Quantifying the Effects of Underground Natural Gas Storage on Nearby Residents

Michaela Jellicoe and Michael S. Delgado

We estimate the potential negative effects of underground natural gas storage on local residents using hedonic regression and a sample of Indiana properties transacted between 2004 and 2013. We find that underground natural gas storage activities significantly reduce property values. Property values increase by about 10 percent at a distance of 1 kilometer from a storage field. Each additional storage well and observation well located near a property reduces the property's value by about 0.43 percent and 2.64 percent, respectively. Our research sheds new light on a previously unexplored aspect of natural gas resource activities.

Key Words: externalities, hedonic, natural gas storage

In recent years, discussions of issues related to natural gas extraction have increased dramatically in academic and public domains and often have been focused on potential risks associated with hydraulic fracturing. Recent economic research includes studies by Muehlenbachs, Spiller, and Timmins (2012) and Gopalakrishnan and Klaiber (2014). Films such as *Gasland* and *The Promised Land* have pushed issues related to hydraulic fracturing and the natural gas industry into the public eye, as have articles in publications such as the *New York Times* and *Forbes*. Other sectors of the natural gas industry, such as underground storage of harvested natural gas, have received little attention to date in academic or public arenas. Yet, underground natural gas storage presents many of the same potential risks as natural gas extraction, including

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impacts on health, the environment, and public amenities. Understanding these potential impacts is essential in developing a complete understanding of the economic impacts of the natural gas industry.

After natural gas is extracted from an underground formation, it is transported via pipeline to processing plants where it is prepared for consumption. However, much of the gas is not consumed immediately and typically is stored in underground geological formations such as depleted aquifers (Energy Information Administration (EIA) 2013a). Traditionally, such storage provided an inventory of harvested natural gas that could be used to meet peak demand or needs associated with seasonal differences. Recently, however, natural gas production has increased following advances in extraction techniques, and demand for underground storage has been increasing, in part because the quantity of natural gas produced at times exceeds available storage capacity, particularly when demand for gas, which is seasonal, is low. Extraction rates do not necessarily follow consumer demand. In addition, especially harsh winters such as the one experienced in 2013/14 can significantly increase demand for natural gas and exceed supplies held in storage, resulting in a need for greater storage capacity. For instance, a recent *Chicago Sun-Times* article (Fahey 2014) reported that levels of natural gas in storage were the lowest they had been since 2008 because of high demand during the winter.

Media attention directed at natural gas extraction activities has heightened public awareness of the potential associated risks, often emphasizing ground and surface water contamination. Like extraction of natural gas, underground storage of the gas poses health and environmental risks that include migration of the gas out of storage, which can result in contamination of ground water sources (Miyazaki 2009); failure of well casings and cement that protect formations above and below the gas well from contamination (this risk can increase as a well ages) (Miyazaki 2009); slow leakage from the wellhead (known as off-gassing), which can result in methane emissions (Environmental Protection Agency (EPA) 2013); and penetration of the storage formation by another well, including one for water. In addition to environmental risks, there are potential disamenities associated with the infrastructure of storage that include noisy compressor stations required to keep the lines pressurized (Federal Energy Regulatory Commission (FERC) 2013) and visible wellheads. These disamenities can be reflected in the value of nearby properties. We hypothesize (i) that properties located over a storage field have lower values than properties not located over a field and (ii) that properties located near underground storage fields or surface facilities have lower values than properties located at a distance from such sites.

We use a hedonic analysis to determine whether the potential disamenities of underground natural gas storage are significant enough to influence the value of nearby properties. Hedonic models are commonly applied to issues relating to energy, environmental quality, and amenities. For instance, hedonic analyses have been conducted on the impact on property values of nuclear power plants (Gamble and Downing 1982), petroleum refineries (Flower and Ragas 1994), hog operations (Palmquist, Roka, and Vukina 1997), water quality (Leggett and Bockstael 2000), and wind power facilities (Heintzelman and Tuttle 2012). Boxall, Chan, and McMillan (2005) found that oil and gas facilities have a significant negative impact on the value of nearby rural residential properties, and Weber (2012) found that natural gas booms are associated with greater growth in total employment and in wage and salary incomes. Guignet (2013) employed hedonic methods to estimate the impact of leaking underground petroleum storage on property values and found that a leaking tank had little effect on nearby housing values regardless of whether the properties relied on private well water.

In response to recent technological advances, increased attention on the natural gas industry, and potential risks associated with extraction, several recent studies in the literature on econometrics have examined the impact of extraction of natural gas through hydraulic fracturing on nearby property values. For example, Muehlenbachs, Spiller, and Timmins (2012) and Gopalakrishnan and Klaiber (2014) used hedonic methods and generally concluded that hydraulic fracturing activities in Pennsylvania had negatively affected the value of surrounding homes. Furthermore, they found empirical evidence that the risk of ground water contamination was an important source of the negative externalities.

We use a semi-log hedonic price function to estimate the impact of proximity and intensity of nearby underground natural gas storage activity on the value of properties in Indiana. Indiana is an ideal location for assessment of the potential impacts because storage activities there are relatively isolated from other natural resource extraction activities, allowing for a more straightforward econometric identification. Our data set consists of 1,512 residential property sales between 2004 and 2013 in sixteen counties. We find that property values increase with distance from the underground storage activity by about 10 percent per kilometer on average. We further find that an additional storage well near a property reduces its value by about 0.43 percent and an additional observation well reduces the value by about 2.64 percent. Our results also demonstrate that properties that have access to public sources of water are relatively insulated from these negative effects and that the effects do not vary significantly according to whether a property is rural or urban or with the size of the properties.

Background on Underground Natural Gas Storage

Underground storage has played an important part in the natural gas industry since the early 1900s (FERC 2004). Typically, processed natural gas is stored in depleted natural gas reservoirs, salt caverns, and depleted aquifers. Figure 1 shows the distribution of natural gas storage activities in the United States; depleted natural gas reservoirs used as storage are spread across the United States while salt cavern storage is primarily concentrated along the Gulf Coast and storage in depleted water aquifers is concentrated in the upper Midwest. According to EIA (2012), total underground storage capacity in the United States in 2012 was 8,991,335 million cubic feet, and in 2013, the nation’s storage capacity increased by 2 percent (EIA 2013b).

