificant at the 12-month time frame regardless of the spatial buffer. The interaction between shale well count and distance to major roadway remains negative and significant in all models. This may support local policymakers concerns regarding degradation of roadways long-after shale activity in an area ceases. Table 6 reports the same temporal and spatial permutations but includes the additional heterogeneous interaction effects on well water and surrounding agricultural land as described above. For interactions with well-water, we find very large and significant negative effects (-73.3292) for homes located within .75 miles and 6 months of a well which become insignificant at 12 months, suggesting a relatively short term impact closely associated with the most active stage of exploration. Interactions with agricultural land are insignificant at the .75 mile range, negative and significant at the 1 mile range (as shown previously) and turn positive and significant at the two mile range. This positive effect at further distances may reflect expectations of potential gains from shale exploration, perhaps associated with the potential for future royalty payments. The implied MWTP values for each of these models are shown in table 8.

5.3 Perceptions of risk

Property values capitalize perceived risk in living close to a disamenity (such as a hazardous waste site) and this perceived risk increases with proximity to a site with unfavorable attributes (McCluskey and Rausser 2001). In the early shale gas exploration phase, due to the absence of clear scientific evidence about the nature and extent of health and environmental risk, peoples' beliefs about potential risk from shale exploration likely depend on proximity to the drilling site and the intensity of activity in the region as we showed previously. We would expect perceived risk of environmental damage to increase as one locates closer to the activity site, and when there are more wells drilled near the property.

To capture the combination of these effects in a single econometric model we create a new variable to explore the impact of perceived risk, measured by the mean inverse distance to wellpads multiplied by the number of wells located within the spatial buffer.[12] This house specific risk measure is given by:

(5) $$R_{ij} = \frac{z_{ij}}{D_{ij}}; \quad \frac{\partial R_{ij}}{\partial z_{ij}} > 0; \quad \frac{\partial R_{ij}}{\partial D_{ij}} < 0$$

where z_{ij} is the number of shale gas wells near a property, and D_{ij} is the average distance to all wellpads located within the distance buffer from the property.[13] The modified hedonic price equation is:

(6) $$\frac{\sqrt{P_{ij}} - 1}{0.5} = \beta_0 + \beta_1 X_i + \gamma \boldsymbol{R_{ij}} + \delta_{jt}\left(N_j * T_t\right) + \varepsilon_{ij}.$$

[12] For consistency with our other specifications, we set inverse distance to 0 for wells beyond a spatial threshold. This is equivalent to assuming an infinite distance.
[13] This specification is similar in spirit to the introduction of risk perceptions employed by McClusky and Rausser (2011) but due to limited data we are unable to fully replicate their model.

In this model, the estimated coefficient γ measures the marginal impact of increased risk from shale activity, which can then be decomposed into a proximity risk effect (holding number of wells constant) and an intensity effect (holding distance constant).

(7) $$R_{ij} = \frac{z_{ij}}{D_{ij}} \Rightarrow \; dR_{ij} = -\frac{\bar{z}}{D_{ij}^2}\, dD_{ij} \; + \frac{1}{\bar{D}_{ij}}\, dz_{ij}$$

The MWTP to avoid an increase in risk from shale activity is:

(8) $$MWTP = \sqrt{\bar{P}}\gamma\left(\frac{\bar{z}}{\bar{D}_{ij}^2}\, dD_{ij} \; + \frac{1}{\bar{D}}\, dz_{ij}\right)$$

where $\bar{P}$ ($148,401) is the average property value in the sample, $\bar{z}$ (3.88) is the mean number of shale wells within a mile, and $\bar{D}$ (3740 ft) is the average distance to a wellpad for properties within one mile from a wellpad. The MWTP for proximity risk can then be measured as[14]:

(9) $$MWTP_{\mathrm{Pr}} = \sqrt{\bar{P}}\gamma\left(\frac{\bar{z}}{\bar{D}_{ij}^2}\, dD_{ij}\right)$$

Similarly, the MWTP to avoid risk associated with an additional shale well located within a mile from an average property in the sample can be measured as:

(10) $$MWTP_{Count} = \sqrt{\bar{P}}\gamma\left(\frac{\bar{z}}{\bar{D}_{ij}^2}\, dD_{ij}\right)$$

In addition to this measure of risk, we also include interaction effects between this risk measure and water source, and the portion of agricultural land around the property as in our previous models. We estimate the hedonic price function in Equation (3) using the new

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[14] We are measuring risk of being located 100ft closer to the shale activity. The negative change in D_{ij} reverses the sign of $\frac{\bar{z}}{\bar{D}_{ij}^2}$.

explanatory variable, R_{ij} rather than the well count alone for comparison to our earlier specifications. Results shown in Table 7 are consistent with earlier specifications indicating an overall negative impact of additional risk (coefficient of -345.431). Including interaction effects, we find a heterogeneous impact on properties that rely on well water (-436.528) and properties that are predominantly surrounded by agricultural land (-719.709). The MWTP associated with increased risk, decomposed into proximity and intensity risk measures is also shown in table 8.

Decomposing the risk effect provides further evidence that, conditional on being located near a wellpad, the intensity effect dominates the proximity effect. A marginal increase in intensity of shale activity (an additional shale well within one mile from the property) results in a negative willingness to pay of $-3,596 and an increase in proximity to shale activity (a property located 100ft closer to a wellpad) will result in a negative willingness to pay of $-377.

5.4 Robustness specifications

We present three robustness checks in an online appendix. The first replaces the municipality by year fixed effects with smaller block-group by year fixed effects in Table A1. These results largely mirror those presented thus far, although with some loss of significance due to sparse sales in many rural block group and year combinations with this more stringent set of fixed effects. Nevertheless, in a model without interactions we find a negative and significant impact of shale exploration (-9.4086) and find qualitatively similar, although not significant, magnitudes and signs for interactions with agricultural land and well-water.

Our second robustness specification replaces the permit date with the spud, or drill, date to gauge the sensitivity of the assumption that impacts are likely to begin around the time of permit date due to the increased visibility of activity between permitting and drilling. We hypothesized that substantial activity begins prior to the actual drilling period and that this activity is important when considering the potential impacts of shale development on surrounding homes. Therefore, we would expect that omitting the period of time between permitting and drilling would result in an attenuation of our results. Results presented in Table A2 support this hypothesis, and show qualitatively similar findings to those reported previously albeit with less significance, as expected.

Our third robustness specification includes nearest wellpad fixed effects to control for potentially unobservable determinants of drilling activity in an area and maintains the municipality by year fixed effects used in our previous models. This specification identifies the impact of increasing numbers of wells over time within a 1 mile buffer of each well-site to directly gauge the importance of measuring well count rather than well pad in our specifications. We report our findings in Table A3 and find qualitatively similar and statistically significant results to those reported in the paper previously, suggesting that our treatment of well counts is appropriate and that households are responding to well activity conditional on the presence or location of well pads.[15] Overall, these robustness specifications provide additional confirmation of our main findings and suggest that our results are not overly sensitive to assumptions on unobservables given the use of spatial-temporal fixed effects at the municipality and sale year level.