For an underground formation to be suitable for natural gas storage, it must have certain geologic characteristics, such as a layer of porous, permeable rock where the natural gas is stored that is surrounded by impermeable rock that prevents gas from migrating out of the porous layer (Dawson and Carpenter 1963). The industry uses three kinds of geologic formations that vary in terms of their capacity and ease of extraction. Once a formation is chosen for storage, it is conditioned for use with installation of aboveground equipment needed to operate the facility. Wells are used for injection and withdrawal of the gas and for observation of the stored gas; in addition, wells may be used to supply and

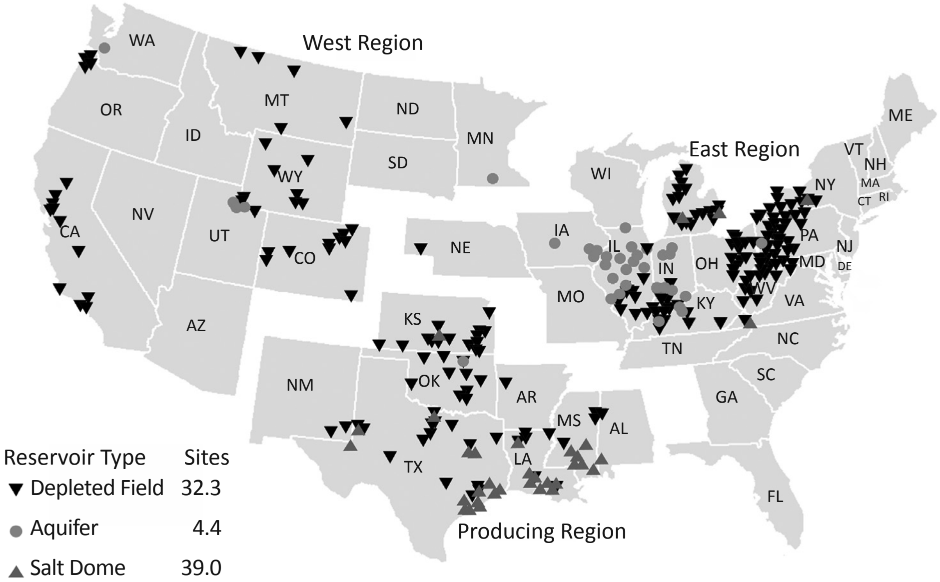

Figure 1. Geographical Location of Underground Natural Gas Storage Activity in the United States in 2012 by Type of Underground Storage Formation

Note: Locations of storage facilities presented in the map are approximate. Some symbols representing storage facilities overlap. Source: Energy Information Administration (2012).

dispose of water. Such wells involve wellhead valve assemblies. Other commonly used equipment includes gathering lines, metering and compression facilities, dehydration units, and generators or transformers (FERC 2013a). Once the underground storage formation is ready for use and required equipment has been installed, the gas is injected into the formation through a wellhead until pressure required to extract the gas later has been established. Consequently, there is a certain amount of gas that cannot be extracted that is referred to as "cushion" gas (Natural Gas Supply Association (NGSA) 2014). The gas that can be extracted is called "working" gas. Each storage formation provides a unique proportion of working gas according to its geology, the facility equipment, and operating processes (EIA 2004).

The most common type of underground formation used for storage is depleted natural gas and oil reservoirs (EIA 2004). Since they had already held natural gas or oil, they had proven capable of storing gas and their geological structures are known (Dawson and Carpenter 1963). Additionally, depleted oil and gas reservoirs may already have some of the needed equipment in place, potentially reducing the cost of operating the storage facility (NGSA 2014).

Aquifers are another storage option. While they naturally stored water (and thus are likely to be geologically capable of storing natural gas), generally less is known about their geologic attributes and collection of such information is often costly. Aquifers also lack any of the infrastructure needed for gas storage (NGSA 2014). Furthermore, the presence of water in the formation leads to a need for additional processing of the gas after it is extracted and the process is subject to stricter regulation by EPA because of the risk of ground water contamination (NGSA 2014).

The third type of underground storage formation, salt caverns, is costly to develop because the caverns must be cleared (FERC 2004), but they have high deliverability, which means that it is relatively easier to extract the stored gas, making them ideal for supplying emergency and peak load demands (NGSA 2014).

Demand for Natural Gas Storage

Traditionally, demand for natural gas has been seasonal, peaking in winter when natural gas is used for heating. Recently, additional natural gas has been used to produce electricity, which has increased demand in summer. Production of natural gas is not seasonal so producers store excess natural gas in periods of low demand for future use. Recent advances in horizontal hydraulic fracturing have greatly increased the efficiency of production, which has exacerbated inconsistencies between supply and demand and increased the need for storage. An additional function of storage is insurance against unexpected events that could disrupt the supply (NGSA 2014). And, since 1994, all interstate pipeline companies have operated in "open access"—third parties can lease storage capacity, allowing them to profit by withdrawing stored natural gas when prices are high and placing gas in storage when prices are low (NGSA 2014).

Legal Requirements

To store natural gas in underground facilities, companies must file an application with FERC and notify all potentially affected landowners, particularly those who own property directly over the storage formation, of the application (FERC 2013).[1] Notification is followed by a program of community outreach that includes open houses and other processes to notify all stakeholders of the project and gather their input (FERC 2012). The company must sign an agreement similar to agreements signed for the right to explore for and produce natural gas with each landowner potentially affected by the storage activity.

At a minimum, operators of storage facilities must obtain the mineral rights to the underground storage facility. In the absence of owning the mineral rights, the company must establish a storage lease or easement agreement with the owners of the rights. When a property is sold, the seller can attach a storage lease or agreement to the land deed and the new property owner can receive compensation for use of the natural gas storage. The company also must obtain a lease or easement for access to any surface facilities that must be installed. When a landowner and storage company cannot reach an agreement regarding either mineral rights or surface access, the company can go to court and may be granted those rights through eminent domain (FERC 2013).

Potential Risks Posed by Storage

Most of the structures necessary for underground storage are located below the surface so some landowners experience little visual impact from the presence of a facility. However, the company monitors the storage formation via

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[1] The Indiana Department of Natural Resources does not require public notice upon filing of a permit application for underground natural gas storage facilities that are regulated by the state but are not under FERC's jurisdiction (Indiana Department of Natural Resources 2014).

surface facilities that can have a visual impact for nearby owners. In addition, compression stations produce noise that can affect nearby residents. FERC (2013) dictates that noise from new or modified compression stations cannot exceed an average of 55 decibels at any "pre-existing noise sensitive area"—areas with schools, hospitals, or residences.

There are potential environmental issues associated with underground natural gas storage. One is the risk of migration of the gas from the underground formation. This can occur vertically through pre-existing wells despite prior assessments of the structural integrity of the formation. Especially in urban and residential areas, leaking natural gas can put homeowners at risk if the gas accumulates within homes (Miyazaki 2009). Over time, both functioning and abandoned wells can degrade. Age increases the risk of failure of the wellhead, thereby increasing the risk of migration of the natural gas (Miyazaki 2009).[2] Federal and state agencies have specific requirements for construction of natural gas wells and regulations regarding abandonment and plugging of wells, but the casings may corrode over time and lead to migration not only of the natural gas but also of brines from deeper formations into shallower ones (Rupp 2011). Migrations of natural gas and brine can pose a threat to sources of ground water. Furthermore, the working gas in an underground storage facility can move from high pressure areas to lower pressure areas in the formation, leading not only to financial losses for the company but also to migration of the gas to other underground formations, including sources of ground water.

Methane emissions and contamination constitute another environmental and health risk associated with natural gas storage (EPA 2013). Methane emissions come from slow leaks (off-gassing) at wellheads and compressor stations, and methane in the oil and natural gas formations can contaminate water wells, presenting a hazard when later exposed to air.[3] There is no federal or state legal standard for levels of methane in drinking water, only general recommendations for safe levels of methane in water (Indiana Department of Natural Resources n.d.).

Thus, it is clear that underground natural gas storage presents a risk of ground water contamination by natural gas, brine, and methane. Generally, these potential risks are similar to ones associated with extraction of natural gas. Homeowners who have access to a public water system may be exposed to less risk since federal and state laws require providers of public drinking water to routinely monitor for contamination and report the results to

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[2] Miyazaki (2009) cites several examples of wellhead and well casing failure, leakage, and natural gas migration in recent years. In Colorado in 1998, a property owner sued an underground storage facility, claiming that a ground water aquifer was contaminated by the storage facility. The natural gas had not migrated out of the property included in the underground storage facility, but some natural gas was discovered in the aquifer. Because of the lawsuit, the storage facility was decommissioned. More extreme cases of migration and risk are linked to salt cavern storage. In Texas in 2004, a well casing failure caused an explosion, which led to a second explosion, loss of a quantity of natural gas worth $30–60 million, and temporary evacuation of nearby residents. The consequences of events like these can range from a financial loss for the storage operator and local businesses to evacuation of nearby residents and even fatalities. In addition, there are environmental consequences, including soil and ground water contamination. Although facilities in salt caverns have had more severe failures in recent years, any negative event tends to increase nearby homeowners' perceptions of risk.

[3] Methane in concentrations of 5–15 percent can be ignited by something as small as a spark in a nearby electrical outlet. Homeowners who rely on well water can educate themselves about the signs of methane in well water, which include bubbling noises in the well and gas bubbles in the water.

state water-quality agencies.[4] EPA sets standards for acceptable levels of contaminants mandated by the Safe Drinking Water Act, which regulates any public water system that serves 25 people or more, and the water provider must give public notice of any violation that occurs. Households that receive water from small providers that serve fewer than 25 people do not have the same protection and thus may be subject to substantial risk of contamination of their water from underground natural gas storage.

Empirical Methodology

The hedonic pricing framework provides a method for measuring the nonmarket value of amenities that are not traded explicitly in a market by breaking a traded commodity such as a home into a bundle of separate attributes. In addition to physical characteristics of the home (e.g., bedrooms), these attributes can include the property's air quality, water quality, and ambient noise level and the occupants' perceptions of the risk posed by proximity to an underground natural gas storage facility. According to Rosen (1974, p. 34), the hedonic hypothesis is that "goods are valued for their utility-bearing attributes or characteristics." Thus, one can use the hedonic hypothesis and theoretical framework with observed prices and attributes to estimate consumers' marginal willingness to pay for individual attributes included in the hedonic price function.

The hedonic price function can be linear or nonlinear, and it is important to specify its functional form correctly to generate accurate estimates of willingness to pay (Cropper, Deck, and McConnell 1988, Kuminoff, Parmeter, and Pope 2010). The log-linear functional form is popular (e.g., Taylor 2003, Heintzelman and Tuttle 2012). Gopalakrishnan and Klaiber (2014) employed a semi-log functional form and a Box-Cox form in the context of natural gas extraction and found that the two models yielded qualitatively similar results. Hence, we follow standard practice and use the log-linear functional form:

$$\ln P_i = \alpha + \beta \mathbf{z}_i + \delta \mathbf{x}_i + \varepsilon_i. \tag{1}$$

In this hedonic price equation, the index $i = 1, 2, \ldots, n$ denotes housing observations, α represents a constant intercept, $\mathbf{z}_i$ is a vector of natural gas storage treatment variables, $\mathbf{x}_i$ is a vector of explanatory variables that typically include housing attributes and indicators for spatial (e.g., county or school district) effects and year of sale, and ε_i is the error term. In our analysis, $\mathbf{z}_i$ contains the variables that measure the impact of underground natural gas storage via the property's location relative to a storage well (over it or near it) and the intensity of storage activity near the property. We include spatial fixed effects to control for omitted variable bias (Kuminoff, Parmeter, and Pope 2010). Inclusion of fixed effects is one effective means of accounting for unobservables in, for instance, geographic or spatial regions (Heintzelman and Tuttle 2012). We also include time dummies for year of sale to account for unobservable time effects that may influence property values (e.g., the recent recession). The coefficient estimates on the treatment variables provide a means of recovering marginal willingness to pay for amenity and housing attributes (given standard

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[4] In Indiana, it is the Department of Environmental Management.

assumptions). In a log-linear specification, the parameters signify a constant percentage change in price.

Data

Overview and Construction

Some recent studies (e.g., Muehlenbachs, Spiller, and Timmins 2012, Gopalakrishnan and Klaiber 2014) have examined negative external effects of hydraulic fracturing in Washington County, Pennsylvania. Although Pennsylvania is home to underground natural gas storage (see Figure 1), it is central to extraction of natural gas through hydraulic fracturing and to extraction of coal and oil. These other extraction activities in Pennsylvania make it difficult to econometrically identify and quantify the value of externalities associated with a single extraction/storage activity. For instance, it is possible that underground natural gas storage contributes no significant additional risk for properties already exposed to extraction of natural gas or other resources, and there may be no way to disentangle the effects of various resource activities econometrically.[5] Hence, in a state like Pennsylvania, it is not clear how underground natural gas storage will affect nearby properties that are in close proximity to other natural resource activities. We focus on identification and estimation of potential negative effects of underground natural gas storage in Indiana, where such storage activities are relatively isolated from other natural resource activities and we can more reliably develop an econometric identification.[6]

Our data set consists of a sample of 1,512 single-family residential transactions, each representing an arms-length property sale, in sixteen counties in Indiana for 2004 through 2013: Cass, Clark, Daviess, Decatur, Greene, Harrison, Huntington, Lawrence, Monroe, Pike, Posey, Pulaski, Randolph, Spencer, Vermillion, and White (shown in Figure 2). We selected all of the counties in Indiana that had at least one underground natural gas storage facility. Within each county, we focus on the properties that were located either directly over a field or within 3.2 kilometers of one.

Figure 3 shows a detailed map of the properties covered by our data set in Monroe County. The central shaded area denotes the location of the underground storage field. Solid dots identify natural gas storage wells and open dots identify observation wells spread within and near the storage field. The pushpins show the locations of property transactions in proximity to the storage field, and the large crosshatched region is the constructed buffer zone that is the focus of our analysis. We chose a 3.2-kilometer buffer zone to focus solely on properties that were located close enough to the storage field to be likely to be subject to any potential externalities. Recent research (e.g., Boxall, Chan, and McMillan 2005, Muehlenbachs, Spiller, and Timmins 2012, Gopalakrishnan and Klaiber 2014) indicates that the effects of natural gas activities are localized to an area with an approximately 3.2 kilometer radius.

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[5] Econometric identification has been an important element of the discussion in most recent works on valuing externalities associated with hydraulic fracturing in general (e.g., Muehlenbachs, Spiller, and Timmins 2012, Gopalakrishnan and Klaiber 2014).

[6] Indiana has potential for extracting natural gas through unconventional activities, but so far, such activities have been limited.