6. **Discussion**

The recent expansion of shale gas development across large regions of the United States has led to copious public discourse over perceived health and environmental risks associated with its expansion. Despite the wide spread public discourse, there is surprisingly little applied

[15] We would like to thank an anonymous referee for this specification suggestion.

research examining direct impacts on surrounding populations. This lack of empirical research is likely due to the relatively recent expansion of this activity, which often occurs in regions with isolated and sparse populations making econometric identification challenging. In this paper, we have assembled a dataset that allows us to examine the early impact of shale gas activity on surrounding homeowners in a relatively populated area of Pennsylvania, Washington County.

We find clear evidence that housing markets respond to shale exploration, with impacts dependent both on proximity and intensity of shale activity. Our findings show a strong negative impact associated with the early stages of shale exploration activity, but these impacts are highly heterogeneous, suggesting that a one size fits all characterization of the impact of shale development on surrounding homeowners is not suitable for policy decisions.

As shale activity is rapidly expanding, for example Ohio is currently experiencing the early stages of expansion into the Utica shale; our findings are of immediate policy relevance to local and state officials in Pennsylvania and surrounding states. For policymakers seeking to both reassure and alleviate any potential negative impacts from shale development our results provide several key insights. First, while we find significant negative impacts to surrounding homeowners, these impacts are largely short term and occur in close proximity to shale activity. This suggests that perceptions of risk may be driving much of these relatively temporary losses. Second, we find that these impacts are heterogeneous and any negative effects disproportionately fall on rural households relying on private well water. Finally, we find that households in close proximity to major roadways, likely heavily used for shale activity, see negative impacts that persist both across time and for longer periods.

To address potential negative impacts, many states are considering or have adopted impact fees associated with shale activity. In 2012, Pennsylvania passed Act 13 to amend the existing Oil and Gas Act of 1984 to address issues associated with unconventional (Marcellus and Utica) shale development. One component of this new legislation is the establishment of a fee associated with unconventional shale exploration designed to compensate local communities for damages and establish a fund to hold additional revenues to cover potential damages. How best to use these new revenues is a key policy concern as this law is implemented and funds are disbursed to local communities.

Our results have direct implications for the disbursement of these monies. First, our findings of significant negative impacts that persist over time associated with proximity to major roadways suggest that more oversight and expenditure on repair and upkeep may be needed. Further restrictions tied to routing of truck traffic to the wellpads may also alleviate some of these concerns by choosing routes to avoid close proximity to households, to the extent possible, even if this routing is slightly more expensive to undertake. Second, the large losses associated with households in close proximity to ongoing shale development who are reliant on well water suggests that more formal regulations surrounding water testing and potential remediation may help alleviate perceived risks. Both baseline testing before activity begins and testing after shale activity is completed may help to address any potential impacts although this alone is not likely to fully reduce risks households may perceive. One step towards reducing these perceived risks could be through additional monies set-aside specifically to address water quality issues and develop contingency plans in case of water quality problems. Finally, the large impacts on homes near surrounding agricultural lands suggests that efforts to reduce visibility such as new regulations on nighttime lighting or deliberate siting of well pads in more inconspicuous locations may help to alleviate these effects.

Moving forward, econometric identification of impacts from shale gas activity will continue to face challenges stemming in large part from the potential for localized housing price inflation due to increased demand for housing from new workers, as well as the influx of additional royalty and lease payments to rural areas. Future work to unbundle these competing affects will likely need to obtain information on land leasing and royalty data, which to date is not readily accessible to researchers. While our results provide convincing evidence of relative winners and losers within Washington County, they do not inform us as to whether there are larger price dynamics that have the potential to make everyone better or worse off across a region. Additional research is also needed to understand the larger implications of shale gas exploration on a region.

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Table 1: Summary Statistics (N = 3646)

Variable	Mean	Std. Dev	Min	Max
Sale Price	148,401	117,683	10,150	1,812,812
Square feet (100s)	16.59	7.19	4.52	72.09
Lot size (acres)	0.61	1.10	0.03	28.68
Bedrooms	2.96	0.81	1.00	9.00
Bathrooms	1.68	0.77	1.00	9.00
Stories	1.82	0.88	1.00	5.00
Age	54.38	33.82	1.00	239.00
Garage (0/1)	0.79	0.41	0.00	1.00
Fireplace (0/1)	0.35	0.48	0.00	1.00
Pool (0/1)	0.02	0.13	0.00	1.00
Well Water (0/1)	0.09	0.28	0.00	1.00
Inv. Dist to highway (1/meters)	0.26	6.58	0.00	361.75
Dist to Pittsburgh (miles)	19.00	5.00	10.58	39.51
Age sq	4,100.71	4,319.92	1.00	57,121.00
Square feet sq	327.01	329.81	20.43	5,196.97
Lot size sq	1.58	14.91	0.00	822.54
Land use buffers (1 mile)				
% Agricultural	0.28	0.24	0.00	1.00
% Forest	0.29	0.15	0.00	0.96
% Residential	0.29	0.17	0.00	0.71
% Water	0.01	0.03	0.00	0.18
% Commercial	0.05	0.06	0.00	0.24
% Industrial	0.02	0.04	0.00	0.14
% Miscellaneous	0.01	0.03	0.00	0.27
Transactions by sale year (counts)				
2008	1324			
2009	1355			
2010	967			

Table 2: Timing of well permitting and drilling

Distance Buffer	Time Window	# Permits	Permit to Drill Time (months) Mean	Std Dev	Min	Max
0.75	6	48	3.08	1.58	1	8
0.75	12	87	3.29	2.42	1	19
1	6	96	3.34	2.42	1	19
1	12	128	3.48	2.63	1	19
2	6	188	3.51	2.45	1	19
2	12	210	3.76	2.68	1	19

Table 3: Number of horizontal wells by distance and time from permit date

Variable	Distance (miles)	Time (months)	Mean	Std Dev	Min	Max	# Obs (count >0)
# Horizontal Wells	0.75	6	0.03	0.30	0	7	38
# Horizontal Wells x (Well Water)	0.75	6	0.00	0.13	0	7	5
# Horizontal Wells x (% Ag)	0.75	6	0.01	0.12	0	4	38
# Horizontal Wells	0.75	12	0.05	0.46	0	8	50
# Horizontal Wells x (Well Water)	0.75	12	0.01	0.22	0	8	11
# Horizontal Wells x (% Ag)	0.75	12	0.02	0.26	0	7	50
# Horizontal Wells	1	6	0.07	0.53	0	10	87
# Horizontal Wells x (Well Water)	1	6	0.01	0.25	0	10	13
# Horizontal Wells x (% Ag)	1	6	0.03	0.28	0	8	87
# Horizontal Wells	1	12	0.11	0.76	0	13	107
# Horizontal Wells x (Well Water)	1	12	0.02	0.38	0	10	21
# Horizontal Wells x (% Ag)	1	12	0.05	0.47	0	11	107
# Horizontal Wells	2	6	0.39	1.43	0	14	397
# Horizontal Wells x (Well Water)	2	6	0.06	0.63	0	11	50
# Horizontal Wells x (% Ag)	2	6	0.14	0.83	0	11	397
# Horizontal Wells	2	12	0.64	2.12	0	19	486
# Horizontal Wells x (Well Water)	2	12	0.11	1.04	0	18	65
# Horizontal Wells x (% Ag)	2	12	0.25	1.27	0	16	486

Table 4: Estimation Results (Spatial Buffer - Distance = 1 mile, Time = 6 months)

Dependent Variable: $\left(\sqrt{P_{ij}}-1\right)/0.5$

Variable	**(1) No Landuse Interactions**	**(2) W/ Landuse Interactions**	**Variable**	**(1) No Landuse Interactions**	**(2) W/ Landuse Interactions**
Square feet (100s)	4.651	4.649	LotSize2	-0.880***	-0.885***
	(2.981)	(2.976)		(0.205)	(0.202)
Lot size (acres)	25.523***	25.803***	# Shale wells within 1 mile *(1/ Dist. to road)	-3.266***	-1.010**
	(2.695)	(2.739)		(0.486)	(0.392)
Number of bedrooms	6.624	6.911	# Shale wells within 1 mile, 6 months	-3.261***	7.586
	(5.357)	(5.486)		(1.102)	(4.893)
Number of baths	13.976***	13.880**	Count Shale Wells * Well water		-15.112***
	(5.257)	(5.272)			(4.159)
Stories	-3.640	-3.563	Count Shale Wells * AgLand		-17.494*
	(2.494)	(2.468)			(9.769)
Age of property	-4.074***	-4.083***	Landuse -- Agriculture	-44.753**	-41.719**
	(0.400)	(0.400)		(18.918)	(18.263)
Garage	58.022***	58.171***	Landuse -- Forest	-30.854	-30.698
	(8.906)	(9.003)		(40.191)	(41.147)
Fireplace	55.922***	55.757***	Landuse -- Water	-245.470	-256.530
	(6.745)	(6.722)		(203.906)	(195.617)
Pool	58.480***	58.930***	Landuse -- Commercial	-267.751***	-277.792***
	(20.587)	(20.441)		(82.446)	(87.448)
Well water	-27.803	-25.765	Landuse -- Industrial	-541.532**	-516.689**
	(19.162)	(18.322)		(226.117)	(212.954)
1/Distance to road	0.022	0.0185	Landuse -- Other	94.097	93.434
	(0.168)	(0.168)		(160.002)	(159.074)
Distance to Pittsburgh	-5.990*	-6.216*	Constant	762.737***	767.653***
	(3.220)	(3.159)		(98.731)	(95.920)
Age2	0.013***	0.013***			
	(0.003)	(0.003)	Year-Municipality FE	Included	Included
Square feet2	0.199**	0.198**			
	(0.079)	(0.079)			
Box-Cox Transformation					
Parameter (theta)	0.4843***	95% CI [0.4564 -0.5123]			
	(0.0142)				
Observations	3,646	3,646			
R-squared	0.799	0.799			

Standard errors clustered by municipality in parenthesis

*** p<0.01, ** p<0.05, * p<0.1

Table 5: Spatial and Temporal Persistence of Shale Impacts

	Model Specification - Spatial-temporal buffers					
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Variable	**0.75 mile 6 months**	**0.75 mile 12 months**	**1 mile 6 months**	**1 mile 12 months**	**2 mile 6 months**	**2 mile 12 months**
Square feet (100s)	4.6712	4.6794	4.6516	4.6653	4.6277	4.6391
	(2.984)	(2.991)	(2.981)	(2.990)	(2.974)	(2.979)
Lot size (acres)	25.6175***	25.6697***	25.5230***	25.2998***	25.7109***	25.6458***
	(2.686)	(2.667)	(2.695)	(2.668)	(2.928)	(2.872)
Number of bedrooms	6.7740	6.7741	6.6238	6.6534	6.8633	6.8188
	(5.410)	(5.396)	(5.357)	(5.345)	(5.386)	(5.357)
Number of baths	14.2079***	14.1417***	13.9760***	13.8743**	14.0353***	13.9115**
	(5.219)	(5.203)	(5.257)	(5.269)	(5.235)	(5.255)
Stories	-3.8289	-3.7832	-3.6398	-3.5620	-3.5358	-3.4614
	(2.580)	(2.632)	(2.494)	(2.484)	(2.452)	(2.445)
Age of property	-4.0642***	-4.0680***	-4.0738***	-4.0749***	-4.0611***	-4.0633***
	(0.402)	(0.403)	(0.400)	(0.400)	(0.401)	(0.401)
Garage	58.1647***	58.2155***	58.0216***	58.1277***	58.0368***	58.1147***
	(8.981)	(8.982)	(8.906)	(8.919)	(8.937)	(9.008)
Fireplace	56.0271***	55.9353***	55.9223***	55.7367***	55.5798***	55.5265***
	(6.697)	(6.734)	(6.745)	(6.786)	(6.694)	(6.698)
Pool	63.2366***	62.7562***	58.4804***	57.8452***	57.6582***	57.6123***
	(19.045)	(19.173)	(20.587)	(20.980)	(20.939)	(20.980)
Well water	-27.7398	-27.4814	-27.8026	-27.6991	-28.1764	-28.3729
	(19.179)	(19.136)	(19.162)	(19.171)	(19.142)	(19.317)
1/Distance to road	0.0155	0.0158	0.0219	0.0221	0.0418	0.0405
	(0.162)	(0.162)	(0.168)	(0.167)	(0.178)	(0.175)
Distance to Pittsburgh	-5.8945*	-5.9393*	-5.9901*	-6.0122*	-6.0121*	-6.0554*
	(3.226)	(3.206)	(3.220)	(3.202)	(3.165)	(3.140)

Table 5, cont.