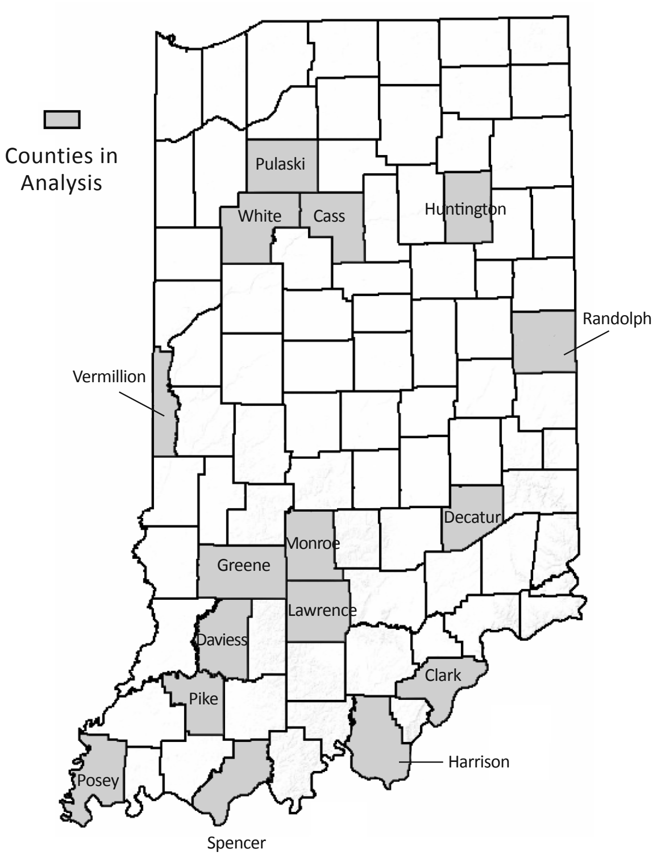

Figure 2. Geographic Location of the Counties in Indiana Used in the Analysis

Base Map Sources: Esri, U.S. Geological Survey, National Oceanic and Atmospheric Administration.

We obtained the data on natural gas storage and observation wells from the Indiana Geological Survey's petroleum database management system and the Indiana Department of Natural Resources. The data provided for each well in the state include the latitudinal and longitudinal coordinates for the well and the date on which construction was completed, which can be used to determine the well's age. The coordinates allow us to pinpoint the exact location of each well using ArcGIS software and then overlay Esri's U.S. county layer package to determine which counties had active storage and observation wells. The Indiana Geological Survey also compiles data on the location, size, and type of each underground field that produces oil and natural gas. We combine the well location and petroleum field maps to determine the location of each underground natural gas and oil formation used to store natural gas.[7]

Prior studies have most often used proximity to natural gas storage activities as a continuous measure of impact. Guignet (2013), however, suggested that

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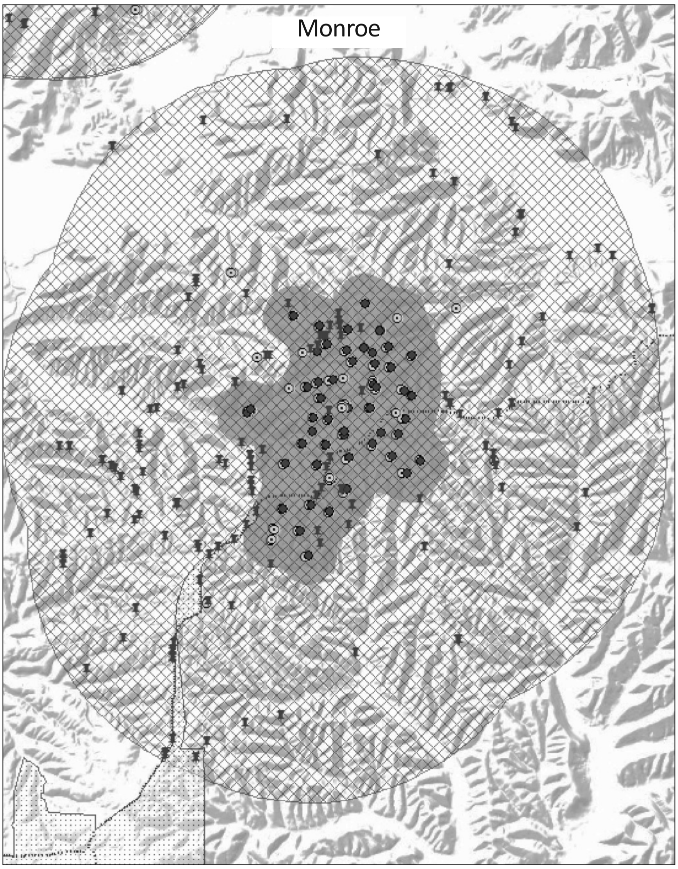
[7] The petroleum field map contains information on natural gas storage activities and oil resource operations. Note that oil resource operations in Indiana generally are not in close geographical proximity to underground storage activities.



The central shaded area shows the location of the underground storage field, the solid dots mark natural gas storage wells, the open dots show the location of observation wells, the pushpins show the location of property transactions, and the large crosshatched region shows the area of study around the storage field.

Figure 3. Map of Data for Monroe County, Indiana

Base Map Sources: Esri, U.S. Geological Survey, National Oceanic and Atmospheric Administration.

distance might not be the most accurate measure. To provide a wide range for measures of the impacts, we include both proximity variables and variables that measure the intensity of natural gas storage activity for each property. The proximity calculations include both the distance to the nearest underground storage field and the distance to the nearest underground natural gas storage and observation wells. We also create a binary variable indicating whether the property is located over an underground storage field. In addition to the proximity treatment variables, we use ArcGIS to count the number of wells within a 3.2-kilometer radius of each property to measure the intensity of natural gas storage activity nearby broken down into the number of storage wells, number of observation wells, and collective number of both types of wells.

Every county in Indiana is required to collect a sale disclosure form for housing transactions. The sale disclosures are submitted to the Department of Local Government and Finance, which maintains a database for the state. Using the sale disclosure online database, we compiled a data set of single-family residential transactions for each county that had active underground natural gas storage wells. The data set provides the parcel number associated with each sale, the date and price of the sale, detailed information about the buyer and seller, and important notes. We removed all observations for $1 sales, which likely represent family or business transactions rather than market (arms-length) sales. We also eliminated all observations for which the GIS software could not match the address to an exact postal address and observations that matched more than one location. We use GIS to map each property in relation to the storage activity data. The data set does not include any information on property attributes or descriptions of houses and their utilities.

Each county's assessor's office maintains records that provide attribute data for each property, including size of the house in finished square feet; size of the property in acres; the home's number of stories, bedrooms, bathrooms, garages, fireplaces, and pools and the year constructed; whether the property has public utilities; and a grade for the quality of construction of the home.

Recent hedonic pricing analyses (e.g., Gopalakrishnan and Klaiber 2014) have used such data to analyze hydraulic fracturing and have identified significant impacts from fracturing on housing values when the homes do not have access to public water. Therefore, the variable for access to public water is particularly important in this analysis. Access to public water does not necessarily mean that the home uses that water, but simply having the ability to connect with a public source can potentially mitigate some of the risk associated with ground water contamination. Any observation that lacked data on the source of drinking water for the property was removed.

We also collected data on each property's distance from the nearest major road, demographics at a census-tract level, the school district for each property, and whether the property was located in an urban area. We defined nearest major roads as primary limited-access roads or interstates, primary U.S. and state highways, and secondary state and county highways. Urban areas include both urbanized areas and urban clusters as defined in the 2010 census. For further details on data construction, see Jellicoe (2014).

Descriptive Statistics

Table 1 provides descriptive statistics for the housing attribute data used in this study. The average sale price of the properties is $94,559.90, average lot size is 1.01 acres, and average home size is 1,664.52 finished square feet. The average home is a little less than 57 years old and is located about 0.82 kilometers from the nearest road. These averages and our indicator of urban properties demonstrate that about 70 percent of the properties are located in rural areas. In addition, most of the homes are constructed with good or average grade materials and 85 percent have garages.