Age2	0.0126***	0.0127***	0.0127***	0.0127***	0.0126***	0.0126***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Square feet2	0.1978**	0.1976**	0.1985**	0.1985**	0.1988**	0.1987**
	(0.079)	(0.079)	(0.079)	(0.079)	(0.079)	(0.079)
LotSize2	-0.8775***	-0.8797***	-0.8802***	-0.8753***	-0.8881***	-0.8876***
	(0.198)	(0.198)	(0.205)	(0.207)	(0.212)	(0.212)
# Wells *(1/ Dist. to road)	-22.8075***	-25.5194***	-3.2663***	-1.5754***	-1.7733***	-1.2150***
	(2.819)	(3.090)	(0.486)	(0.381)	(0.492)	(0.359)
# Shale wells	-7.8991**	-2.3267	-3.2608***	-0.4168	0.2743	0.6990
	(3.496)	(4.729)	(1.102)	(1.721)	(1.027)	(1.083)
Landuse -- Agriculture	-45.7158**	-44.8913**	-44.7526**	-44.5137**	-43.6425**	-43.7651**
	(18.919)	(19.010)	(18.918)	(18.974)	(19.240)	(19.540)
Landuse -- Forest	-30.4850	-30.4325	-30.8544	-30.5211	-29.0084	-27.2913
	(40.169)	(40.157)	(40.191)	(40.146)	(40.915)	(41.179)
Landuse -- Water	-247.9609	-247.2639	-245.4702	-250.0823	-248.7829	-250.6307
	(205.965)	(203.678)	(203.906)	(201.384)	(199.235)	(197.606)
Landuse -- Commercial	-270.0197***	-268.1460***	-267.7508***	-268.1420***	-267.6369***	-265.0781***
	(83.221)	(83.302)	(82.446)	(83.706)	(85.278)	(86.675)
Landuse -- Industrial	-543.3444**	-538.1955**	-541.5316**	-535.4750**	-533.1277**	-530.5826**
	(225.661)	(225.909)	(226.117)	(223.251)	(223.286)	(221.611)
Landuse -- Other	95.7250	94.4380	94.0965	92.8047	92.5308	90.4115
	(160.541)	(161.153)	(160.002)	(160.463)	(159.805)	(159.388)
Constant	759.7057***	760.4119***	762.7371***	763.2948***	761.4022***	762.1125***
	(99.380)	(99.073)	(98.731)	(98.110)	(96.569)	(96.060)
Year-Municipality FE	Included	Included	Included	Included	Included	Included
Observations	3,646	3,646	3,646	3,646	3,646	3,646
R-squared	0.799	0.799	0.799	0.799	0.799	0.799

Standard errors clustered by municipality in parenthesis; *** p<0.01, ** p<0.05, * p<0.1

Table 6: Spatial-Temporal Persistence including Landuse and Water source interactions

	Model Specification - Spatial-temporal buffers					
	(1)	(2)	(3)	(4)	(5)	(6)
Variable	0.75 mile 6 months	0.75 mile 12 months	1 mile 6 months	1 mile 12 months	2 mile 6 months	2 mile 12 months
Square feet (100s)	4.7352	4.6394	4.6490	4.6694	4.5508	4.5940
	(3.021)	(3.018)	(2.976)	(3.007)	(2.947)	(2.958)
Lot size (acres)	25.3614***	25.6315***	25.8031***	25.1591***	25.8173***	25.8343***
	(2.641)	(2.717)	(2.739)	(2.671)	(2.941)	(2.903)
Number of bedrooms	6.6565	6.9558	6.9106	6.7990	6.8842	6.8787
	(5.378)	(5.404)	(5.486)	(5.399)	(5.481)	(5.422)
Number of baths	14.0829***	14.3495***	13.8798**	13.7689**	14.1631***	13.9913***
	(5.240)	(5.265)	(5.272)	(5.335)	(5.225)	(5.213)
Stories	-3.7366	-3.8427	-3.5634	-3.5184	-3.5512	-3.5398
	(2.547)	(2.572)	(2.468)	(2.469)	(2.385)	(2.398)
Age of property	-4.0665***	-4.0751***	-4.0831***	-4.0844***	-4.0546***	-4.0592***
	(0.402)	(0.406)	(0.400)	(0.403)	(0.402)	(0.400)
Garage	58.7264***	57.9756***	58.1713***	58.1691***	57.9402***	58.0861***
	(9.286)	(9.010)	(9.003)	(9.034)	(8.883)	(8.946)
Fireplace	55.9261***	56.1305***	55.7570***	55.7989***	55.4491***	55.4375***
	(6.683)	(6.765)	(6.722)	(6.793)	(6.662)	(6.680)
Pool	63.2028***	62.6848***	58.9298***	57.2782***	58.0861***	57.7715***
	(19.112)	(19.220)	(20.441)	(21.065)	(21.115)	(20.931)
Well water	-25.5278	-29.3010	-25.7648	-28.1295	-28.7315	-31.4377
	(18.383)	(18.214)	(18.322)	(17.596)	(19.372)	(19.209)
1/Distance to road	0.0118	0.0166	0.0185	0.0214	0.0483	0.0489
	(0.161)	(0.160)	(0.168)	(0.165)	(0.177)	(0.174)
Distance to Pittsburgh	-6.0698*	-5.8530*	-6.2155*	-6.0588*	-5.8479*	-5.8797*
	(3.186)	(3.256)	(3.159)	(3.208)	(3.064)	(3.091)

Table 6, continued

Age2	0.0128***	0.0127***	0.0128***	0.0127***	0.0126***	0.0126***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Square feet2	0.1969**	0.1977**	0.1981**	0.1983**	0.2001**	0.1992**
	(0.080)	(0.080)	(0.079)	(0.079)	(0.079)	(0.079)
LotSize2	-0.8661***	-0.8775***	-0.8848***	-0.8700***	-0.8930***	-0.8957***
	(0.194)	(0.200)	(0.202)	(0.207)	(0.213)	(0.214)
# Shale wells within 1 mile * (1/ Dist. to road)	18.2717**	-34.6445***	-1.0096**	-1.7208	-1.9479***	-1.4251***
	(7.429)	(9.398)	(0.392)	(1.371)	(0.505)	(0.386)
# Shale wells	-3.5545	-0.4511	7.5857	3.8731	-3.4767	-1.4252
	(7.943)	(4.616)	(4.893)	(2.639)	(2.452)	(0.928)
Count Shale Wells * Well water	-73.3292***	23.3776	-15.1122***	4.3982	0.1648	2.0747
	(22.495)	(16.832)	(4.159)	(8.588)	(2.131)	(2.048)
Count Shale Wells * AgLand	-8.3825	-13.9250	-17.4935*	-10.2687**	7.9185**	3.4083*
	(26.751)	(10.808)	(9.769)	(4.970)	(3.762)	(1.724)
Constant	762.1840***	759.8818***	767.6529***	764.9372***	759.9020***	761.0478***
	(98.217)	(100.150)	(95.920)	(97.622)	(96.244)	(96.551)
Year-Municipality FE	Included	Included	Included	Included	Included	Included
Observations	3,646	3,646	3,646	3,646	3,646	3,646
R-squared	0.800	0.799	0.799	0.799	0.799	0.799

Standard errors clustered by municipality in parenthesis
*** p<0.01, ** p<0.05, * p<0.1
Land use categories included but not shown here.

Table 7: Estimation results with constructed risk perception measure

Dependent Variable: $\left(\sqrt{P_{ij}}-1\right)/0.5$

Variable	(1) No Landuse Interactions	(2) W/ Landuse Interactions	Variable	(1) No Landuse Interactions	(2) W/ Landuse Interactions
Square feet (100s)	4.6648	4.6651	# Shale wells within 1 mile *(1/ Dist. to road)	-2.6974***	-1.2098***
	(2.985)	(2.981)		(0.420)	(0.355)
Lot size (acres)	25.4977***	25.6953***	Risk	-345.4305***	83.9191
	(2.688)	(2.703)		(35.830)	(155.508)
Number of bedrooms	6.4909	6.7308	Risk * Well water		-436.5284**
	(5.304)	(5.421)			(172.794)
Number of baths	14.0231***	13.8884**	Risk * AgLand		-719.7087*
	(5.276)	(5.296)			(394.464)
Stories	-3.7058	-3.6143	Landuse -- Agriculture	-44.5880**	-42.0804**
	(2.524)	(2.485)		(18.733)	(18.103)
Age of property	-4.0691***	-4.0765***	Landuse -- Forest	-31.0126	-30.2647
	(0.401)	(0.400)		(40.121)	(40.638)
Garage	58.0919***	58.3437***	Landuse -- Water	-242.3662	-248.2973
	(8.994)	(9.141)		(205.754)	(201.956)
Fireplace	55.9825***	55.9254***	Landuse -- Commercial	-269.1082***	-274.1509***
	(6.794)	(6.783)		(82.054)	(83.521)
Pool	59.1614***	59.5071***	Landuse -- Industrial	-545.5344**	-529.5074**
	(20.079)	(20.141)		(226.923)	(219.673)
Well water	-27.3069	-25.5820	Landuse -- Other	96.2736	95.4046
	(18.866)	(18.198)		(160.556)	(159.710)
1/Distance to road	0.0196	0.0164	Constant	762.9149***	765.7001***
	(0.167)	(0.166)		(98.345)	(96.824)
Distance to Pittsburgh	-6.0107*	-6.1729*			
	(3.203)	(3.162)	Year-Municipality FE	Included	Included
Age2	0.0127***	0.0128***			
	(0.003)	(0.003)			
Square feet2	0.1985**	0.1981**			
	(0.079)	(0.079)			
LotSize2	-0.8774***	-0.8806***			
	(0.203)	(0.200)			
Observations	3,646	3,646			
R-squared	0.799	0.799			

Clustered robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 8: Marginal Willingness to Pay Measures

Model Specification	MWTP ($)	% Change in property value
Average Property Value	$148,400.90	
Baseline Buffer: 1 miles, 6 months		
No land use interaction	-$1,256.15	-0.8%
No well water, Surrounding Ag land = 20%	$1,576.05	1.1%
No well water, Surrounding Ag land =80%	-$2,467.46	-1.7%
Well water, Surrounding Ag land = 20%	-$4,244.75	-2.9%
Well water, Surrounding Ag land = 80%	-$8,288.27	-5.6%
Spatial Buffer: 0.75 miles, 6 months		
No land use interaction	-$3,042.96	-2.1%
No well water, Surrounding Ag land = 20%	-$2,013.20	-1.4%
No well water, Surrounding Ag land =80%	-$3,950.13	-2.7%
Well water, Surrounding Ag land = 20%	-$30,262.00	-20.4%
Well water, Surrounding Ag land = 80%	-$32,198.93	-21.7%
Spatial Buffer: 2 miles, 6 months		
No land use interaction	$105.67	0.1%
No well water, Surrounding Ag land = 20%	$715.75	0.5%
No well water, Surrounding Ag land =80%	$2,546.01	1.7%
Well water, Surrounding Ag land = 20%	$779.24	0.5%
Well water, Surrounding Ag land = 80%	$2,609.50	1.8%
Risk Measure: 1 miles, 6 months		
Mean Distance to wellpad within buffer (in 100s ft)	37.488	
Mean number wells within buffer	3.88	
Overall Risk	-$3,973.61	-2.7%
Intensity Risk (one additional shale well within 1 mile)	-$3,596.47	-2.4%
Proximity Risk (locating 100ft closer to wellpad)	-$377.14	-0.3%

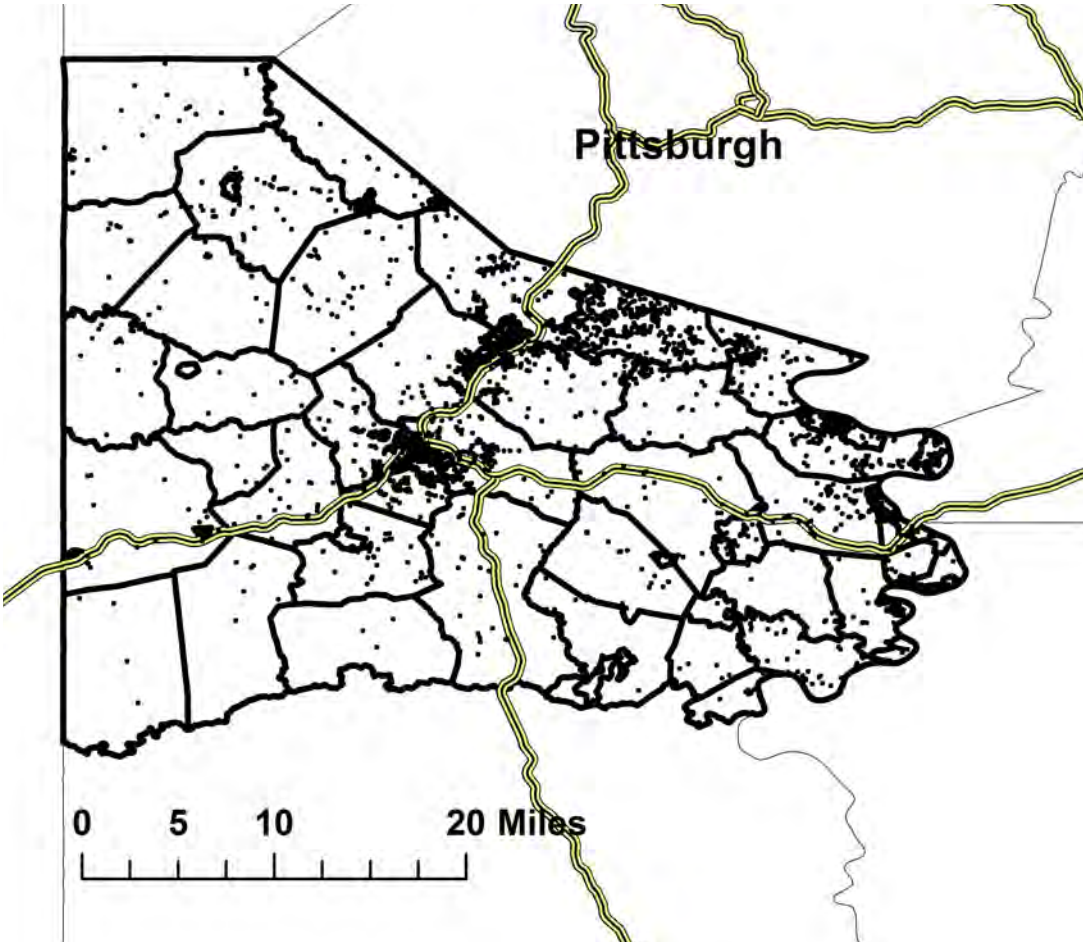

Figure 1: Study area with municipal boundaries and transactions (circles)