A few details are worth mentioning. First, the minimum sale price in the data set is $10; all $0 and $1 sales were eliminated to restrict the data to arms-length sales. Definitions of arms-length transactions vary so we err on the side of caution and include all other low-value sales. However, only 122 of the 1,512 sales were for less than $10,000, and regressions in which we excluded those 122 sales were only negligibly different from the full regressions reported in this analysis. Second, the minimum value for lot size, which is reported in acres in sale disclosures made by sellers, is zero. Some of the lots are quite small and the acreage was rounded to zero. We conducted regressions in which we excluded

Table 1. Descriptive Statistics for Housing Attribute Data

Variable	Mean	Std. Dev.	Min.	Max.
Sale price (dollars)	94,559.90	2,192.91	10	625,000
Lot size (acres)	1.01	2.96	0	75.42
Height of home (number of stories)	1.22	0.39	1	3
Finished living area (square feet)	1,664.52	798.91	0	9,478
Fireplaces	0.43	0.74	0	4
Bedrooms	2.77	0.80	0	9
Full bathrooms	1.47	0.65	0	5
Half bathrooms	0.23	0.43	0	2
Age of home (years)	56.97	1.05	0	194
Distance to nearest major road (kilometers)	0.82	1.20	0	8.48
Grade building-quality indicator				
Excellent	0.08	0.27	0	1
Good	0.40	0.49	0	1
Average	0.51	0.50	0	1
Poor	0.02	0.13	0	1
Urbanized area indicator	0.29	0.45	0	1
Garages	0.85	0.55	0	3
Pools	0.05	0.21	0	1
Public water indicator	0.68	0.47	0	1

observations with a lot size of zero and the results were not qualitatively different from the results for the entire data set. Third, the minimum value in the data set for finished living area also is zero. This is possible because a few homes included in the data set are extremely small and of poor quality and thus may have no finished living space.

Table 2 reports summary statistics for our natural gas storage treatment variables. Only 11 percent of the properties are located directly over an underground storage field, and the average distance to the center of the nearest storage field is 9.02 kilometers. The average distance to the nearest natural gas storage well is just under 2.5 kilometers, and the average distance to the nearest observation well is 17.35 kilometers. While we restricted our focus to transactions of properties within 3.2 kilometers of the storage field, the average distance measured can be greater since, for example, some storage wells do not have an observation well. In that case, a property near the storage well would be relatively far from the nearest observation well. The number of such observations is relatively small and inconsequential for the analysis. The median distance to the nearest storage well is about 2.3 kilometers, and the median distance to the nearest observation well is 2.5 kilometers. The average property is close to 15.4 storage activities (storage and/or observation wells), 11.62 storage wells, and 3.78 observation wells.

Table 2. Descriptive Statistics for Storage Treatment Variables

Variable	Mean	Std. Dev.	Min.	Max.
Natural gas storage field indicator	0.11	0.32	0	1.00
Distance to nearest natural gas field (kilometers)	9.02	9.93	0	33.90
Distance to nearest storage well (kilometers)	2.45	1.64	0.05	14.48
Distance to nearest observation well (kilometers)	17.35	30.48	0.02	86.01
Storage intensity measure (storage and observation wells)	15.40	20.06	0	78
Gas storage well intensity measure	11.62	15.64	0	60
Observation well intensity measure	3.78	5.25	0	20

Results

We report the results of the regressions for each of our five models in Table 3. To provide a benchmark set of results, the first regression (model 1) uses only the basic hedonic attributes characterizing each property, the year of each sale, and the county indicators. These results are shown in column 1 of Table 3. They indicate that the hedonic attributes generally have the expected impacts on property values. Homeowners prefer larger properties and larger homes that are of higher quality and offer greater amenities. Our estimates indicate that for every one-acre increase in lot size the property value increases 3.84 percent. Every square-foot increase in finished living area raises the value of the property 0.02 percent. Both estimates are statistically significant. The coefficients for height of the home in stories and number of bedrooms and bathrooms are insignificant, suggesting that buyers generally do not prefer a larger number of rooms that are relatively small since square footage is held constant.

We find that the coefficient for the age of the home is negative, significant, and nonlinear: at a mean value of 56.97 years, a home decreases in value by 0.51 percent. The turning point at which a home starts to increase in value due to an additional year of age can be calculated as $x = |\delta_1 / 2\delta_2|$ in which δ_1 is the coefficient on *Age* and δ_2 is the coefficient on Age^2. This turning point is 119.5 years, indicating that, in general, a home loses value as it ages but begins to increase in value once it reaches about 120 years. The coefficient for the number of fireplaces is positive and significant, representing a 9.96 percent increase in property value for each additional fireplace.

Following Halvorsen and Palmquist's (1980) interpretation of the impact of dummy variable coefficients, we can determine the impact of different quality grades for the homes. Halvorsen and Palmquist (1980) showed that the percentage effect of a dummy variable on price in a log-linear model

Table 3. Results of the Preliminary Hedonic Regression and Linear-form Regressions for Storage Proximity

Variable	Benchmark	Located above Field	Distance from		
			Storage Field	Storage Well	Observ. Well
Lot size (acres)	0.0384***	0.0383***	0.0393***	0.0384***	0.0383***
	0.0094	0.0094	0.0094	0.0094	0.0094
Height of home	–0.1262	–0.1278	–0.1195	–0.1261	–0.1262
(number of stories)	0.0829	0.0830	0.0831	0.0829	0.0829
Finished living area	0.0002**	0.0002**	0.0002**	0.0002**	0.0002**
(square feet)	0.0001	0.0001	0.0001	0.0001	0.0001
Fireplaces	0.0996**	0.0988**	0.1004**	0.0998**	0.0993**
	0.0410	0.0410	0.0410	0.0412	0.0411
Bedrooms	–0.0034	–0.0017	–0.0060	–0.0034	–0.0035
	0.0384	0.0385	0.0384	0.0384	0.0384
Full bathrooms	0.0975	0.0972	0.0982	0.0975	0.0980
	0.0637	0.0637	0.0637	0.0637	0.0638
Half bathrooms	–0.0120	–0.0122	–0.0111	–0.0119	–0.0126
	0.0712	0.0712	0.0712	0.0714	0.0713
Age of home (years)	–0.0098***	–0.0098***	–0.0101***	–0.0098***	–0.0099***
	0.0032	0.0032	0.0032	0.0032	0.0032
Age squared	0.00004*	0.00004*	0.00004*	0.00004*	0.00004*
	0.00002	0.00002	0.00002	0.00002	0.00002
Distance to nearest major	0.00001	0.00001	0.00001	0.00001	0.00001
road (meters)	0.00003	0.00003	0.00003	0.00003	0.00003
Excellent grade building	1.8527***	1.8569***	1.8655***	1.8523***	1.8561***
quality indicator	0.2568	0.2570	0.2571	0.2575	0.2580
Good grade building	1.7207***	1.7231***	1.7248***	1.7204***	1.7224***
quality indicator	0.2219	0.2220	0.2219	0.2223	0.2223
Average grade building	1.1496***	1.1526***	1.1481***	1.1494***	1.1510***
quality indicator	0.2136	0.2138	0.2136	0.2139	0.2140
Urbanized area indicator	–0.2019	–0.2024	–0.2179*	–0.2016	–0.1993
	0.1282	0.1283	0.1291	0.1289	0.1297
Garages	0.2372***	0.2356***	0.2387***	0.2372***	0.2366***
	0.0517	0.0518	0.0517	0.0518	0.0519
Pools	0.1129	0.1127	0.1160	0.1131	0.1124
	0.1284	0.1285	0.1285	0.1286	0.1285
Public water indicator	0.0392	0.0374	0.0341	0.0391	0.0401
	0.0816	0.0817	0.0817	0.0818	0.0819
Storage field indicator	—	–0.0666	—	—	—
	—	0.1196	—	—	—
Distance to nearest	—	—	–0.0204	–0.0007	0.0034
field or well (kilometers)	—	—	0.0193	0.0259	0.0244
R-squared	0.4393	0.4395	0.4398	0.4393	0.4393