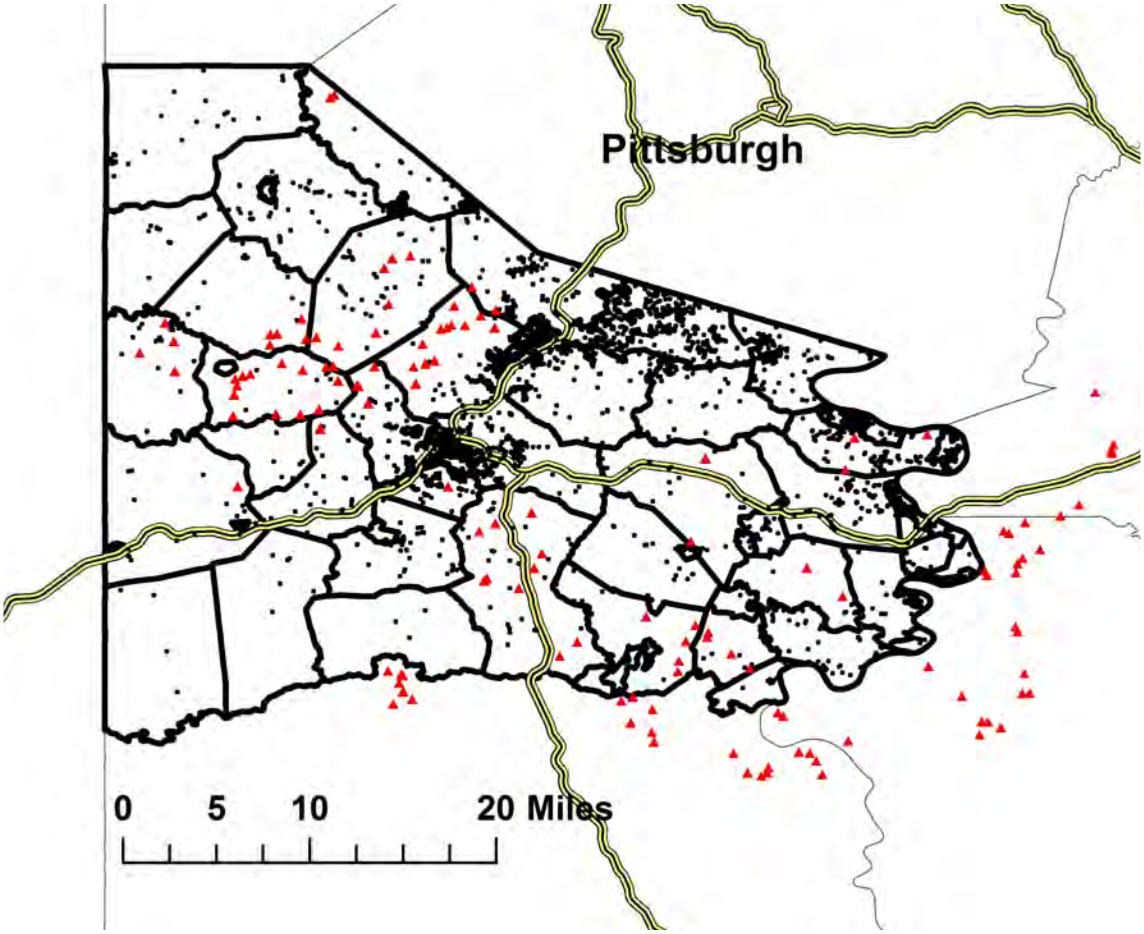

Figure 2: Housing transactions (circles) and shale gas wells (triangles)