Standard errors are reported below each coefficient. Asterisks indicate statistical significance at a 1 percent (***), 5 percent (**), and 10 percent (*) level. All regressions include county and year dummies and a constant. The sample size for all regressions is 1,512 observations.

can be calculated by $100(e^{\delta_1}-1)$ where δ_1 is the coefficient on the dummy variable. Relative to a home with a poor quality grade, a home with an excellent quality grade is 537.7 percent more valuable, a home with a good quality grade is 458.84 percent more valuable, and a home with an average grade is 215.69 percent more valuable. These magnitudes are large but are reasonable when viewed within the context of the enormous difference in average price of the homes in each quality group. Average sale price is $18,121 for poor quality (the baseline group), $48,166 for average quality, $126,574 for good quality, and $254,227 for excellent quality.

As seen in Table 3, the impacts of the housing attribute variables on property values are stable across all five model specifications and consistent with our expectations. We next focus specifically on the relationship between underground natural gas storage activity and property values.

Proximity to Underground Storage Activity

We examine the impact of proximity to storage activities by adding four simple linear proximity treatment variables—an indicator for a property located directly above a storage field, distance to the nearest field, distance to the nearest storage well, and distance to the nearest observation well—to the basic hedonic regression. All of the coefficients from these basic linear functional forms, reported in Table 3, are statistically insignificant. Thus, apparently, either there are no negative external effects from underground gas storage activities or there are effects but they are not strong enough to have a substantial impact on property values. However, a more complex functional form that includes quadratic and cubic terms may be more enlightening if the simple model neglects significant nonlinearities.

To capture potential nonlinear impacts from proximity to underground natural gas storage, we run similar proximity treatment regressions but deploy squared and cubic functional forms. The results from those regressions are reported in Table 4.

Table 4. Regression Results for Proximity Measures Using the Nonlinear Form

	Quadratic Functional Form			Cubic Functional Form		
Variable	**Field**	**Storage Well**	**Observ. Well**	**Field**	**Storage Well**	**Observ. Well**
Distance to nearest field or well (kilometers)	0.0286	0.1225***	0.0053	0.0434	0.0326	0.1390***
	0.0277	0.0458	0.0306	0.0494	0.0913	0.0457
Distance to nearest field or well squared	–0.0026**	–0.0144***	0.0000	–0.0048	0.0099	–0.0164***
	0.0011	0.0044	0.0003	0.0062	0.0217	0.0042
Distance to nearest field or well cubed				0.0001	–0.0014	0.0001*
				0.0001	0.0012	0.0000
R-squared	0.4421	0.4434	0.4393	0.4421	0.4439	0.4452

Standard errors are reported below each coefficient. Asterisks indicate statistical significance at a 1 percent (***), 5 percent (**), and 10 percent (*) level. All regressions include a full hedonic conditioning set, county and year dummies, and a constant. The sample size for all regressions is 1,512 observations.

The percentage impact of an additional meter of distance for any of the proximity treatment variables in the quadratic specification can be calculated as $100(\beta_1 + 2\beta_2 z)$ in which β_1 is the coefficient on the linear proximity term, β_2 is the coefficient on the quadratic proximity term, and z is the proximity term. In the cubic specification, the percentage impact is calculated as $100(\beta_1 + 2\beta_2 z + 3\beta_3 z^2)$ in which z is the proximity treatment variable, β_1 is the coefficient on the linear term, β_2 is the coefficient on the quadratic term, and β_3 is the coefficient on the cubic term. When the functional form is nonlinear, the impact of proximity to storage activities on property value depends on the distance.

In the quadratic model, proximity to the nearest gas field and distance to the nearest observation well are not significant (when considering the significance of the average marginal effect, not the individual coefficients) but distance from the nearest gas storage well is significant for both the linear and the quadratic terms. At a distance of 1 kilometer, an additional kilometer of distance increases property values by 9.2 percent. At the mean distance of about 2.5 kilometers, the impact of an additional kilometer of distance on property values is 5.13 percent. These results indicate that the impact of proximity to a storage well is not constant; it decreases as distance from the well increases. This is expected since properties farther from wells would be less sensitive to activities associated with them. Additionally, both terms are jointly statistically significant at a 5 percent level. However, the terms become insignificant when evaluated at the mean distance of 2.5 kilometers, which indicates that the impact of nearby storage wells is quadratic and significant at a distance of 1 kilometer from a home but is no longer significant at a distance of 2.5 kilometers or more. In the top panel of Figure 4, we plot the nonconstant marginal effect of distance from the nearest storage well on property values. Given the confidence bounds, it is clear that the impact of proximity to a storage well becomes insignificant at a distance of about 1 kilometer. At shorter distances, the marginal effect is significant.

The nonlinear estimation results clearly indicate that proximity of underground natural gas storage wells has a significant nonlinear impact. It follows that other types of wells could have nonlinear impacts as well so we consider a cubic functional form. We find that the coefficients in the cubic specification for distance to the nearest well and distance to the nearest storage well are insignificant while the coefficient for distance to the nearest observation well is statistically significant. A 1-kilometer increase in the distance to the nearest observation well results in a 10.03 percent increase in property value. And in the cubic specification, the three proximity terms are jointly significant at a distance of 1 kilometer or more. These results indicate that the impact of proximity of an observation well is nonconstant and is positive for distances of 1 kilometer or more; that is, buyers are willing to pay more to reside farther from observation wells. This marginal effect is plotted in the bottom panel of Figure 4.

The results of the nonlinear proximity regressions indicate that storage and observation wells significantly and negatively affect property values.

Intensity of Underground Storage Activity

Proximity may not entirely identify the external effects of underground natural gas storage (Guignet 2013) so we also perform the regressions using a measure

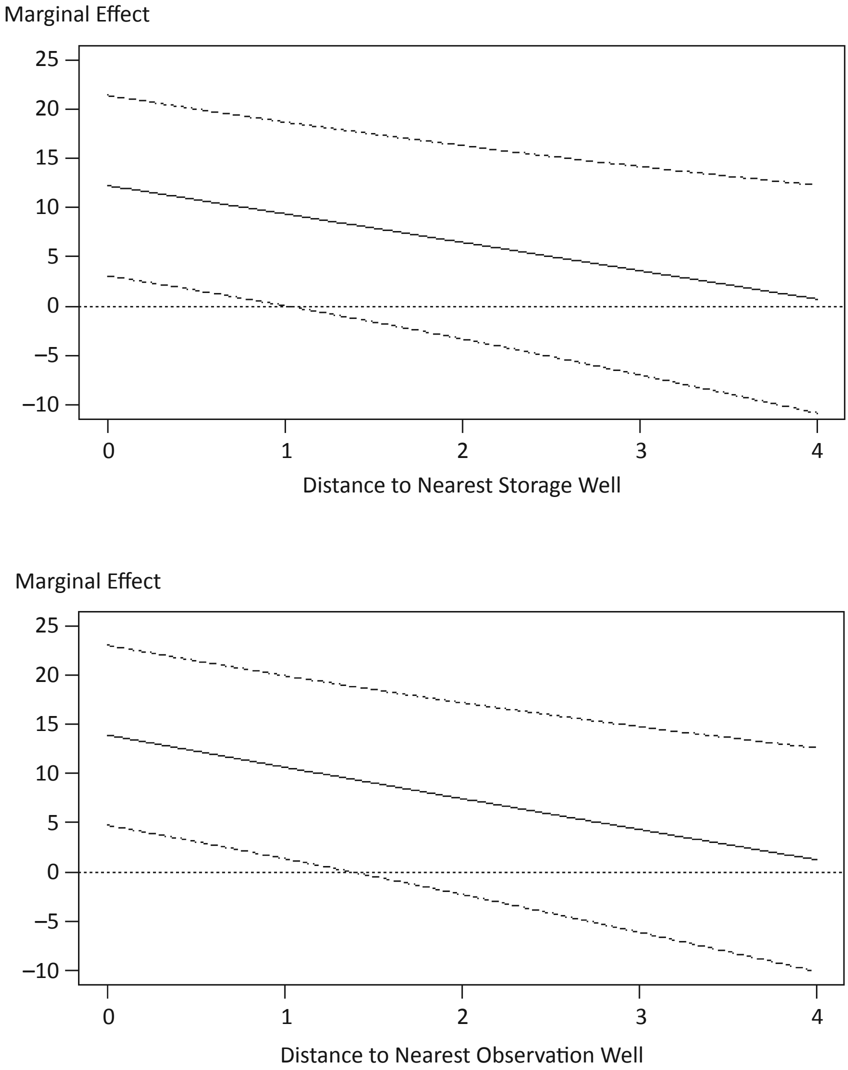


Figure 4. Plots of Nonconstant Marginal Effects of Distance to Nearest Storage and Observation Wells on Property Values

Note: Upper and lower 95-percent confidence bounds appear above and below the marginal effect at each point.

of storage intensity—the number of wells of each type within 3.2 kilometers of a property—and report the results in Table 5. We find that a greater intensity of underground storage activity decreases property values; the three coefficients (all wells, storage wells, and observation wells) are significant at a 10 percent level. An additional well of any type decreases property values 0.43 percent, which equates to a loss of $406.61 in the value of a property at the mean sale price of $94,559.90 and a loss of $2,687.50 in the value of a property at the maximum sale price of $625,000. One additional storage well leads to a 0.48 percent reduction in value, and one additional observation well leads to a 2.64 percent reduction in value. These results are in line with

Table 5. Regression Results for Hedonic Models Using Intensity Measures

	Intensity of		
Variable	Storage (Any Well Type)	Storage Wells	Observation Wells
Coefficient of intensity measure	–0.0431* 0.0241	–0.0477* 0.0281	–0.2640* 0.1379
R-squared	0.4406	0.4404	0.4407

Standard errors are reported below each coefficient. An asterisk denotes statistical significance at a 10 percent level. All regressions include a full set of hedonic conditioning variables, county and year dummies, and a constant. The sample size for all regressions is 1,512 observations. All results reported are scaled by a factor of ten.

the results of the proximity measure—both indicate that the presence of underground natural gas storage activity has a statistically significant and negative impact on the value of nearby properties.

Interestingly, the impact of observation wells appears to be larger in magnitude than the impact of storage wells. As shown in Table 2, the average number of storage wells near a property is 11.62 while the average number of observation wells is much smaller, 3.78. It is reasonable to think that storage wells would impact property values at a diminishing rate—as the number of existing wells exceeds some value, the impact of adding another well would be small. Thus, on average, an additional storage well located near a property may appear to have a smaller impact since most of the properties in the data set are already near a relatively large number of storage wells. Alternatively, landowners may perceive differences between storage and observation wells. Observation wells are used to monitor the storage field for migration of natural gas out of the formation, and homeowners may experience a greater perception of risk when the need for monitoring of a facility is apparent.

Water Source Interactions

Previous studies analyzing the impact of shale gas extraction on nearby property values have found little impact from proximity variables alone. However, several studies of interactions between natural gas extraction and water sources (e.g., Muehlenbachs, Spiller, and Timmins 2012) have revealed more severe impacts for properties that rely on private sources of water. Underground natural gas storage, like natural gas extraction, presents a risk of ground water contamination that is likely to be greater for homeowners who rely on well water. Despite insignificant coefficients in the simple linear models for proximity of underground natural gas storage, we hypothesize that adding an interaction term for water source to the regressions will result in a statistically significant impact for homes without access to public water.

Table 6 presents the results of estimates from interactions of the proximity and intensity treatment variables with an indicator for access to public water. When a property has access to public water ($z = 1$), the percent impact on the property's value can be calculated as $\%\Delta p = 100(\beta_1 + \beta_3)$ for the simple equation $\ln p = \alpha + \beta_1 z + \beta_2 x + \beta_3 zx$ in which z is the proximity treatment variable and x is the binary variable for access to public water.

Table 6. Regression Results for Models That Consider Water Source Interactions

Proximity Measure	Located above Field	Distance to Field	Distance to Storage Well	Distance to Observ. Well
Public water indicator	0.0697	–0.0335	–0.0807	0.1164
	0.0867	0.1189	0.1254	0.0915
Natural gas storage field indicator	0.1604	—	—	—
	0.2363	—	—	—
Distance to nearest field or well (kilometers)	—	–0.0227	–0.0280	0.0012
	—	0.0196	0.0338	0.0244
Interaction with public water	–0.2670	0.0055	0.0513	–0.0044*
	0.2396	0.0070	0.0407	0.0024
R-squared	0.4399	0.4400	0.4399	0.4407

Intensity Measure	Storage	Storage Wells	Observ. Wells
Public water indicator	–0.1308	–0.1189	–0.1047
	0.1056	0.1047	0.1012
Intensity measure (number of wells)	–0.1320***	–0.1530***	–0.6120**
	0.0440	0.0543	0.2015
Interaction with public water	0.1010**	0.1210**	0.3790**
	0.0418	0.0534	0.1601
R-squared	0.4428	0.4424	0.4429

Notes: Standard errors are reported below each coefficient. Asterisks indicate statistical significance at a 1 percent (***), 5 percent (**), and 10 percent (*) level. All regressions include a full hedonic conditioning set, county and year dummies, and a constant. The sample size for all regressions is 1,512 observations. All intensity variable results reported are scaled by a factor of ten.

We find that interactions between public water access and location above a natural gas storage field, distance from the nearest field, and distance from the nearest storage well are statistically insignificant while distance from the nearest observation well is significant.

The terms for the interaction between water source and all of the intensity measures are significant at the 5 percent level. Note that coefficients on the intensity measures in these regressions are all negative and significant while the interaction terms are positive and significant. These results indicate that the impact of storage intensity is significantly negative for properties that do not have access to public water. The impacts on properties that have access to public water are substantially smaller. An increase in storage intensity by one additional well leads to a 1.32 percent decrease in the value of nearby properties that lack access to public water. At the mean sale price of $94,559.90, this is a $1,248.19 reduction in value. A property with public water decreases only 0.31 percent in value. With the exception of intensity of observation wells, none of the intensity measures and interaction terms are jointly significant, suggesting that properties with access to public water are not significantly affected by underground gas storage fields and wells.