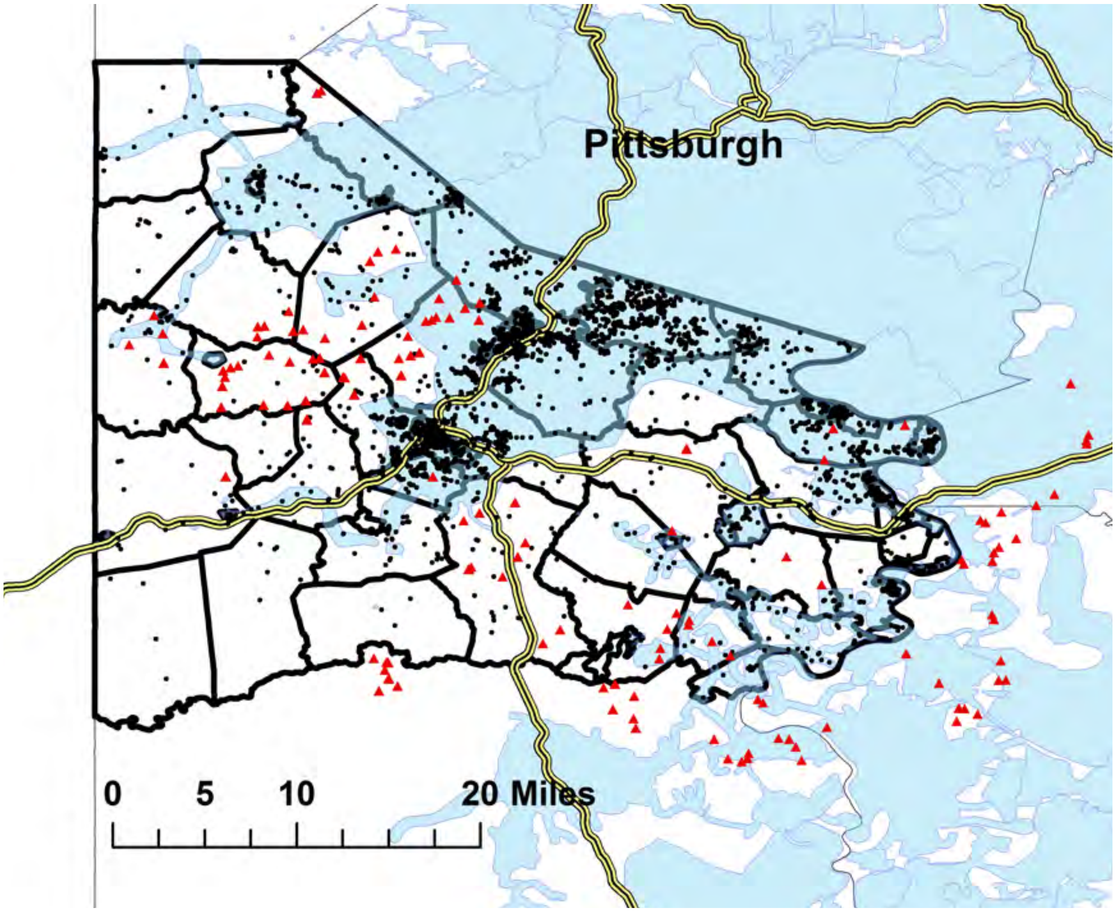

Figure 3: Water provider service areas

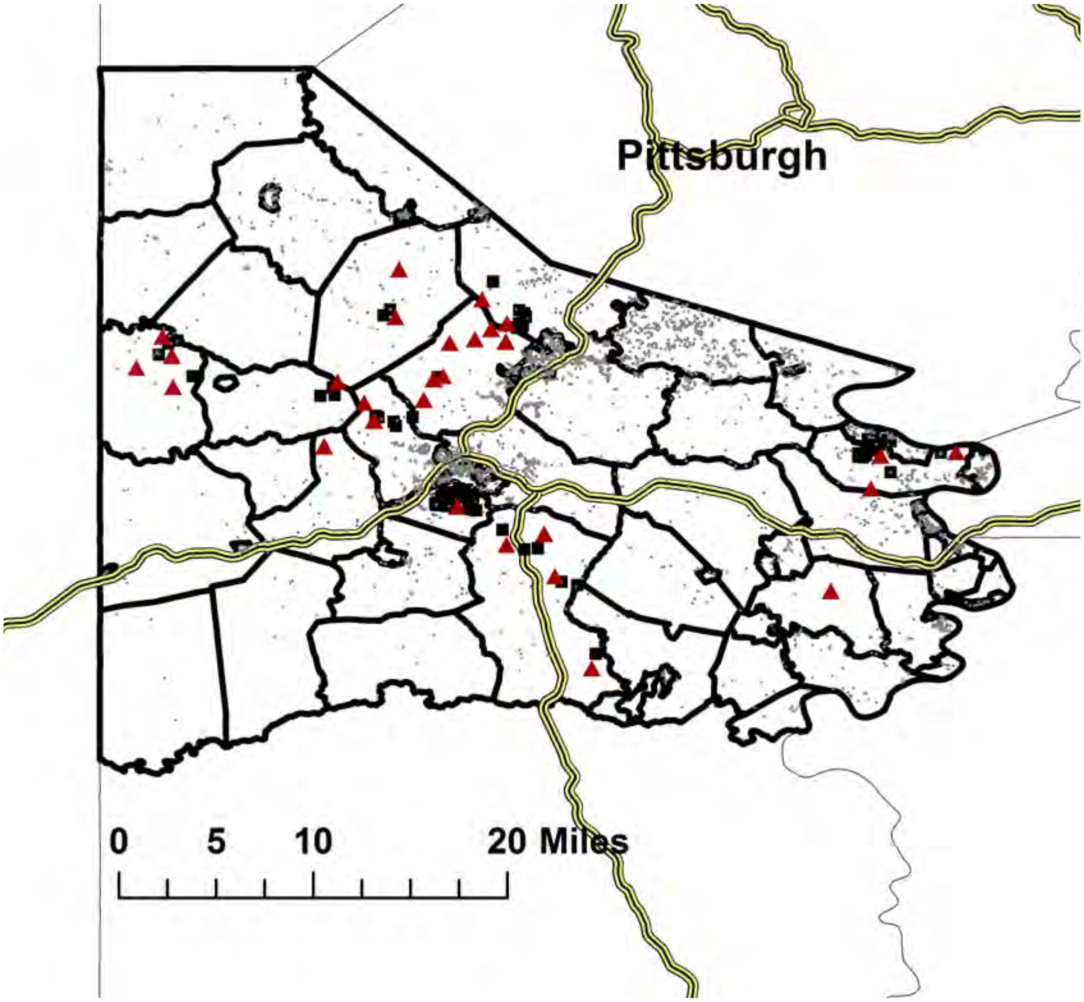

Figure 4: Treated (square) and control (dots) observations with shale wells (6 months, 1 mile)

Appendix: Additional Robustness Results

Table A1: Estimation results with Block Group by Year Fixed Effects

Variable	(1) No Landuse Interactions	(2) W/ Landuse Interactions	Variable	(1) No Landuse Interactions	(2) W/ Landuse Interactions
Square feet (100s)	4.567**	4.535**	LotSize2	-0.771***	-0.781***
	(2.269)	(2.266)		(0.213)	(0.213)
Lot size (acres)	25.392***	25.811***	# Wells within 1m *(1/ Dist. to road)	-1.728	0.074
	(4.892)	(5.013)		(2.506)	(2.332)
Number of bedrooms	7.838*	8.036*	# Shale wells within 1 mile, 6 mo	-9.409*	2.879
	(4.714)	(4.708)		(5.631)	(9.406)
Number of baths	13.183**	13.13**	Count Shale Wells * Well water		-14.965
	(5.670)	(5.675)			(9.591)
Stories	-1.781	-1.80	Count Shale Wells * AgLand		-13.812
	(2.874)	(2.871)			(13.108)
Age of property	-4.511***	-4.519***	Landuse - Ag	-27.709	-27.538
	(0.406)	(0.407)		(51.997)	(52.189)
Garage	51.59***	51.850***	Landuse - Forest	-60.074	-59.236
	(7.995)	(7.993)		(62.183)	(62.366)
Fireplace	46.898***	46.811***	Landuse - Water	-419.419	-416.144
	(5.792)	(5.818)		(370.528)	(369.661)
Pool	54.154***	54.70***	Landuse – Comm.	-128.954	-125.925
	(18.926)	(19.001)		(175.076)	(174.951)
Well water	-33.806**	-32.544**	Landuse -- Industrial	-174.276	-164.401
	(13.951)	(13.845)		(418.331)	(417.653)
1/Distance to road	0.110	0.108	Landuse – Other	-166.611	-170.281
	(0.219)	(0.219)		(235.590)	(235.999)
Distance to Pittsburgh	-4.135	-4.449	Constant	758.54***	764.852***
	(5.987)	(6.105)		(144.750)	(147.392)
Age2	0.017***	0.017***			
	(0.003)	(0.003)	Year-Block group FE	Included	Included
Square feet2	0.181***	0.181***			
	(0.060)	(0.060)			
Observations	3,646	3,646			
R-squared	0.83	0.83			

Standard errors clustered by block group in parenthesis

*** p<0.01, ** p<0.05, * p<0.1

Table A2: Estimation using well-drilled dates

Variable	(1) No Landuse Interactions	(2) W/ Landuse Interactions	Variable	(1) No Landuse Interactions	(2) W/ Landuse Interactions
Square feet (100s)	4.6710	4.6765	# Shale wells within 1 mile *(1/ Dist. to road)	-1.4048**	-1.6899
	(2.992)	(3.000)		(0.530)	(1.306)
Lot size (acres)	25.3537***	25.2287***	# Shale wells within 1 mile, 6 mo	-2.9734	0.3419
	(2.686)	(2.678)		(3.349)	(1.876)
Number of bedrooms	6.5936	6.6750	Count Shale Wells * Well water		7.8052
	(5.300)	(5.375)			(10.188)
Number of baths	13.9079**	13.8243**	Count Shale Wells * AgLand		-11.7408*
	(5.264)	(5.343)			(5.980)
Stories	-3.6570	-3.6879	Landuse -- Agriculture	-44.2650**	-43.4009**
	(2.544)	(2.513)		(18.808)	(18.277)
Age of property	-4.0730***	-4.0774***	Landuse -- Forest	-30.8842	-31.9095
	(0.401)	(0.402)		(40.200)	(40.357)
Garage	58.1519***	58.1390***	Landuse -- Water	-247.0652	-249.8944
	(8.954)	(9.022)		(203.273)	(202.928)
Fireplace	55.8294***	55.9651***	Landuse -- Commercial	-267.913***	-270.3866***
	(6.796)	(6.860)		(83.175)	(83.449)
Pool	57.9499***	57.5554***	Landuse -- Industrial	-538.15**	-534.8394**
	(20.802)	(20.788)		(225.369)	(221.917)
Well water	-27.5449	-28.2325	Landuse -- Other	94.5195	96.2322
	(18.990)	(17.731)		(160.893)	(161.938)
1/Distance to road	0.0198	0.0195	Constant	763.212***	763.3719***
	(0.165)	(0.164)		(98.209)	(98.267)
Distance to Pittsburgh	-6.0167*	-6.0052*			
	(3.213)	(3.217)			
Age2	0.0127***	0.0127***			
	(0.003)	(0.003)			
Square feet2	0.1985**	0.1983**			
	(0.079)	(0.079)	Year-Municipality FE	Included	Included
LotSize2	-0.8768***	-0.8730***			
	(0.207)	(0.208)			
Observations	3,646	3,646			
R-squared	0.799	0.799			

Standard errors clustered by municipality in parenthesis
*** p<0.01, ** p<0.05, * p<0.1

Table A3: Estimation results including Wellpad Fixed Effects

Variable	(1) No Landuse Interactions	(2) W/ Landuse Interactions	Variable	(1) No Landuse Interactions	(2) W/ Landuse Interactions
Square feet (100s)	4.6575	4.6589	# Shale wells within 1 mile *(1/ Dist. to road)	-2.1597***	-0.1117
	(3.122)	(3.117)		(0.398)	(0.358)
Lot size (acres)	25.7549***	26.0024***	# Shale wells within 1 mile, 6 mo	-3.477***	7.688***
	(2.709)	(2.722)		(0.824)	(2.853)
Number of bedrooms	6.7203	7.0052	Count Shale Wells * Well water		-12.364***
	(4.898)	(5.016)			(3.364)
Number of baths	13.7984***	13.7517***	Count Shale Wells * AgLand		-19.864***
	(5.122)	(5.118)			(5.662)
Stories	-3.2663	-3.1952	Landuse -- Agriculture	-57.069***	-54.789***
	(2.561)	(2.542)		(18.353)	(18.361)
Age of property	-4.0492***	-4.0630***	Landuse -- Forest	-29.4316	-30.321
	(0.378)	(0.377)		(42.745)	(43.295)
Garage	58.1540***	58.2777***	Landuse -- Water	-272.660	-285.941
	(8.923)	(8.984)		(222.931)	(213.169)
Fireplace	52.9948***	52.9431***	Landuse -- Commercial	-261.835**	-268.508**
	(6.902)	(6.894)		(113.062)	(117.151)
Pool	57.3414***	57.6403***	Landuse -- Industrial	-642.574**	-617.807**
	(20.442)	(20.177)		(242.856)	(234.130)
Well water	-35.1062*	-33.1527*	Landuse -- Other	58.1985	53.393
	(19.270)	(18.525)		(170.389)	(169.935)
1/Distance to road	0.0197	0.0196	Constant	529.638***	537.355***
	(0.156)	(0.159)		(100.290)	(99.995)
Distance to Pittsburgh	-6.3944**	-6.5567**			
	(2.673)	(2.724)	Year-Municipality FE	Included	Included
Age2	0.0129***	0.0130***			
	(0.003)	(0.003)	Wellpad Fixed Effects	Included	Included
Square feet2	0.1936**	0.1931**			
	(0.085)	(0.085)			
LotSize2	-0.9017***	-0.9057***			
	(0.201)	(0.198)			
Observations	3,646	3,646			
R-squared	0.806	0.806			

Standard errors clustered by municipality in parenthesis
*** p<0.01, ** p<0.05, * p<0.1

Table A4: Estimation including well count interaction with large lots (>5acres)

Dependent Variable: $\left(\sqrt{P_{ij}}-1\right)/0.5$					
	(1)	(2)		(1)	(2)
Variable	**No Landuse Interactions**	**W/ Landuse Interactions**	**Variable**	**No Landuse Interactions**	**W/ Landuse Interactions**
Square feet (100s)	4.6516	4.6106	# Shale wells within 1 mile *(1/ Dist. to road)	-3.2663***	0.0101
	(2.981)	(2.952)		(0.486)	(0.312)
Lot size (acres)	25.5230***	26.2021***	# Shale wells within 1 mile, 6 mo	-3.2608***	0.7675
	(2.695)	(2.835)		(1.102)	(2.357)
Number of bedrooms	6.6238	6.9018	Count Shale Wells * Large Lot		-27.1307***
	(5.357)	(5.519)			(2.481)
Number of baths	13.9760***	13.9321**	Landuse -- Agriculture	-44.7526**	-44.8938**
	(5.257)	(5.258)		(18.918)	(19.096)
Stories	-3.6398	-3.6209	Landuse -- Forest	-30.8544	-30.1849
	(2.494)	(2.486)		(40.191)	(40.385)
Age of property	-4.0738***	-4.0785***	Landuse -- Water	-245.4702	-249.1741
	(0.400)	(0.398)		(203.906)	(199.151)
Garage	58.0216***	58.1541***	Landuse -- Commercial	-267.7508***	-269.9076***
	(8.906)	(8.970)		(82.446)	(84.133)
Fireplace	55.9223***	55.4737***	Landuse -- Industrial	-541.5316**	-531.9391**
	(6.745)	(6.756)		(226.117)	(218.657)
Pool	58.4804***	60.1845***	Landuse -- Other	94.0965	92.74
	(20.587)	(19.973)		(160.002)	(159.090)
Well water	-27.8026	-26.8200	Constant	762.7371***	763.8412***
	(19.162)	(18.855)		(98.731)	(97.151)
1/Distance to road	0.0219	0.0209			
	(0.168)	(0.169)	Year-Municipality FE	Included	Included
Distance to Pittsburgh	-5.9901*	-6.0461*			
	(3.220)	(3.181)			
Age2	0.0127***	0.0127***			
	(0.003)	(0.003)			
Square feet2	0.1985**	0.1988**			
	(0.079)	(0.079)			
LotSize2	-0.8802***	-0.8982***			
	(0.205)	(0.205)			
Observations	3,646	3,646			
R-squared	0.799	0.799			

Clustered robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1