Homes without access to public water decrease 1.53 percent in value in response to one additional storage well and 6.12 percent in value in response to one additional observation well. Thus, homes that lack access to public water are subject to statistically significant and larger impacts than homes with public water.

Additional Robustness Checks

So far, we have used proximity and intensity measures to identify and estimate impacts of underground natural gas storage activity on property values. We find statistically significant negative impacts. To ensure that these results are robust, we consider a variety of alternative specifications.

For the county-level fixed effects, we employ a set of dummy variables representing school districts to specify smaller spatial regions and to reflect the impact of school district on property values. The primary difference in results between the county-level fixed-effects models and the school-district-level fixed-effects models is the significance of the variable for number of full bathrooms; it is not significant in the county-level model but is significant at the 5 percent level in the school-district model. The estimates for the hedonic attributes remain consistent, even in the model in which census-block demographic variables are included, and are generally consistent in sign and magnitude with our expectations. Furthermore, goodness of fit for the county-level effects is nearly identical to the goodness of fit for the school-district effects. Also nearly identical are the estimates from measures of distance to the nearest well and distance to the nearest well interacted with water source. The school districts in the area are relatively large so there are only small geographic differences between the results for school districts and counties.

To determine if proximity to natural gas storage activities affects urban and rural homes differently, we interact the proximity treatment variables with a binary variable that identifies properties that are in urban areas. The results, presented in Table 7, identify statistically significant interaction effects between proximity to storage activities and urban properties, and the interaction effect between storage wells and observation wells is also significant. A property in an urban area increases 16.33 percent in value in response to a 1-kilometer increase in distance from the nearest gas storage well. The parameter on the distance to nearest storage well is negative but insignificant.

Table 7. Regression Results for Models That Consider Urban Interactions

Variable	Storage Field	Storage Well	Observ. Well
Distance to nearest field or well	–0.0205	–0.0257	–0.0077
(kilometers)	0.0193	0.0278	0.0247
Interaction of distance with urban	0.0070	0.1890**	–0.0079**
	0.0156	0.0760	0.0031
R-squared	0.4398	0.4417	0.4418

Notes: Standard errors are reported below each coefficient. Asterisks indicate statistical significance at a 1 percent (***), 5 percent (**), and 10 percent (*) level. All regressions include a full hedonic conditioning set, county and year dummies, and a constant. The sample size for all regressions is 1,512 observations.

Table 8. Regression Results for Models That Consider Lot Size Interactions

Variable	Located above Field	Distance to Field	Distance to Storage Well	Distance to Observ. Well
Natural gas storage field indicator	–0.0475	—	—	—
	0.0956	—	—	—
Distance to nearest field or well (kilometers)	—	–0.0230	–0.0080	0.0042
	—	0.0210	0.0290	0.0244
Interaction with lot size	–0.0351	0.0031	0.0040	0.0004
	0.0227	0.0022	0.0080	0.0004
R-squared	0.4052	0.4405	0.4395	0.4396

Standard errors are reported below each coefficient. All regressions include a full hedonic conditioning set, county and year dummies, and a constant. The sample size for all regressions is 1,512 observations.

The impact from proximity to an observation well for an urban property decreases 1.56 percent per kilometer. As with storage wells, the effect of distance to the nearest observation well is negative but not significant, indicating that the magnitude of the impact of increasing distance from the nearest observation well is larger for urban homes. In general, we find no robustness in the interactions between the well intensity measures and urban properties; perhaps such interactions are more complex than simple linear interactions.

Parsons (1990) argued that neglecting to weight a treatment effect (or any attribute that is dependent on location) by lot size may lead to a bias in estimates of the impact of those attributes. For example, a larger lot could result in a smaller impact from proximity to natural gas storage than a small lot. To test for a relationship between the size of the property associated with a home and proximity to natural gas storage activity, we include a regression with a term interacting a continuous variable measuring lot size with the continuous proximity treatment variables and present the results in Table 8. None of the interaction terms are statistically significant. Additionally, when we compare these results to the results of the initial linear proximity treatment, we find that the signs and magnitudes of the results are not materially different. Overall, there is little, if any, interaction between lot size and the proximity treatment effects. Thus, the impact of underground gas storage on property values is unlikely to depend on the size of the property in acres.

Conclusion

Recent years have seen considerable attention paid to the natural gas industry and shale gas extraction. The potential for damage to the environment and various amenities from activities related to natural gas are known, but little attention has been paid to the potential negative effects of underground natural gas storage on nearby residents. As demonstrated by Miyazaki (2009), underground natural gas storage fields present a variety of risks ranging from mild ones such as noise and visual impacts to extreme impacts such as contaminated ground water and evacuations. These risks have been publicized during events, but economists have yet to evaluate the impact of such risks on nearby property values. In a climate of increasing scrutiny of the natural gas industry, quantification of these potential negative effects is especially relevant.

By applying the hedonic method to data on home sales in Indiana, we aim to recover estimates of the impact of underground natural gas storage activities on nearby property values. Results from our county-level fixed-effects models suggest that such activities have a negative impact on property values based on both proximity and intensity measures. In particular, we find that the impacts of distance to the nearest storage well and observation well are significantly nonlinear, diminishing as the distance to a well increases. We show that the intensity of natural gas storage activities is also significant—property values decline significantly with marginal increases in the number of storage and observation wells within 3.2 kilometers. Furthermore, we find that observation wells have a particularly large negative impact on property values relative to storage wells, perhaps because observation wells are more visible or because the homes captured in the data have a relatively large number of storage wells nearby.

The additional regressions provide several useful insights for policymakers wishing to better understand the negative effects identified by our models. Our results indicate that properties with access to public water generally are insulated from the negative effects. Properties without access to public water decrease, on average, about 1.3 percent in value—about $1,248—for each additional well. These results are a general indication that much of the perceived risk associated with underground natural gas storage activities is related to concerns about ground water contamination. We find no evidence that the impact of natural gas storage on property values significantly varies for rural and urban properties or with lot size. All of these aspects are important dimensions of public policy related to natural gas storage.

Policymakers and industry participants can use these results to improve regulations related to underground natural gas storage and to improve lease agreements with homeowners for future storage facilities. In the current environment of increasing demand for natural gas throughout the year, natural gas companies may be planning to increase storage capacity. With a more complete understanding of the impacts of the facilities, they can be better prepared to account for the full costs of the facilities and to respond to increased scrutiny.

Policymakers also need a complete picture of the impacts of the natural gas industry on nearby residents so they can accurately weigh the costs and benefits of new and expanded activities. They will be expected to respond to the greater awareness of risks among their constituents and to determine whether the value of development of new storage facilities outweighs the social cost. These results can aid policymakers in protecting homeowners from the negative impacts of underground storage while assisting the industry in responding to the demand for energy throughout the country.

Quantification of impacts may help both homeowners and the industry negotiate for access to mineral rights. The location of new underground storage facilities is limited by geological requirements, but a more complete understanding of the impacts of the facilities on property values can help the industry and stakeholders make decisions about their development and use. In addition, with this information, policymakers can more effectively update regulations regarding underground natural gas storage facilities on private land as needed.

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